Renewable and Sustainable Energy Reviews 132 (2020) 110135

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: http://www.elsevier.com/locate/rser

On the integration of phase change materials with evacuated tube solar thermal collectors

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ARTICLE INFO

Keywords:
Evacuated tube solar collector
Vacuum tube solar collector
Phase change material
PCM
Thermal energy storage

ABSTRACT

Evacuated tube solar collectors (ETSCs) have gained a significant share of the solar thermal collector (STC) market. Compared to other collector types, ETSCs cover a relatively wide range of operating temperatures, mostly offer higher thermal efficiency, and are available at reasonable prices. But similar to other solar energy technologies, ETSCs are suffering from two main drawbacks associated with intermittency of solar radiation. Phase change materials (PCMs) have been widely used to overcome this challenge. If properly designed and utilised, PCMs can reduce the energy fluctuations and store the solar thermal energy during the daytime and release it in the absence of sunlight. There have been many studies conducted on the integration of PCMs with ETSCs, but the lack of a comprehensive systematic review study focused on such integrated energy systems has remained to be a gap in the literature. This gap is addressed by the present review study. Based on both theoretical and experimental results reported in the literature, the present study focuses on PCM assisted ETSC systems from different perspectives such as integration types, design parameters, and performance. Four main types of integration between PCMs and ETSCs are identified and advantages and disadvantages of each type compared to the others are discussed. Furthermore, state of the art is also clarified, the knowledge gaps are identified, and a roadmap for further studies on these energy systems is provided accordingly.

1. Introduction

Evacuated tube solar collectors (ETSCs) are of the most popular type of solar thermal collectors (STCs) being used. According to the latest report released by the International Energy Agency (IEA) on the global deployment status of solar thermal technology, 'Solar Heat Worldwide' [1], in the year 2017 ETSCs have had a share of 71% in the global STC market. Wide range of operating temperature (i.e., 50 °C and 200 °C) [2], high thermal efficiency, and relatively low costs of ETSCs seem to be the main reasons for their domination in the market. There are few studies reporting better or similar performance for other collectors in special operating and environmental conditions [3]; however, generally, ETSCs are reported to have the highest thermal efficiency in low to mid-temperature applications compared to other STCs [4]. Higher efficiencies are achievable by ETSCs because they are less sensitive to the sunlight direction. The cylindrical shape of ETSCs allows them to absorb the sunlight in different solar azimuths and from both direct and diffuse solar radiations [5]. They also have a vacuum medium that is a perfect insulator eliminating convective heat losses [6]. With such capabilities, even during cold seasons in a temperate climate, ETSCs can reach temperatures between 50 °C and 65 °C [7].

The unique specifications and features of ETSCs have made them a very popular choice for solar thermal applications. However, like all other solar technologies, ETSCs suffer from drawbacks caused by the intermittent nature of sunlight availability. The more solar irradiance the collector receives, the more thermal energy it will produce. However, in many cases there is a high chance of discrepancies between the availability of sunlight and the energy demand being supplied by solar energy [8]. Most importantly, the primary source of energy is absent during the night, when the ETSCs cannot produce any thermal energy.

The main approach to address these drawbacks of solar thermal collectors, including ETSCs, is the employment of thermal energy storage (TES) solutions. By storing the excess thermal energy produced by the collectors and releasing it to meet the supply deficit when required, TES can help matching the supply and demand of energy [9]. The addition of energy storage can also lead to higher overall energy efficiencies for the solar thermal system, and hence reduction in the size and costs of the collectors, especially for regions with high availability of solar irradiance (i.e., due to improved performance of the system) [10].

There are two main types of TESs being widely used in different applications, namely latent heat storage (LHS) and sensible heat storage

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https://doi.org/10.1016/j.rser.2020.110135
Received 27 February 2020; Received in revised form 2 July 2020; Accepted 20 July 2020
Available online 30 July 2020
1364-0321/

Nomenclature

a, a_1, a_2, b, b_0	Defined constants
A	Surface area (m^2)
c_p	Specific heat capacity ($kJ/kg.^{\circ}C$)
f	PCM liquid fraction
G	Solar irradiance (kW/m^2)
h	Heat transfer coefficient ($kW/m^2.^{\circ}C$)
$\overline{\Delta h}$	Average enthalpy difference (kJ/kg)
$\overline{\Delta h}$	Incident angle modifier
m	Mass (kg)
M	Total mass (kg)
q	Specific heat (kJ/kg)
Q	Heat transfer amount (kJ)
$\dot{Q}$	Heat transfer rate (kW)
R	overall thermal resistance ($^{\circ}C/kW$)
SF	Solar fraction
t	Time (s)
T	Temperature
$\overline{T}$	Average temperature ($^{\circ}C$)
$\Delta\overline{T}$	Average temperature difference ($^{\circ}C$)
U	Overall heat transfer coefficient ($kW/m^2.^{\circ}C$)

Abbreviations

ETSC-PCM	ETSC integrated with PCM
C-D	Charge and Discharge
CNT	Carbon nanotube
CPC	Compound parabolic concentrator
ETSC	Evacuated tube solar collector
HTF	Heat transfer fluid
LHS	Latent heat storage
ORC	Organic Rankine cycle
PCM	Phase change material
PCS	Phase change slurry
SHS	Sensible heat storage
STC	Solar thermal collector
TES	Thermal energy storage
TTHX	Triplex tube heat exchanger

Subscripts

a	Ambient
$ab.$	Absorber
$Aux.$	Auxiliary heater
b	Direct irradiance
c	Condenser
cd	Conduction
$ch.$	Charging
cn	Convection
$col.$	Collector
d	Diffuse irradiance
e	Evaporator
f	final
hp	Heat pipe
HTF	Heat transfer floor
i	Inlet, initial
l	Liquid state or losses
m	Mean value
$melt$	PCM melting point
o	Outlet
O	Optical
r	Radiation
s	Solid state
$sol.$	Solar energy
$solid$	PCM solidification point
$st.$	Storage
U	Useful
w	Tube wall

Greek letters

ε	Emittance
η	Efficiency
θ	Solar incident angle (degree)
σ	Stefan-Boltzmann constant (kW/m^2K^4)

(SHS). These TES types, their specifications, advantages, and disadvantages will be discussed further in section 2.2. LHS is achievable by phase change materials. PCMs store and release the thermal energy through the latent heat transfer during their phase-change process [11]. This is the main characteristic of a PCM that results in its other desirable specifications. Among those specifications is their ability of almost isothermal storage and release of heat, even in variable temperature mediums [12]. This isothermal heat transfer makes PCMs able to reduce the output temperature fluctuations of the thermal energy system in which the PCM is employed [13]. Hence, PCMs are specifically good choices for the storage of solar thermal energy, which has a totally variable behaviour. It has been repeatedly reported that employment of PCM is one of the most effective methods to store solar thermal energy [14].

The literature has specifically suggested that the integration of PCMs with ETSCs is very effective for improving the collector performance [4, 15]. While still being researched for further development, there have been some international projects defined at a commercial level based on such integration, including the EU funded projects COMTES [16], Innova MicroSolar [17,18], and “Mediterranean AIRCOND” [19].

For better readability in the present paper, from now on, ‘an ETSC integrated with PCM’ will be named as ETSC-PCM.

Numerous ETSC-PCM designs have been proposed, and their performance has been investigated and reported in the literature. Despite being described as a promising idea, requirement for further research and development for ETSC-PCMs systems has been suggested by many studies conducted on this topic to date. Few studies, especially of numerical ones, have reported this technology can completely satisfy the energy demands of the applications that they have been designed for [20]; however, such a conclusion has not been fully supported by several experimental studies indicating that the benefit of using PCMs for enhancing the reliability of ETSCs has been overstated in some cases [21–23]. These studies have reported limited improvement in operating time of the ETSC-PCM systems, such as a few hours extension of operation during the absence of sunlight [19].

A review of the studies on ETSC-PCM systems can be very helpful in identifying their state of the art, the gaps in the field, and how this technology can be improved further. But very few studies have been undertaken to review such systems by focusing on their specifications, capabilities, challenges, and opportunities. Fertahi et al. [24] have focused on the stratified storage tanks used with solar water heaters. There are some studies on PCM integration with stratified storage tanks that are covered in their review. One of the solar collector types they have considered is ETSC. However, in their study, ETSC-PCMs have not received a due attention. Moreover, their study is mainly on modelling methods and parametric study of the performance indicators. Khan et al. [25] have reviewed PCM integration with different types of solar collectors. Their study is highly focused on flat plate collectors; however, they have briefly included ETSC and photovoltaics in their study too. Chopra et al. [4] have also reviewed the advancement of ETSCs by mostly focusing on two main types of ETSCs, methods for their thermal analysis, and their applications; however, in their review, the integration of PCMs with ETSCs is received a little attention. It is noteworthy that in several review studies, PCMs and ETSCs have investigated as individual technologies, while their integration was not discussed in details [26,27].

The extensive literature review conducted for this study indicated that despite being highly promising, a comprehensive review of ETSC-PCM technology is a clear gap in the literature. Hence, the present paper is trying to address this gap by reviewing its state of the art and identifying opportunities for future research and development.

2. Integration of phase change materials with evacuated tube solar collectors: the principles overview

2.1. Evacuated tube solar collectors

To provide a better understanding of the subject, firstly, some information about ETSCs' and PCMs' working principles are provided. The main components of an ETSC are: a glass tube with vacuum space inside; a solar selective coating as a thermal absorber layer in the shape of a tube or a plate inside the glass tube; heat transfer components in a variety of designs inside or connected to the absorber layer; and in most cases a container at the top, called the manifold, to store the thermal energy produced by the collectors or pass it to the heat transfer fluid (HTF). Fig. 1 shows the schematics of a typical ETSC design. In this figure, the heat pipe ETSC type is presented, which is one of the most common and most efficient heat transfer designs for ETSCs [28].

There are also other designs being applied inside the inner tube of ETSC to receive and transfer the incident solar thermal energy. According to the literature and current status of the technology, there are five main designs for solar thermal energy collection by ETSCs. Fig. 2 shows simplified schematics of these main ETSC designs.

In all the designs shown in Fig. 2, the dotted area is the vacuumed space between the absorber and the outer glass tube. The primary mechanism by which the absorbed heat can be lost is convection, and the vacuum acts as a strong thermal insulator and eliminates the losses by convection heat transfer. In many cases, for the first two types, i.e., all-glass and metal-glass tubes [29,30], and always for the heat pipe type, the absorbed heat is transferred by the thermosyphon mechanism. But for the other two designs, the HTF gets warmed up as it passes through the tube. This mechanism is also applicable to the all-glass and metal-glass tube types. In general, the heat pipe type that typically is filled with water or ethylene glycol [31], usually has a better performance than other designs [28,32].

As discussed earlier, because of their cylindrical shape, ETSCs absorb both direct and diffuse solar irradiance. The effects of these two types of radiation can be shown by a general equation for calculatiing the rate of solar thermal energy collection by ETSCs [33–36]:

$$\frac{\dot{Q}_{col.}}{A_{col.}} = \eta_{Ob} K_b(\theta) G_b + \eta_{Od} G_d - a_1 (T_m - T_a) - a_2 (T_m - T_a)^2 \tag{1}$$

where $\dot{Q}_{col.}$ is the rate of collected solar thermal energy (kW), $A_{col.}$ is the aperture area of the collector (m^2), $K_b(\theta)$ is the incident angle (θ) modifier, T_m is the collector mean temperature ($^\circ C$), T_a is the ambient temperature ($^\circ C$), η_{Ob} and η_{Od} are collector optical efficiency for direct and diffuse solar irradiance, G_b and G_d are the direct and diffuse solar irradiance (kW/m^2), a_1 and a_2 are the constant and temperature-dependent parts of the overall heat loss coefficient, respectively. The values of A_c, η_{Ob}, η_{Od}, a_1, and a_2 are determined based on ETSC performance data. It must be noted that several methods are reported for calculating the rate of solar thermal energy collection by ETSCs and here only one of the methods that has been repeatedly employed in the literature [33–36] is presented by Eq. (1). Moreover, with the aim of more accurate calculations, several modifications of Eq. (1) have also been derived and presented in various studies [37,38]. Two of the most detailed modifications on the same method are discussed by Hertel et al. [39] and Barone et al. [6]. More information on the concept of this method is available in the two latter references.

Eq. (1) is applicable for both steady and transient assumptions. When a steady state is assumed for the problem, average values are considered for the parameters that are variable in time [35]. On the other hand, for calculations with a transient assumption, mostly a numerical approach is used to calculate the transient rate of solar thermal energy collection [36–39]. With that regard, the whole modelling duration is divided into short time intervals. Then, momentary values are taken for time-dependent parameters such as the solar irradiance, incident angle, and ambient temperature [36]. Doing so, a time-dependent profile for the rate of solar thermal energy collection will be obtained and in the next step the total amount of collected solar thermal energy is achievable.

It is noteworthy that one of the terms which is mostly used for transient modelling with modified versions of Eq. (1) is $-a_3\frac{dT_m}{d_t}$. Similar to the other coefficients in Eq. (1), the value of a_3 is determined by the specifications and overall performance of the ETSC itself.

A simple relation for calculatiing the incident angle modifier, presented in Eq. (1), is as below [33]:

$$K_b(\theta) = 1 - b_0\left(\frac{1}{\cos\theta} - 1\right) \tag{2}$$

where b_0 is another constant parameter based on ETSC performance. The value of the incident angle is also obtainable by some relations which are not aligned with the aims of this paper. More information on the calculation of incident angle can be found in other studies [40]. Eq. (1) is a rather simple method for calculating the amount of collected thermal

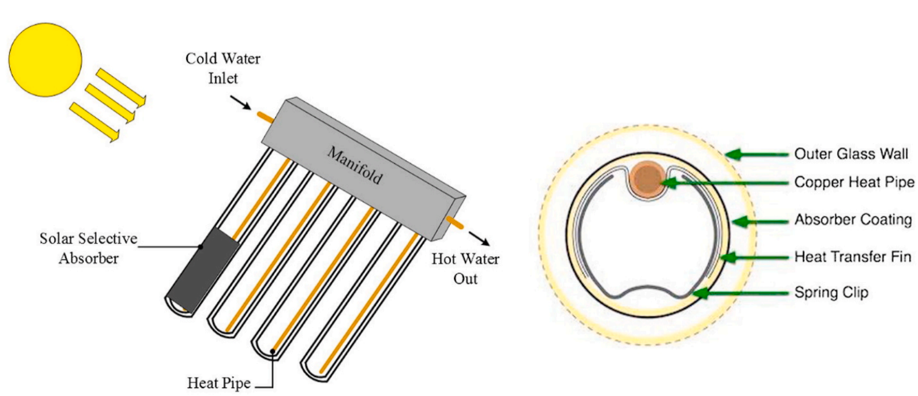

Fig. 1. Schematics of a typical heat pipe ETSC [9] (with permission of reuse from Elsevier).

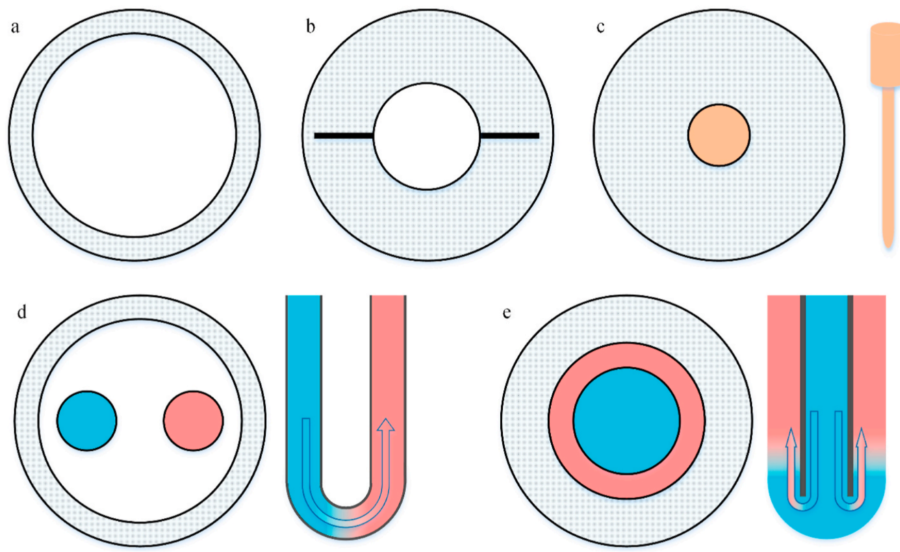

Fig. 2. Various ETSC types. a) all-glass tube b) metal-glass tube c) heat pipe d) U-tube e) double-pipe.

energy [33]. This equation shows the effects of both direct and diffuse solar irradiance on ETSCs. However, ETSCs also have some heat losses, and the useful thermal energy collected by ETSC is [41]:

$$\dot{Q}_U = \dot{Q}_{col.} - U_l A_{col.}(T_m - T_a) \tag{3}$$

where $\dot{Q}_U$ is the useful collected thermal energy rate (kW) and U_l is the overall heat loss coefficient ($kW/m^2.^{\circ}C$). ETSCs have three main heat losses: radiant and conductive heat losses from the absorber to the outer tube wall, and convective heat loss from the outer tube to the ambient [41]. Hence, the value of U_l can be calculated by Eq. (4) [41]:

$$U_l = \left(\frac{1}{h_{r,ab.}} + \frac{1}{h_{cd,ab.}} + \frac{1}{h_{cn,w}}\right)^{-1} \tag{4}$$

where $h_{r,ab.}$ is the radiative heat transfer coefficient between the absorber and outer tube wall ($kW/m^2.^{\circ}C$), $h_{cd,ab.}$ is the conductive heat transfer coefficient between the absorber and the tube inner wall ($kW/m^2.^{\circ}C$), and $h_{cn,w}$ is the convective coefficient of heat transfer from the outer tube wall to the ambient ($kW/m^2.^{\circ}C$). It is noteworthy that because of the vacuum between the tube inner and outer walls, the only heat transfer between these two surfaces is based on the radiation mechanism [41]. The values of $h_{cn,w}$ and $h_{cd,a}$ depend on the specifications of the ETSC and ambient. $h_{r,ab.}$ is calculated by the equation below [41,42]:

$$h_{r,ab.} = \frac{\sigma\varepsilon_{ab.}\left(T_{ab.}^2 + T_w^2\right)(T_{ab.} + T_w)}{1 + \frac{A_{ab.}\varepsilon_{ab.}}{A_w\varepsilon_w}(1 - \varepsilon_{ab.})} \tag{5}$$

where σ is the Stefan-Boltzmann constant (kW/m^2K^4), $\varepsilon_{ab.}$ and ε_w are the emittance, $T_{ab.}$ and T_w are the ambient and tube wall temperatures (K), respectively, and $A_{ab.}$ and A_w are the surface area of the absorber and the outer tube (m^2), respectively. The above relations are a simplified method for energy analysis of ETSCs. A more detailed energy and heat loss analysis is presented by Chopra et al. [15].

Eqs. (1)–(5) can be generally used for ETSCs, but there are numerous variations and modifications on ETSC components, and in such cases the energy relations must be modified too. The variations in ETSC structure also create different opportunities for integration of PCMs. Based on the working principles of different ETSC types, several designs have been presented and examined in the literature. Some cases can be independent of the ETSC structure, especially the ones equipped with an external PCM units. All these flexibilities offer chances for even more novel designs to be proposed in the future.

2.2. Thermal storage options for solar thermal technologies

Before going through the details of ETSC-PCM systems, their potentials, advantages, and disadvantages of different thermal storage types compared to each other must be studied. Many studies have reported that the utilisation of thermal storage solutions can improve the efficiency of solar thermal collectors [43–45], including ETSCs [29,46–48].

As mentioned earlier, two major options of LHS and SHS are the possibilities to be used as TES with ETSCs. PCMs are among the LHS materials and as a well-known SHS material water can be referred which has been chosen as the storage medium in many studies on SHS integration with ETSCs [49,50]. The main advantage of LHS over SHS is their higher storage density, nearly isothermal heat storage, and less heat losses [51]. It has been reported that in the same volume, PCMs, as the means for LHS, are able to store 5–14 times more thermal energy than the SHS type materials [52]. For the same amount of energy storage, LHS materials usually have higher viscosity and less weight and volume compared to SHS. Hence, less heat losses are expected in the case of using LHS [53]. But despite all these advantages, currently, SHS is dominant in the market due to its lower cost [54]. However, especially the above-mentioned advantages have encouraged a considerable attention towards LHS type thermal storage during the past few decades.

The advantages of LHS is more pronounced when they are coupled with solar thermal collectors. Many applications require a heat source with a specific energy transfer rate or temperature. When it comes to STCs, with the sun as an intermittent source of heat, providing a uniform output by the collectors is not possible. Because of their high thermal capacity, PCMs not only store a high amount of thermal energy (i.e., compared to other thermal storage solutions), but also buffer the fluctuations of the energy source and help the system with providing thermal energy at an almost constant temperature [55]. Moreover, in many cases, the demand side is variable too and cannot be directly matched with the highly variable supply of heat by the STCs [56]; or in an extreme example, solar energy is not even available during nighttime to supply any demand during this period. As mentioned, compared to SHS, LHS solutions are capable of releasing the stored solar thermal energy in more extended periods with less heat losses. This characteristic helps PCMs provide more thermal energy, when the collector alone cannot supply the energy demand [57] and this has increased the popularity of PCM solutions too [58].

It is noteworthy that some studies have not supported PCMs as advantageous solutions to be used with STCs. For instance, through a numerical study, Delgado-Torres and García-Rodríguez [59] have claimed that when an organic Rankine cycle (ORC) is operated solely by a STC, employment of PCMs instead of SHS materials is not a thermodynamically efficient choice. They have reasoned that PCMs will reduce the collector outlet temperature, and consequently, the ORC heat source temperature. Furthermore, the reduction in ORC heat source temperature is equivalent to a reduction in its overall efficiency. On the contrary, in another numerical study, Villarini et al. [60] have recently obtained opposite results. For a design integrated with PCM compared to another one with SHS, they have predicted a higher electrical efficiency. However, because the main aim of their work was to compare two novel solar-driven ORCs with heat storage, they have studied two different vacuum tube-based collectors. The PCM and SHS were integrated with a linear Fresnel and a compound parabolic collectors, respectively. The linear Fresnel collector could provide higher operating temperature for the heat storage unit and hence a higher efficiency of the ORC was obtained for the design with PCM.

On the other hand, by a numerical study, Tascioni et al. [18] have claimed that an optimised integration of PCM can increase the electrical efficiency of an ORC. Luu et al. [61] also discussed that for solar thermal applications, by choosing a proper design and optimising the involvement of heat storage, better results are achievable by PCMs rather than SHS. Considering the results found in the literature, these claims seem to be valid.

Most of the studies on the comparison of SHS and LHS integration with ETSCs have selected the LHS type as a better choice for storing heat. Tyagi et al. [22] have experimentally obtained higher thermal efficiency and output temperature of an ETSC filled with PCM compared to the same ETSC filled with thermal oil as a sensible heat storage. Through a numerical comparison between PCM and metallic sensible heat storage in an ETSC integrated solar still, Mazraeh et al. [62] have reported that with PCM, the system could provide more thermal energy to the application they studied (i.e., water desalination). For an ETSC assisted ORC, Villarini et al. [60] have numerically achieved higher electrical energy efficiency by employing LHS rather than SHS. Similarly, in another numerical study, Freeman et al. [10] have obtained 20% more electrical energy generation from an ETSC assisted ORC by replacing SHS unit with an LHS solution. Nevertheless, in the meantime, Villarini et al. [60] indicated that when ETSC is not able to bring the PCM into its melting point during the cold seasons, higher heat losses will occur, and that leads to a lower performance by the system.

On the other hand, it was indicated by a few studies that using SHS rather than LHS with ETSCs can result in a better performance. Riffat et al. [63] have tested the performance of a heat pipe ETSC filled first with water (i.e., as an SHS) and then with PCM. Their experimental study had shown a better performance when water was used as TES. However, they have only considered the period during which the PCM was storing thermal energy and the PCM heat-releasing period was not included in their study. Qu et al. [64] have found the same results but recommend that simultaneous usage of LHS with SHS could offer a better performance.

It can be concluded that generally, the integration of LHS, obtainable by PCMs, results in better performance of ETSCs. However, this behaviour is not always expected for different solar thermal technologies or different operating conditions. As suggested by Villarini et al. [60] and Tascioni et al. [18], design and management of energy storage solutions are the key items to be optimised for different solar thermal systems operating under different conditions, in order to achieve the best outcomes.

2.3. Performance of phase change materials integration with evacuated tube solar collectors

It was discussed that employment of PCMs in ETSCs is mostly more effective than using SHS type; hence, this section specifically focuses on the effect of using PCMs with ETSCs. There are many studies focused on this matter that have compared the performance of normal ETSCs with integrated ETSC-PCM systems.

Naghavi et al. [21] have numerically shown that the addition of a PCM unit to an ETSC can stabilise its performance during variable solar irradiance, and even increase its thermal efficiency. Yongtai et al. [48] have achieved the same results experimentally. They have reported that PCM can stabilise the ETSC output thermal energy and make it available for extended periods. The experiments by Wu et al. [47] have also shown 30% less energy fluctuations by filling a heat pipe type ETSC with PCM. The addition of PCM also made their setup able to maintain an output temperature of 50 °C during a summer night.

Xie et al. [65] have numerically reported that higher temperatures can be achieved by employing PCM inside an ETSC. However, they have only considered the temperatures inside the ETSC and not the HTF passing through it. Tyagi et al. [22] have obtained similar results experimentally. By testing an ETSC with and without filling inside the tubes with PCM, they have achieved higher collector efficiency and output temperature in the case of using PCM. Kumar and Mylsamy [29] have tested the integration of a PCM container inside the manifold of an ETSC. Their experimental results showed that by adding the PCM unit, the temperature of the stored water in the manifold after 24 h of operation increased from 33.1 °C to 37.0 °C. It must be noted that their experiments were conducted in India during the cold months of January to March 2018. They have also calculated the efficiency of the ETSC-PCM and reported a 10.9% and 2.4% increase in energy and exergy efficiencies, respectively. Chopra et al. [66] have also obtained up to 24.27% and 5.51% increase in the average overall daily energy and exergy efficiencies of an ETCS by filling its tubes with PCM, respectively. Abokersh et al. [67] have experimentally tested the performance of a U-tube ETSC to produce hot water. By simulating real operation requirements, they have obtained about 13% higher efficiency by filling the ETSC tubes with PCM.

A widely used parameter called solar fraction (SF) is another suitable factor to describe and compare the performance of solar thermal collectors. SF is the percentage of the total energy demand that is supplied from solar thermal energy [68]. PCMs are capable of increasing the SF value by storing extra solar thermal energy and releasing it to the system (demand side) when there is no adequate sunlight. Based on this capability, through a numerical study, Delgado-Torres and García-Rodríguez [59] have reported that for a steady operation of an ETSC-sourced ORC equipped with auxiliary heaters, adding an external PCM unit to the system can increase the SF by a 10–30%. According to Delgado-Torres and García-Rodríguez [59], during non or low availability of sunlight, the stored solar thermal energy is added to the ORC by the PCM. Hence, presence of PCM reduces the energy demand from the auxiliary heaters which means an increase in the share of solar energy in supplying the thermal energy demand of the ORC. In another numerical study by Li et al. [34], depending on the climate conditions, from 10% to more than 50% increase in SF of an ETSC-based carbon capture process was achieved by adding a PCM unit. Feliński and Sekret [69] have also experimentally reported a 20.5% increase in SF of an ETSC-based water heater by the employment of PCM.

Other benefits have also been reported for using PCM with ETSCs. As an example, in the case of using the heat pipe type ETSCs, filling them with PCMs could help with overcoming their drawback of overheating [15].

Adding PCMs to ETSCs has not always led to a satisfactory outcome in terms of improving their performance. Xue [70] has tested PCM employment in two ETSC operating modes. Their design included a collector and a hot water storage tank. During the "exposure" mode, as soon as the collector cover is removed, the water flows inside the collector, and the operation starts. With the "constant flow rate" the water flows through the system before removing the collector cover. When the water flow reaches a steady state, the cover is removed, and the operation begins. An 11–15% reduction in collector thermal efficiency was reported for the exposure mode. In the meantime, their results for the constant flow rate mode showed a 7% increase in the same performance indicator. However, in their experiments, a U-tube type collector was employed for the ETSC-PCM, and an all-glass collector was tested as an ETSC without PCM integration. Since their results were based on two different ETSC types, the effects of adding PCM cannot be independently discussed. Feliński and Sekret [71] also have reported a negative impact on the performance of an ETSC when filled with PCM. However, during their experiments, the ETSC temperature was high enough that the PCM did not get the chance of discharging the stored thermal energy. In other words, by storing the thermal energy and not releasing it back to the system, the PCM was acting as a thermal resistance.

In a comparative experimental study on an ETSC-PCM, Essa et al. [72] have shown that when the PCM goes through a complete phase change the best system efficiency is achievable. Kabeel and Abdelgaied [73] have tested a vacuum-tube parabolic trough collector equipped with an external PCM storage unit. They have reported a 44% decrease in efficiency of the primary system (solar still). However, in the meantime, they have achieved 140% more production of the distilled water. It must be noted that they have compared their design with a solar still without PCM and ETSC units. Hence, this comparison also could not accurately determine only the effects of PCM on the system. Mazraeh et al. [62] have numerically achieved similar results for an ETSC sourced solar still. According to their results, although addition of a PCM unit decreased the system efficiency, it helped increase the amount of distilled water. Feliński and Sekret [69] have experimentally reported that for an annual average day in a temperate climate, the integration of PCM in an ETSC unit reduced the collector output temperature but just for 5 h of the day. Their results showed that during the period with the highest solar radiation, the addition of PCM reduced the output temperature up to 5 °C. But for the rest of the day, up to 10 °C temperature rise was observed as the result of introducing PCM. Similar results were reported by Iranmanesh et al. [41] as well.

As discussed above, in the literature, different ETSC-PCM operation parameters have been studied and compared with those of a normal ETSC, and various and sometimes contradictory behaviours were reported. However, even in the studies reporting some negative effects of PCMs on the system, other desirable effects and outcomes are obtained. Some of these studies' results are summarised in Table 1.

As presented in Table 1, most of the studies listed there have reported that the addition of PCMs enhances the performance of ETSCs. However, there are also few studies that have reported the opposite. It is noteworthy that it has been claimed that the testing procedures can affect the results, which can be part of the justification for these contradictory outcomes: i.e., Fang et al. [75] have experimentally proven that because of the variations in the characteristics of PCMs during the phase change process, the calculations can sometimes end up in misleading results. However, it can be concluded that generally, a proper design of such integrated systems can lead to a better performance.

To achieve high-performance ETSC-PCMs, their different types and designs must be studied, and opportunities and potentials for optimising their performance must be identified. The first step in designing an ETSC-PCM system is determining how the PCM and ETSC can be integrated and how the heat is transferred between them. Therefore, here, different ETSC-PCM configurations are further investigated by reviewing the literature, and their specifications and performance characteristics are discussed.

Table 1
Overall performance of ETSC-PCM integration.

Integration type	Studied parameter	Results	Study type	Ref.
PCM-filled U-tube ETSC	Collector thermal efficiency	7% increase	Experimental	[70]
		11%–15% decrease	Experimental	[70]
		11% increase	Experimental	[48]
		13% increase	Experimental	[67]
PCM-filled heat pipe ETSC	Collector thermal efficiency	16–24% increase	Experimental	[66]
		32–37% increase	Experimental	[74]
	Collector output thermal energy	24.6% increase	Experimental	[47]
		45–79% increase	Experimental	[46]
	Energy collection efficiency	15% increase	Experimental	[47]
	Collector exergy efficiency	3–5% increase	Experimental	[66]
	Application thermal efficiency	26%–66% increase	Experimental	[9]
	Solar fraction	20.5% increase	Experimental	[69]
PCM unit inside ETSC manifold	Collector thermal efficiency	10.88% increase	Experimental	[29]
	Application thermal efficiency	−5%–23% increase	Numerical	[21]
	Collector output temperature in a 24 h period	4 °C increase	Experimental	[29]
External PCM unit	Energy collection efficiency	50% increase	Experimental	[64]
	Application thermal efficiency	44% decrease	Experimental	[73]
	Solar fraction	10%–50% increase	Numerical	[34]
	Application production	20% increase	Numerical	[62]
		140% increase	Experimental	[73]
	Application operation time	Extended for 800 h	Numerical	[17]

3. Main integration configurations

3.1. Using the phase change materials inside the collectors

One of the most popular and highly-effective ETSC-PCM configurations is the employment of PCM inside the ETSC tubes [76] that has been patented by Zakhidov et al. [52] in 2015. Fig. 3 illustrates this integration for a heat pipe type ETSC. The main advantage of such configurations is their compact design without the need for an external thermal energy storage unit [46]. With this configuration, heat absorption and storage co-occur inside the ETSC unit. However, the main disadvantage of this arrangement is that the storage volume is limited, and there is less flexibility for custom-sizing/designing the thermal energy storage part of the system [46]. Variations of this design can be found in fifteen other studies [9,42,46,47,63,66,69,71,74–80] that will be reviewed in this paper.

Feliński and Sekret [46] have used aluminium fins for a more uniform heat distribution inside the PCM. They have reported that lower output temperatures were obtained by their design, but it reduced the heat losses by 31%. Reduction in temperature fluctuation was also reported by Chopra et al. [66] and Pawar et al. [80] on a similar design. Pawar et al. [80] have numerically obtained the fin maximum temperature of around 90 °C and around 138 °C for the tubes with and without PCM, respectively. In the meantime, they have reported that during the evening, up to 30 °C higher fin temperature is achievable by introducing PCM into the tubes. They have also mentioned that presence of PCM can be helpful in avoiding the damages that can be caused by overheating inside the tube too. The experiments by Chopra et al. [66] also showed that since the early hours in the morning and till noon, when the solar irradiance reaches to its maximum value, the collector without PCM had a higher output temperature. But by the passage of time, the collector with PCM showed higher output temperatures in the afternoon. Overall, they obtained up to 24% increase in thermal efficiency of the collector by filling it with PCM. Similar behaviour was observed by Chopra et al. [74] with another arrangement of fins and heat pipe inside the collector

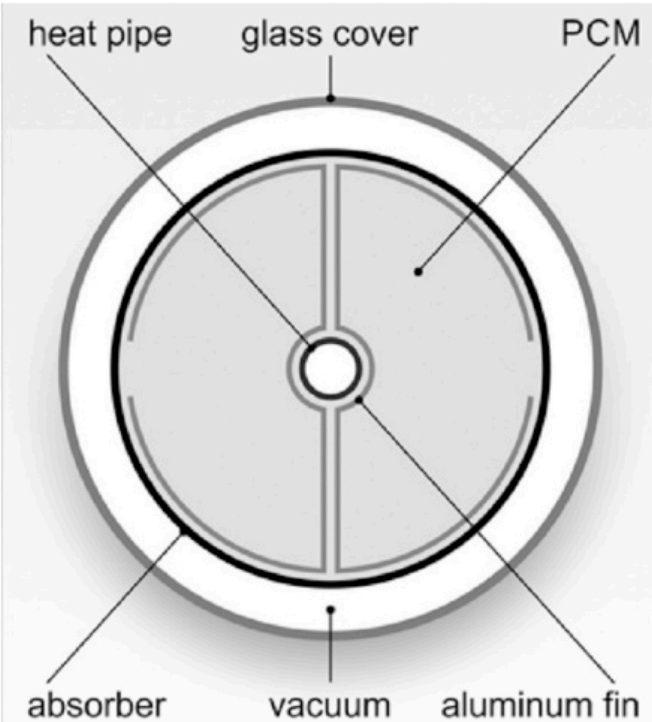

Fig. 3. Schematics of PCM-filled heat pipe type ETSC proposed by Feliński and Sekret (Recreated from a figure in Ref. [46] with permission of reuse from Elsevier).

tubes. Papadimitratos et al. [9] have tested a similar configuration but with a modification on PCM filling. They have selected two PCMs with different melting points of 72 °C and 118 °C and compared the ETSC performance while filled with each of them. Then they have proposed a dual ETSC-PCM in which half of the collector tubes are filled with the high-melting-point and the other half with the low-melting-point PCMs. The dual design has shown the best performance with up to 66% increase in the collector efficiency compared to the ETSC without PCM.

Another modification on this ETSC-PCM type was proposed by Bai et al. [76] that offered the possibility of adjusting the inclination angle of the collector. Fig. 4 shows the schematics of their design.

According to Bai et al. [76], using heat pipes significantly improves the heat transfer from and into the PCM. They have reported that this design is in particular highly efficient during the nighttime. But in their study during the daytime, only the PCM is charged, and there is no heat removal from the ETSC. The stored heat was then considered to be utilised in the nighttime.

Another novel heat pipe ETSC design was presented by Wu et al. [47]. As shown in Fig. 5, they have utilised oscillating heat pipes inside a PCM-filled ETSC. They have not compared the performance of their design with that of a normal heat pipe type ETSCs; however, their experimental results showed that the addition of PCM reduces the fluctuations in average collecting efficiency by 30%. It also could maintain the output temperature of the system at around 50 °C on a summer night, which could not be achieved in the absence of PCM.

Another popular design was proposed by Tyagi et al. [22] in 2012, which was almost based on the same principles of the PCM-filled heat pipe ETSC design. The only significant difference is that Tyagi et al. [22] have utilised the U-tube type ETSC. There were also six other studies found in the literature working on this integration type [48,67,70,72,81,82]. A schematic of this design with different fin implementation types is presented in Fig. 6.

Essa et al. [72] have tested a PCM-filled U-tube ETSC in different operating conditions and compared its performance with a normal U-tube ETSC without PCM. They have shown that the employment of

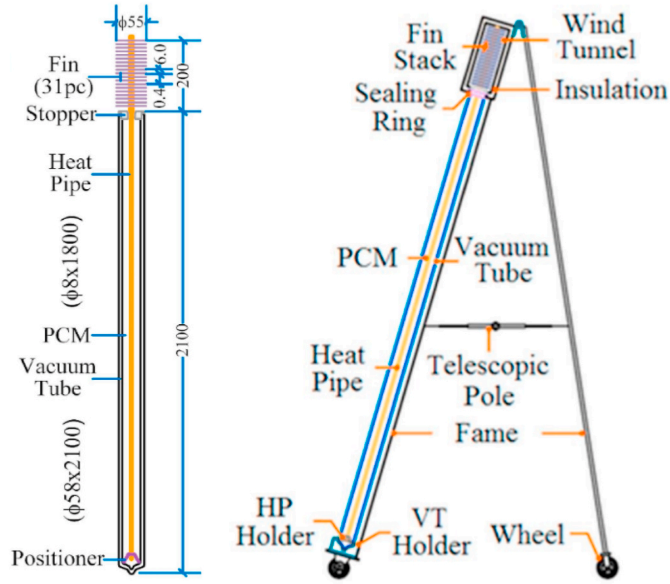

Fig. 4. Adjustable PCM-filled ETSC design by Bai et al. (recreated using multiple figures in Ref. [76] with permission of reusing the figures from Elsevier).

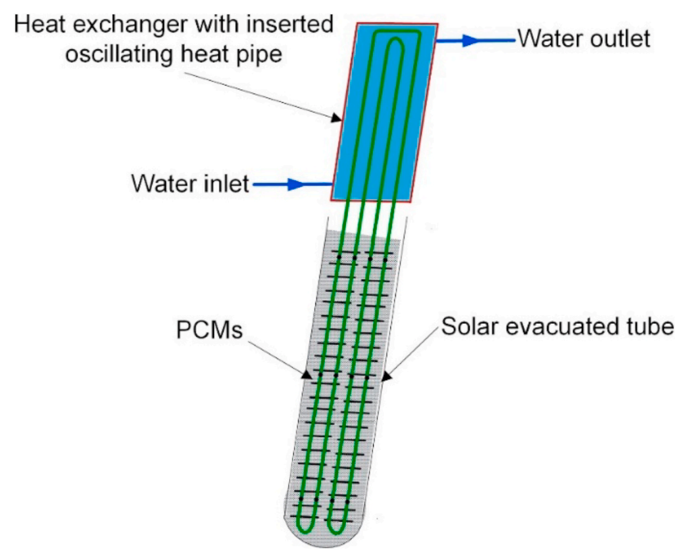

Fig. 5. Novel ETSC-PCM with oscillating heat pipe [47] (with permission of reuse from Elsevier).

PCM can both improve and worsen the performance of an ETSC depending on the design parameters. A modified version of this design in which cylindrical fins are installed on the U-tubes perpendicularly was proposed by Huang et al. [82]. Yongtai et al. [48] further changed this design and studied the parallel and serial-parallel connections of the ETSCs in this configuration. Their proposed design configurations are shown in Fig. 7.

Yongtai et al. [48] have experimentally recorded 7.8% and 10.9% enhancement in collector thermal efficiency by filling of the series-parallel and parallel types with PCM, respectively.

There are also various modifications on other types of ETSC that have been investigated and reported in the literature. By a novel modification, Li et al. [83] eliminated the manifold from the ETSC. They have filled the ETSC with PCM, and the HTF flows through a coil that is placed inside the PCM. The schematic of this design is given in Fig. 8. This design was then claimed to be promising because of its low costs, high rate of heat transfer to HTF, low heat losses, and its compact structure.

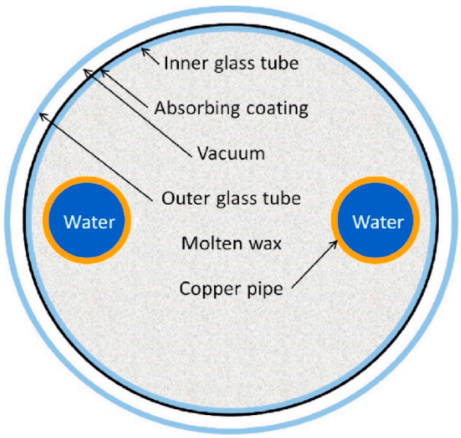

Fig. 6. Schematics of U-tube ETSC filled with PCM with and without Aluminum fins [67] (with permission of reuse from Elsevier).

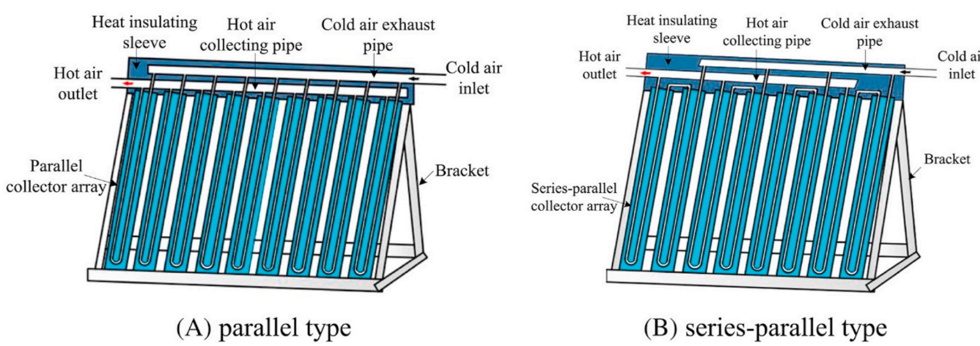

Fig. 7. Parallel and serial-parallel connection of PCM filled U-tube ETSCs designed by Yongtai et al. [48] (with permission of reuse from Wiley).

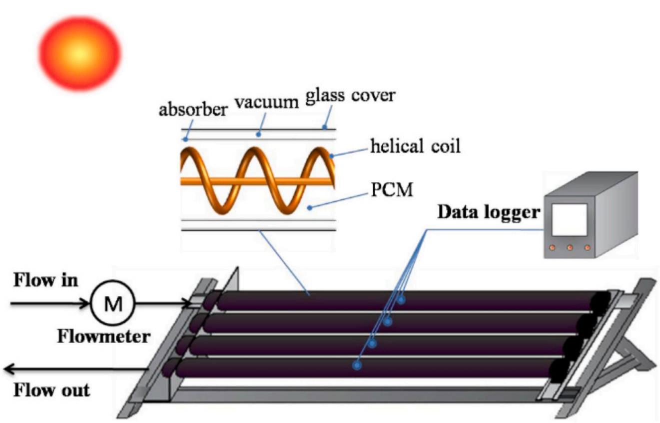

Fig. 8. ETSC-PCM design without manifold [83] (with permission of reuse from Elsevier).

In a very interesting innovative experimental design, Hassanipour et al. [84] and Sobhansarbandi et al. [78] replaced the conventional absorber coating of the ETSC inner tube with a novel PCM composite. They covered the inner tube with multiple layers of Carbon nanotube (CNT) sheets with PCM microspheres dispersed between the layers. By employment of CNT sheets, they have obtained a near-ideal black body with sunlight absorbance of 98% [84]. Usage of PCMs has also enabled the ETSC to simultaneously store and transfer the absorbed solar energy [78], reducing its fluctuations and making it available during the periods with low or zero solar irradiance [84]. They have compared the performance of ETSCs with normal coating and coatings with different number of CNT layers to find out the optimum number of CNT layers for this design. Their CNT design had higher absorbance resulting in heat generation at higher temperatures. In the next step, they added micro-encapsulated PCMs between the CNT layers. Their experimental tests showed that during both high and low solar intensity days, applying more PCMs resulted in higher temperatures of the HTF inside the manifold.

For any of the designs mentioned above, the collected thermal energy by the ETSCs would be transferred to both PCM and heat transfer fluid inside the collectors. The overall energy balance, while the PCM is being charged, is given by Eq. (6) [29]:

$$\dot{Q}_U = \dot{Q}_{st.} + \dot{Q}_{HTF} \tag{6}$$

where $\dot{Q}_{st.}$ is the rate of storing thermal energy in PCM (kW), and $\dot{Q}_{out}$ is the rate of transferring thermal energy from ETSC to HTF (kW). Depending on the time considered for calculations in Eq. (6), and the status of PCM the value of $\dot{Q}_{st.}$ will be determined. Assuming that in the selected period, the PCM fully melts and its temperature rises to values more than its melting point, the amount of thermal energy stored in PCM while charging can be calculated by the equation below [85]:

$$Q_{st.} = m_{PCM} \times \left[c_{p,PCM,s}\left(T_{PCM,melt} - T_{PCM,i}\right) + q_{PCM,latent} + c_{p,PCM,l}\left(T_{PCM,f} - T_{PCM,solid}\right)\right] \tag{7}$$

where $Q_{st.}$ is the amount of energy stored in PCM (kJ), m_{PCM} is the total mass of PCM (kg), $q_{PCM,latent}$ is the specific latent heat of PCM (kJ/kg), $c_{p,PCM,s}$ and $c_{p,PCM,l}$ are the specific heat capacities of PCM ($kJ/kg.^{\circ}C$) in solid and liquid phases, $T_{PCM,melt}$ and $T_{PCM,solid}$ are the PCM melting and solidification points ($^{\circ}C$), and $T_{PCM,i}$ and $T_{PCM,f}$ are the initial and final PCM temperatures ($^{\circ}C$) during the whole heat storage process, respectively. In Eq. (7) the term $c_{p,PCM,s}(T_{PCM,melt} - T_{PCM,in})$, $q_{PCM,latent}$, and $c_{p,PCM,l}(T_{PCM,out} - T_{PCM,solid})$are related to the heat transfers in the solid state, phase change, and liquid state, respectively. If the PCM is not fully melted, Eq. (7) must be modified based on the amounts of PCM in the solid and liquid forms and the term m_{PCM}cannot be used for all the three types of heat transfer. If only one of these heat transfer types occurs, the corresponding part of Eq. (7) can calculate its amount.

Eq. (7) calculates the stored thermal energy in a given mass of PCM, regardless of where it has been placed and it can be employed for any types of PCM-filled ETSCs. But the value of $\dot{Q}_{HTF}$depends on the ETSC type. When the HTF passes directly through the ETSC, such as in U-tube and double-pipe designs, the useful amount of thermal energy that is collected can be calculated by Eq (8) [81]:

$$\dot{Q}_{HTF} = \dot{m}_{HTF} c_{p,HTF} \left(\overline{T}_{HTF,o} - \overline{T}_{HTF,i}\right) \tag{8}$$

where $\dot{m}_{HTF}$is the flow rate of the fluid inside the tube (kg/s), $c_{p,HTF}$is its specific heat capacity ($kJ/kg.^{\circ}C$), and $\overline{T}_{HTF,o}$and $\overline{T}_{HTF,i}$are the average outlet and inlet HTF temperature ($^{\circ}C$), respectively. A simplified relation for calculating the rate of thermal energy transfer for heat pipe types is as below [53]:

$$\dot{Q}_{HTF} = \frac{\left(T_{hp,e} - T_{hp,c}\right)}{R_{hp}} \tag{9}$$

where $T_{hp,e}$and $T_{hp,c}$are the temperatures inside heat pipe evaporator and condenser sections ($^{\circ}C$), respectively and $R_{hp}$is the overall thermal resistance ($^{\circ}C/kW$) of the heat pipe. The relations for thermosyphon ETSCs are very complicated and are out of the scope of this paper. The readers can follow references [85–88] for more information on the energy analysis of thermosyphon ETSCs.

3.2. Using phase change materials in the collector manifold

Another approach for the integration of PCM with ETSCs investigated by some studies is the employment of PCM inside the ETSC manifold. Naghavi et al. [21] proposed this configuration in 2015, and later on in another study, they report on an improved version by adding fins to their design [53]. Having compared their designs with the one without PCM unit and based on the HTF flow rate, they reported from 5% decrease to 23% increase in overall efficiency. The HTF flow rate range they have considered was between 50 l/h and 80 l/h, and the performance enhancement was obtained for the flow rates more than 55 l/h. They also have shown that the addition of PCM makes the system efficiency less sensitive to HTF flow rate. The addition of fins had also enabled the system to provide the required thermal energy during nighttime or when the available solar irradiance was insufficient. Similar designs with the same concept have been also tested in a few other studies [15,29,86]. Schematic and experimental setup of this design is shown in Fig. 9.

Mehla and Yadav [30,85,89–91] have presented another novel method for integrating PCM in the manifold of an ETSC. Through five publications, they have investigated and reported the performance and behaviour of their design with several modifications and in different applications [30,85,89–91]. Their proposed design is shown in Fig. 10. Their design was applied for air heating and included an insulated manifold connected to two arrays of ETSCs on its both sides' surfaces. Inside the manifold, there were three channels. The outermost channel was considered for water that could collect the heat from ETSCs and transfer it to the middle channel, which was filled with PCM. Air could flow in the most inner channel and get warmed up by the heat received from the PCM. They achieved 7 h of desirable air heating during nighttime in winter.

3.3. Externally connected thermal storage unit

One of the common ETSC-PCM configurations is the addition of an external PCM unit to store the thermal energy supplied by the ETSCs. In the most common design of this type, the HTF leaving the ETSC, transfers the absorbed solar thermal energy, partially or fully to a PCM unit. This configuration includes an additional component, which is the storage tank and is typically filled with more PCM than that is usually used in internally PCM-filled ETSCs. Accordingly, compared to the internal designs, the external designs usually have higher capital costs. However, more thermal energy can be stored by using this design [92]. This external integration is more flexible than the previously-explained internal types (sections 3.1 and 3.2) since many performance parameters of the PCM unit can be studied independent of the performance parameters of the ETSCs.

The majority of studies found in the literature on ETSC-PCMs have employed this design configuration. Most of these studies have determined the specifications of their PCM units by only considering the requirements of their applications [93,94]. It is noteworthy that there have been some novelties reported in the literature on designing this ETSC-PCM type. Buonomano et al. [95] have presented an interesting design for external PCM units connected to ETSCs. They have proposed and experimentally tested adding a variable number of PCM units to an ETSC-sourced absorption refrigeration cycle. By taking advantage of control valves, the cycle itself regulates the number of involved PCM units in the process. By increasing the gap between the supply and demand sides, the system could self-regulate itself by engaging more PCM units. However, in their numerical calculations, they have reported a relatively low solar fraction of 20% compared to that of other

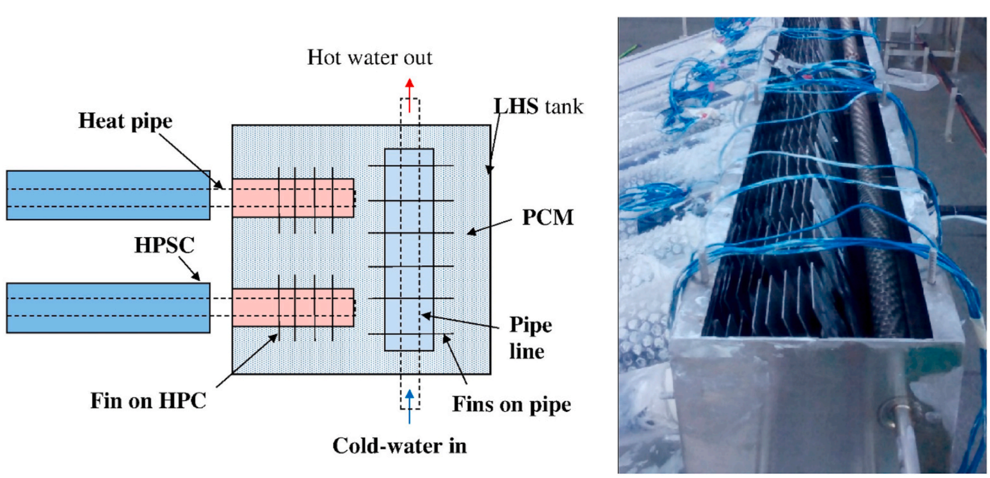

Fig. 9. A novel design of PCM integration inside ETSC manifold (recreated using multiple figures in Ref. [53] with permission of reusing figures from Elsevier).

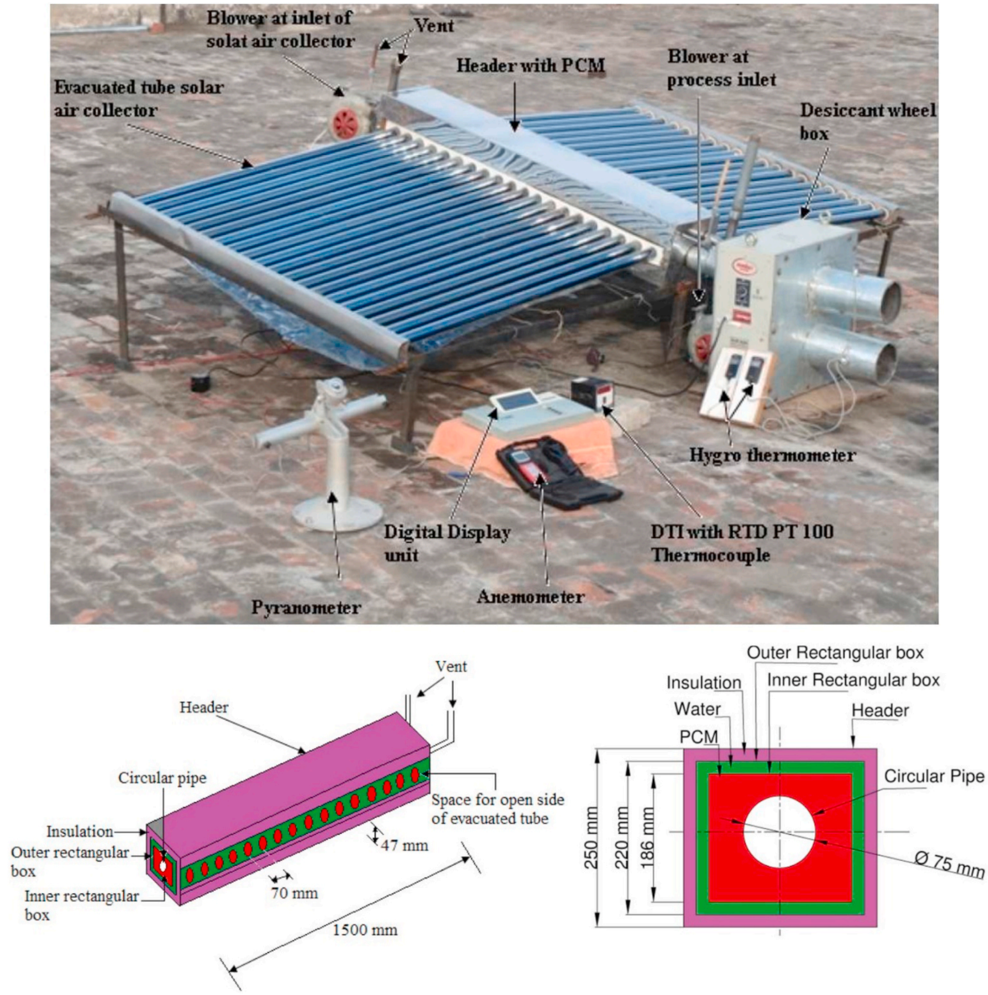

Fig. 10. Actual image and schematics of the novel ETSC-PCM design by Mehla and Yadav (recreated using multiple figures in Refs. [89] with permission of reusing figures from Taylor & Francis).

ETSC-PCMs, which is around 40–70% [96–100]. Nagappan and Devarajan [101] have developed another design, including three different PCMs, to apply the same concept discussed above. They have obtained an exergy efficiency of 60.4%, which is a high value compared to other reported values for exergy efficiency (i.e., between 2% and 90%) [29,62, 102].

It has been proven that increasing the heat transfer area will improve the overall heat transfer process [103]. As an attempt to increase the heat transfer area between the PCM and the HTF, Egea et al. [104] have offered and successfully taken advantage of a shell and tube heat exchanger with 12 tube passes. The shell section of their heat exchanger was filled with PCM and the HTF was flowed inside the tubes. They have just studied the performance of their proposed design and have not compare it with a design without PCM to determine how much the presence of PCM can improve the performance of the whole design. Another efficient way to increase the heat transfer area between the PCM and HTF is the utilisation of a triplex tube heat exchanger (TTHX) [105]. Al-Abidi et al. [106,107], Mat et al. [108], and Abdulateef et al. [109,110] have worked on the same design to find an efficient way for transferring solar thermal energy collected by the ETSC to the PCM unit. Their design was composed of three co-centric tubes called as horizontal TTHX. With their proposed design, the HTF from the ETSC could be divided into two flows and warm up the PCM from both inside and outside, in order to effectively utilise the body of the PCM. Fig. 11 shows the cross-section of the TTHX in which the middle part is filled with PCM, and the ETSC HTF flows inside the inner and outer tubes. By comparing this design with the ones in which the PCM is only being charged from one side, it was claimed that this design transfers more thermal energy into PCM. Because the PCM receives thermal energy from two sides and through more heat transfer area, more amount of heat can be transferred to PCM. Moreover, this design helped the thermal energy to be transferred more uniformly inside PCM. Through experiments and numerical models, it was shown by using the TTHX, the PCM could reach higher temperatures in shorter periods (even at lower heat source temperatures) compare to the traditional design in which heat is supplied to the PCM from one side only.

3.4. Other designs for combining PCMs with ETSCs

There have been some other designs reported in the literature in which PCMs and ETSCs were combined; however, the purpose of using PCM was not storing the thermal energy supplied by the ETSCs. The PCM units in these designs have been employed as a part of the primary process. An innovative design of this type is the one presented by Faegh and Shafii [111]. They have utilised ETSC as an external heat source of a solar still and the PCM as an external condenser that could also be utilised as a heat recovery unit. The PCM unit could receive the solar thermal energy indirectly after it has been consumed in the primary process. They have also presented an interesting way to discharge the stored energy to the solar still. In their proposed configuration, the PCM unit is placed under the solar still setup, and heat pipes are installed inside PCM, and the top part of the heat pipes are placed at the bottom of

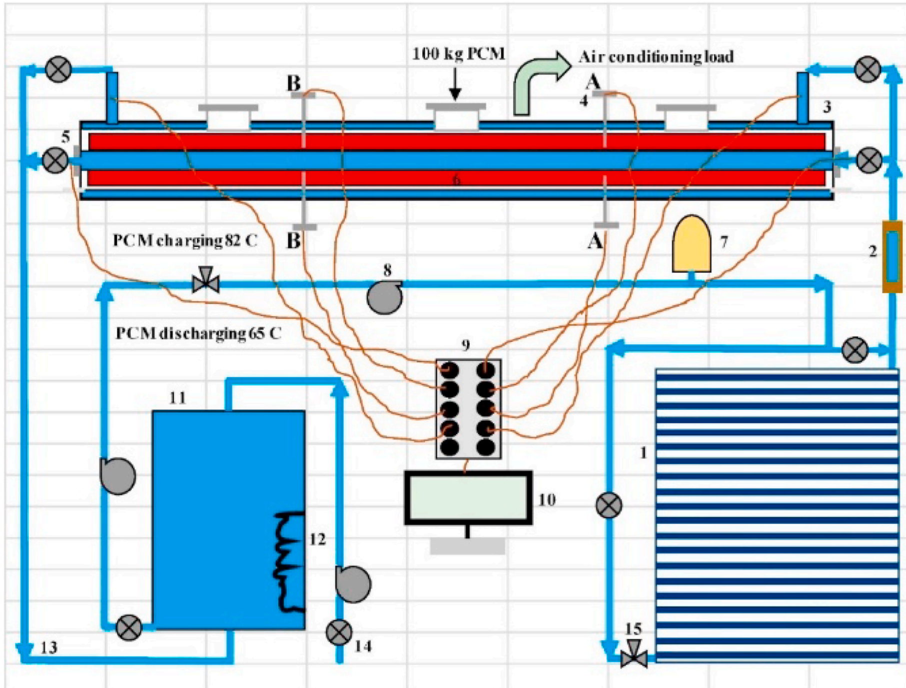

Fig. 11. The TTHX design for ETSC thermal energy storage designed and investigated by Al-Abidi et al. [106,107], Mat et al. [108], and Abdulateef et al. [109,110] (with permission of reuse from Elsevier).

solar still. This design concept is schematically shown in Fig. 12.

In their study, Faegh and Shafii [111] have compared the system performance with and without the employment of PCM. According to their experimental results, during the daytime, the presence of PCM makes almost no difference in the amount of distilled water. But after the sunny hours, the setup equipped with PCM continues the water production and produces about 20% more distilled water.

Some studies have utilised vacuum tubes in other solar thermal collector types and investigated their integration with PCMs. Kabeel and Abdelgaied [73] have employed a parabolic trough collector equipped with a vacuum tube as an auxiliary heat source for a PCM-integrated solar still. Compared to the setup without the collector and PCM, they have experimentally obtained about 20% lower overall efficiency, but in the meantime, about 140% more distilled water production. In a theoretical study, Cioccolanti et al. [17] have investigated the employment of linear Fresnel reflectors equipped with two vacuum tubes connected to an external PCM unit. They have employed this configuration as the heat source of a solar ORC. Compared to the system without PCM, and by controlling the involvement of PCM in the process, they have numerically achieved 800 h more operating time annually.

As discussed in this section, based on the literature, there are four main types of integration between PCMs and ETSCs. As a summary to this section and for a better understanding of the classification presented in this work, Fig. 13 shows the main concept of the four integration types.

In Fig. 13 the shaded areas indicate placement of PCM. As shown in this figure, only the tubes for the heat pipe and U-tube types of ETSCs are capable of being filled with PCM.

4. Design parameters of the major components

4.1. Selection of phase change materials

Many studies have investigated the effects of different design parameters on the performance of ETSC-PCMs. The material that a PCM is made of is one the most important parameters that determine its performance, and hence the success or failure of a system in which the selected PCM is employed [48,61]. The first and most important

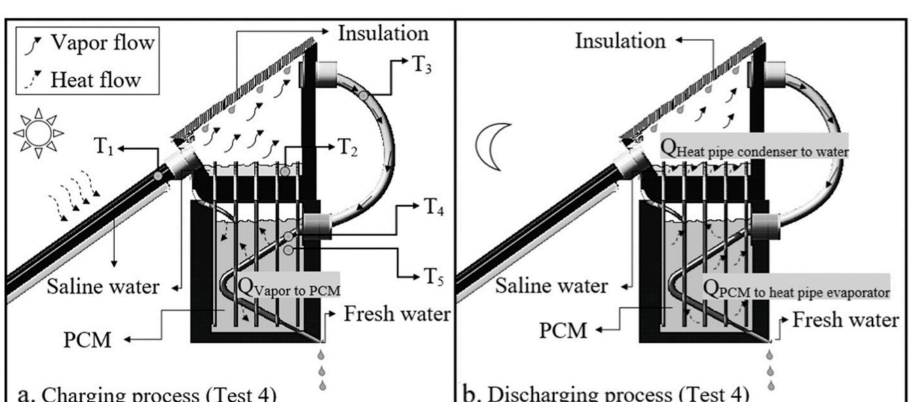

Fig. 12. Schematics of the novel ETSC-PCM equipped solar still [111] (with permission of reuse from Elsevier).

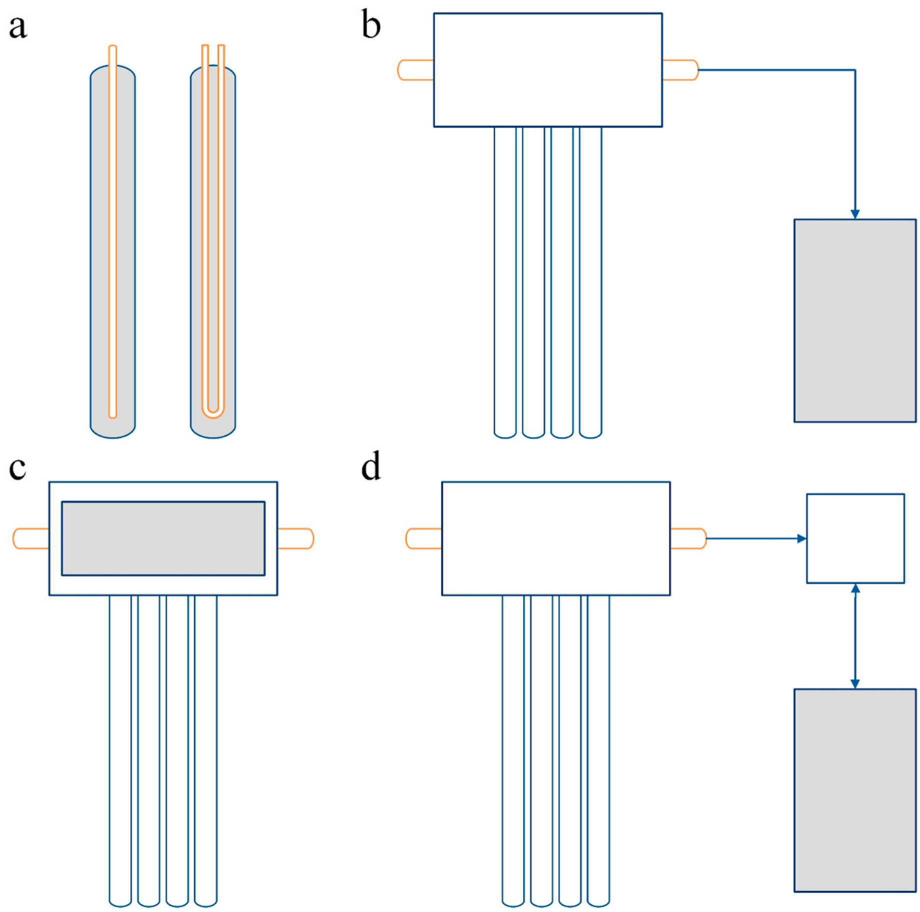

Fig. 13. Four main types of integration between PCMs and ETSCs, a) filling collector tubes with PCM, b) direct connection of ETSC with an external PCM unit, c) placing PCM unit inside collector manifold, d) indirect connection between ETSC and PCM.

criterion for choosing a specific PCM is its melting point [14,112]. If the melting point does not match the operating temperature range of the application, the phase change phenomenon will not occur, and the employment of PCM would be pointless. Other critical criteria are the PCM thermophysical, chemical, and kinetic properties such as high heat of fusion, thermal and chemical stability, low phase change expansion and contraction, and nontoxicity [15,48,112]. Availability and low costs are also very important factors to consider, when selecting PCMs. The application for which the PCM is employed will also suggest some limitations on material selection. For example, if the configuration with PCM inside ETSC is selected for a particular ETSC-PCM application, PCMs with higher melting points are required [9]; or similarly, when an external heat storage unit is used, usually PCMs with lower melting points are the preferred candidates [9].

This section is mostly focused on selection criteria of suitable PCMs for different ETSC-PCM applications. A thorough investigation of the literature indicates that Paraffin and its derivatives are the most common PCMs used with ETSCs. The melting point of Paraffins, as alkanes with general chemical formulation of C_nH_{2n+2}, is in the range of 5 °C [9] to above 100 °C [106], and their latent heat capacity is in the range of 120–270 kJ/kg [9,14]. Their melting point and latent heat of fusion increase with their molecular weight [113]. Availability in a wide range of melting points and latent heat capacities, low costs, nontoxicity, physical and chemical stability even at high temperatures (e.g., 100 °C–200 °C [9]), long-term durability, low probability of supper cooling and phase segregation, and having no health and safety hazards are the main reasons, making them the most preferred PCM type for use in solar thermal applications [9,15,53,81]. The main drawback of Paraffins is their relatively low thermal conductivity, causing them to have an undesirable heat transfer performance, especially while releasing the stored energy [46]. They also show a relatively high volume variation during the phase change process [46]. However, these issues are not limited only to Paraffins, and most PCMs suffer from the same limitations [114]. There are some solutions reported in the literature to address these challenges, which will be discussed later in section (4.2) of this paper.

Among the non-Paraffin PCMs investigated in the literature for integration with ETSCs, Erythritol ($C_4H_{10}O_4$) seems to be more popular than the others. Some studies have even suggested Erythritol as a better option than Paraffin-based PCMs [9,115]. Erythritol is a sugar alcohol with a high energy density, and because of its availability, stability in melting and solidification, low probability of supercooling, and low costs, it has been widely utilised in mid-range temperature solar thermal applications (i.e., around 120 °C) [77]. Erythritol melts at 118 °C with a fusion latent heat of 340 kJ/kg and is non-toxic and safe enough that even makes them suitable for applications in the food industry [9]. However, the main disadvantage of Erythritol is its 10% volume change during its phase change [116] that can be a problem for applications with limited storage mediums. However, because of more flexibilities in design and configuration, in case of using an external PCM unit, solving such issues would be easier. But when the PCM is employed inside the ETSC, the volume expansion can cause some difficulties such as cracking of the tube. Papadimitratos et al. [9] have faced similar problems and have proposed the use of small Aluminum bags filled with Erythritol to solve the problem. Fig. 14 shows the actual Aluminum bags and the schematics of how they can be fitted inside an ETSC. They filled the ETSC with Silicon oil to create a high convective medium so that the PCM can receive the input thermal energy more uniformly.

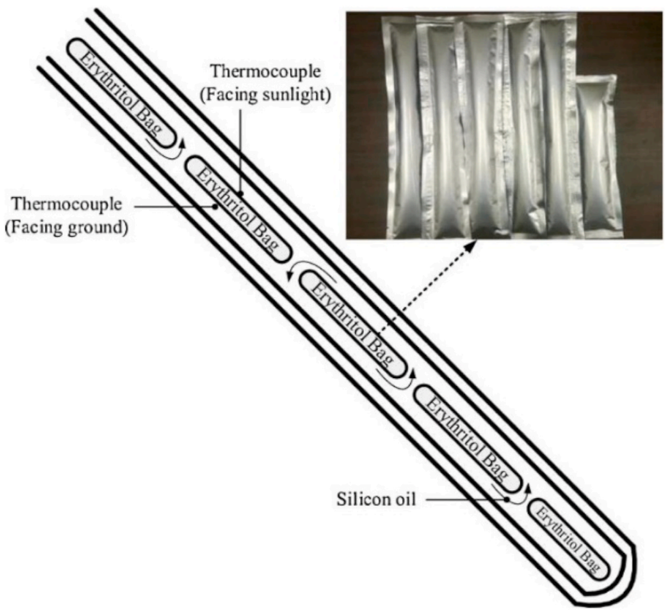

Fig. 14. Usage of Aluminum bags filled with Erythritol to overcome problems caused by PCM volume change [9] (with permission of reuse from Elsevier).

As discussed in section 3.1, Papadimitratos et al. [9] have obtained up to 66% increase in overall efficiency of an ETSC by their specific dual-PCM arrangement but the share of encapsulation alone in this improvement is not studied in their work. However, by encapsulating Erythritol with Aluminum bags, they have overcome the PCM volume change issues. Such a method can be used for other ETSC-PCM configurations with limited space and high volume-change PCMs too.

Stearic acid is another widely used PCM in solar thermal applications. It shares many similarities in characteristics with Paraffins, such as availability, low costs, and nontoxicity [66,74,117]. The main advantage of stearic acid over Paraffins is its higher latent heat of fusion and thermal conductivity [15]. Stearic acid is also more durable and more stable compared to Paraffins. Experimental results by Vasu et al. [118] have shown that after 200 thermal cycles, the latent heat capacity and the melting point of a Paraffin wax was reduced by more than 25% and 33%, respectively. On the other hand, Yang et al. [119] have reported that during a 10,000 thermal cycle experiment, stearic acid thermophysical properties remained almost constant. The disadvantage of stearic acid is that its melting point is about 70 °C [120], and it is not available in a wide range of melting points. This probably explains why only very few studies have employed it in their ETSC-PCM arrangements.

Salt hydrates are also common types of PCMs employed in different thermal energy storage applications. Among them, Sodium Sulfate Decahydrate ($Na_2SO_4{\cdot}10H_2O$) [64], Aluminum Ammonium Sulfate Dodecahydrate ($NH_4Al(SO_4)_2{\cdot}12H_2O$) [14], Calcium Chloride Hexahydrate ($CaCl_2{\cdot}6H_2O$) [16], Magnesium Nitrate Hexahydrate ($Mg(NO_3)_2{\cdot}6H_2O$) [115,116], Magnesium Chloride Hexahydrate ($MgCl_2{\cdot}6H_2O$) [115,116], and Potassium Aluminum Sulfate ($KAl(SO_4)_2{\cdot}12H_2O$) [116] have been investigated in the literature as the PCMs integrated with ETSCs. Salt hydrates are mostly cheaper than organic PCMs and have a higher latent heat capacity [10]. However, their variable density and melting point during the phase change operation and their tendency to the supercooling phenomenon are their key disadvantage [121]. that make them less suitable for ETSC-PCM applications. Tarwidi et al. [115] have numerically studied the performance of a solar cooker equipped with an ETSC-PCM arrangement by using five different PCMs, including Magnesium Nitrate Hexahydrate, Magnesium Chloride Hexahydrate, Erythritol, and two Paraffin-based PCMs. Their simulation results showed the highest storage capacity for Magnesium Chloride Hexahydrate and the fastest heat transfer rate and highest temperature range for Erythritol. For all the above comparisons, Paraffin based PCMs were reported to show the lowest performance.

As a PCM selection guide for the studies on ETSC-PCM designs, Table 2 provides the thermophysical characteristics of the PCMs studied in the literature. This table can help with choosing a proper PCM considering the intended application requirements, or identifying other suitable materials that have not been investigated in the literature on ETSC-PCMs. The information given in Table 2 is based on the data presented in the literature on different ETSC-PCM systems. The materials are sorted based on their melting point, from the lowest to the highest temperatures.

The data given in Table 2 suggests that the PCMs that have been coupled with ETSCs in the literature can be categorized into four main chemical classes. Those classes are of Paraffins, sugar alcohols such as Erythritol and D-Sorbitol, fatty acids such as Ethyl hexadecanoate and Dodecanoic acid, and salts (organic and inorganic) such as solar salt and Sodium sulfate decahydrate. Using the same data, the melting point range for each of those chemical classes are shown in Fig. 15.

Fig. 15 shows that Paraffins have been employed in a wide range of melting points, from about 5 °C up to about 110 °C. At low temperatures fatty acids, and at high temperatures sugar alcohols have been utilised in a relatively small range of melting points of about 25–55 °C and 95–165 °C. The widest range of melting points is covered by different type of salts, from about 30 °C up to about 220 °C. Such a wide range of melting point is due to the availability of salts in a vast variety of chemical compounds. However, as discussed earlier in this section, because of their many advantages, different grades of Paraffins have had the highest share in the PCMs studied in the literature.

It must be noted that the present discussion on melting points and the data shown in Fig. 15 are based on the literature on the integration of PCMs with ETSCs. There are other materials of each chemical classification or oven other chemical compounds that have not been integrated with ETSCs, and thus are not included in this discussion. Considering the operating temperature of the ETSC, the results given in Table 2 and Fig. 15 can be helpful guides for selecting a proper PCM.

4.2. Performance enhancement of phase change materials

As discussed earlier, a key drawback of PCMs is their poor heat transfer properties, especially their low thermal diffusivity and conductivity. A common method to address this issue is creating a PCM composite by adding materials with high thermal conductivity. Usually, small fractions of such materials can significantly improve the thermal conductivity of PCMs with negligible effects on the other thermophysical properties [129]. For example, Table 3 shows the experimental results presented by Li et al. [42] for Erythritol-expanded Graphite composite thermal properties.

The results given in Table 3 indicate that the latent heat of fusion and melting point of the composite will undergo very slight changes, but its thermal conductivity will significantly improve in small concentrations. Fig. 16 shows the percentage of changes in these three parameters.

Fig. 16 indicates that by adding expanded Graphite to Erythritol, up to 3 wt%, the latent heat of fusion and melting point of the composite will be about 2.6% and 0.5% less than those of pure Erythritol. With the same concentration, a thermal conductivity enhancement of about 240% (i.e. compared to pure Erythritol) could be achieved. Therefore, employment of composite PCMs can considerably improve the heat transfer in ETSC-PCM systems. However, as also can be seen in Fig. 16, the rate of changes in thermal properties of PCMs increases with concentration. Higher concentrations will lead to better PCM heat transfer properties but also will decrease the latent heat of fusion.

The experimental results of the above work by Li et al. [42] is supported by other studies on PCM-based composites too. Many studies have reported the similar behaviour of increase in thermal conductivity but decrease in latent heat of fusion by introducing highly conductive

Table 2
Thermophysical properties of the materials studied in the literature as the heat storage medium of ETSC-PCMs.

PCM	Melting Point (°C)	Latent Heat of Fusion (kJ/kg)	Specific Heat (kJ/kg.°C)		Thermal Conductivity (kJ/m.s.°C)		Ref.
			Solid	Liquid	Solid	Liquid	
Parafol 14[a]	4	223	–	–	–	–	[122]
RT10[a]	8.7	176	–	–	–	–	[122]
RT11[a]	12	160	2	2	0.2	0.2	[32]
Parafol 16[a]	17.4	249	–	–	–	–	[122]
RT20[a]	17.8	155	–	–	–	–	[122]
PX21[a]	19.6	86	1.7	–	0.05	–	[35]
Heptadecane[a]	21.3	168	–	–	–	–	[122]
BioPCM Q23	23	180	4.5	2.2	2.5	0.15	[123]
Ethyl hexadecanoate	23.2	187	1.63	2.09	–	–	[124]
RT27[a]	27	149	2	2	0.2	0.2	[32]
Octadecane[a]	28.1	244	0.48	0.56	0.15	0.148	[78]
Gallium	29.78	80.16	0.372	0.397	33.68	33.49	[62]
PC210[a]	30	–	3	3	–	0.4	[75]
Sodium Sulfate Decahydrate	32.4	241	1.76	3.3	0.7	0.544	[64]
Dodecanoic acid	43	180	1.95	2.4	0.15		[124]
RT44HC[a]	43	225	2	2	0.2	0.2	[62]
a commercial grade of Paraffin	47	176	2.8	–	0.21	–	[125]
RT50[a]	47.5	168	2	2	0.2	0.2	[61]
PureTemp 48[a]	48	230	2.1	2.27	0.25	0.15	[126]
a commercial grade of Paraffin	48	234	3.2	2.8	–	–	[47]
a commercial grade of Paraffin	50	238.2	3.2	2.8	–	–	[76]
DX53[a]	52	144.6	Variable	Variable	0.039	–	[100]
a commercial grade of Paraffin	53.04	183.1	2.05	–	0.21	–	[22]
a commercial grade of Paraffin	54	189	–	–	0.21	0.21	[72]
a commercial grade of Paraffin	55	164	2.76	2.48	0.349	0.167	[53]
a commercial grade of Paraffin	55	212	2.38	–	–	–	[101]
OM55[a]	55	210	2.73	2.38	0.135	0.135	[113]
ASTMD87[a]	55	163	2.48	2.76	0.35	0.17	[86]
a commercial grade of Paraffin	56	226	2.95	2.51	0.24	0.24	[73]
a commercial grade of Paraffin	56	226	2.95	2.51	0.24	0.24	[62,73]
PT56[a]	56	237	2.47	2.71	–	–	[96]
Hexacosane[a]	56	250	0.68	0.87	–	–	[9]
C58[a]	56	260	2.26	2.55	0.57	0.74	[86]
a commercial grade of Paraffin	58	158.2	3.35	2.7	0.35	0.15	[82]
Stearic acid	58	191	2.83	2.38	0.3	0.1	[66]
Sodium Acetate Trihydrate	58.92	173	4.02	3.68	0.005	0.005	[127]
a commercial grade of Paraffin	60	189	2.3	–	0.21	0.21	[46]
a commercial grade of Paraffin	61	213	2.3	1.8	0.4	0.4	[113]
a commercial grade of Paraffin	63.74	140.2	–	–	0.18	–	[29]
a commercial grade of Paraffin	64	174	2.76	2.48	0.349	0.167	[21]
a commercial grade of Paraffin	72	224	3.2	2.8	0.35	0.15	[115]
Tritriacontane[a]	72	256	0.87	1.11	0.21	0.21	[80]
RT70HC[a]	72	159	2.05	2.34	0.22	0.2	[86]
Acetamide	81	263	1.94	1.94	0.5	0.5	[85]
Barium hydroxide octahydrate	81.83	193	–	–	–	–	[70]
Magnesium Nitrate hexahydrate	89	162.8	1.84	2.51	0.611	0.49	[115]
Ammonium alum	93.5	300	–	–	0.55	–	[14]
D-Sorbitol	95	187	2.49	–	–	–	[101]
RT100[a]	99	168	1.8	2.4	0.2	0.2	[115]
RT82[a]	109	176	2	2	0.2	0.2	[106]
Magnesium Chloride Hexahydrate	116.7	168.6	2.25	2.61	0.704	0.57	[115]
Erythritol	118	339.8	1.38	2.76	0.733	0.326	[115]
Acetanilide	118.9	222	2	–	–	–	[128]
Polyethylene	130	200	–	–	–	–	[122]
KNO_3–$NaNO_2$–$NaNO_3$	142	80	–	–	–	–	[122]
Isomalt	145	170	–	–	–	–	[122]
Polypropylene	153	87	–	–	–	–	[122]
D-Mannitol	163	318	2.5	–	–	–	[101]
Mannitol	165	315	–	–	–	–	[122]
Solar salt	220	161	1.05	1.5	0.76	0.516	[65]

[a] Different grades of Paraffin.

materials to the PCM [130]. Latent heat of fusion is the most important characteristic of PCMs that makes them able to store thermal energy. Except for lowering the latent heat of fusion, higher concentrations reduce the PCM thermal stability too [29]. Therefore, it is of high importance to choose an optimum level of concentration to minimise such negative impacts.

There are other studies in the literature that also reported the performance of composite materials in ETSC-PCMs. Kumar and Mylsamy [29] have experimentally tested the composition of 1 wt% SiO_2 nanoparticles in paraffin wax and compared its performance with that of pure Paraffin wax. The modified PCMs (enhanced by nanoparticles) have been placed in a container inside the manifold of an ETSC water heater. The paraffin wax with nanoparticles exhibited 22.78% better thermal conductivity than pure paraffin wax. Furthermore, this composition has led to ETSC-PCM improvements in energy and exergy efficiencies from 69.62% to 74.79% and from 22.0% to 24.6%, respectively. They have also reported that after 24 h of ETSC-PCM operation, the temperature of the water stored in the manifold was increased by

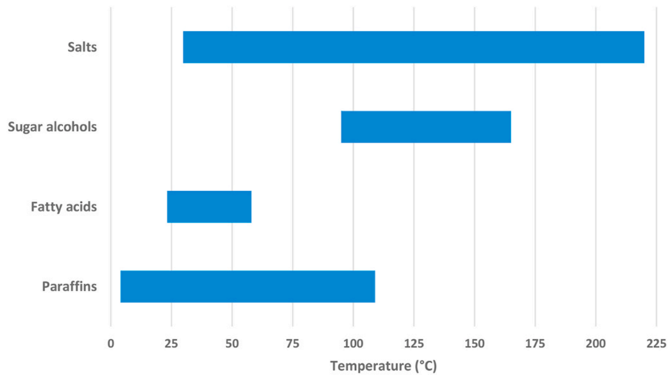

Fig. 15. Melting point range of the different PCM types reported in the studies on integration of PCMs with ETSCs.

Table 3
Thermal properties of Erythritol-expanded Graphite composite in different concentrations [42].

Expanded Graphite concentrations (wt%)	Melting point (°C)	Latent heat of fusion (kJ/kg)	Thermal conductivity (W/m.k)
0	119.30	320.7	0.7030
1	119.20	318.4	0.8442
2	118.98	315.5	1.2640
3	118.69	312.2	2.4000

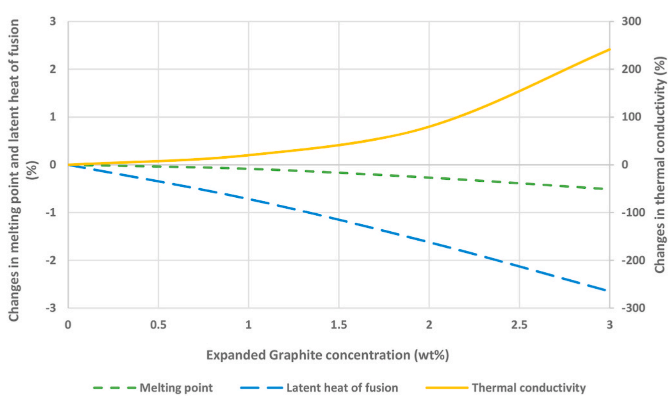

Fig. 16. Changes in melting point, latent heat of fusion and thermal conductivity in different concentrations of Erythritol-expanded Graphite composite, based on the results by Li et al. [42].

2.6 °C in the case of adding nanoparticles to the PCM.

Li and Zhai [77] have numerically assessed the performance of a PCM-filled heat pipe ETSC by employing five different concentrations of expanded Graphite dispersed in Erythritol, up to 4 wt%. Their results showed the highest thermal conductivity for the highest nanoparticle concentration. However, a relatively low improvement was achieved by increasing the concentration from 3 wt% to 4 wt%. Moreover, it was observed that increasing the concentration affected the flowability of the PCM. Hence, the concentration of 3 wt% was chosen as the authors' choice in their study.

Li et al. [83] have also tested the addition of expanded Graphite in different concentrations into Stearic acid PCM. Similar to Li and Zhai [77], a PCM-filled ETSC was utilised in their research. They compared pure PCM with those having expanded Graphite concentrations of 2 wt %, 6 wt%, and 10 wt%. They have obtained thermal conductivities of 2.9 and 13.7 times more than that of pure Stearic acid for 2 wt% and 10 wt% concentrations, respectively. Because of large heat capacity, high thermal conductivity, and low price, they have selected the mass fraction of 6 wt% as the optimum concentration. Compared to pure Stearic acid, by addition of expanded Graphite at 6 wt%, they achieved 63.3% less melting time and 9.6 times higher thermal conductivity, as well as a much more uniform heat transfer inside the PCM.

Low thermal conductivity is not the only drawback of PCMs. There are some studies focused on other shortcomings of PCMs, particularly when they are integrated with ETSCs. With the aim of increasing the stability and avoiding supercooling of the PCM in a tank connected to an ETSC, Wang et al. [7] have tested different compositions of the PCM Sodium Dihydrogen Phosphate Dodecahydrate ($Na_2HPO_4{\cdot}12H_2O$) with water, alumina powder and sodium carboxymethyl cellulose. They have reported the composition with 30% water, 2% alumina powder, 5% sodium carboxymethyl cellulose, and 63% $Na_2HPO_4{\cdot}12H_2O$ provided the best stability and thermal properties.

Another way to overcome some of PCMs drawbacks is the utilisation of phase change slurry (PCS). PCS is the mixture of PCM particles in another material with a continuous liquid phase in the temperature range of the application [131]. A typical example of PCSs is dispersed Paraffin inside water [132]. PCSs are very helpful, especially in the applications that the PCM must be pumpable even after solidification [133]. Higher heat transfer rates are also achievable by PCSs [134]. This modification on PCMs will allow them to not only be used as a heat storage medium but also as the heat transfer fluid of the primary process [135]. Microencapsulation technique is being widely used to synthesize PCSs. In this technique, the PCM is encapsulated in microscale shells, made of metal or polymers [136]. Few studies have been conducted on integration of PCSs with ETSCs. Joemann et al. [135] have employed a PCS in a subsection of a solar assisted steam ejector cycle but have not specifically focused on studying its effect on the process. Similarly, without a particular focus on the PCS, Zheng et al. [137] have considered the employment of a PCS inside an HVAC system with an ETSC as the heat source.

4.3. Charge and discharge operations

One of the most important parameters affecting the performance of ETSC-PCM systems is how the charge and discharge (C-D) operations of the PCM are designed to be performed [72]. PCMs store energy during charging and release that energy when discharging. Thermal energy discharging of PCMs is usually faster than their charging. Because the charging process starts with PCM being in solid-state when the main heat transfer mechanism is conduction; however, during discharging the process starts with the PCM being in the liquid phase for which the heat transfer rate is relatively faster (boosted by convection) [113,125]. Because of the same reason, there is usually a sharp temperature increase for the part of the PCM that is in contact with the heat source [53]. This characteristic of PCMs also causes the melting rate to increase as more amounts of PCM gets melted [125]. But, depending on the system design, PCM can show an opposite behaviour during charging. If the PCM receives a constant rate of thermal energy from the heat source, the above-mentioned behaviour is expected. However, when the heat transfer is occurred because of the temperature difference between the PCM and its surrounding medium, the charging process becomes slower as more amount of the PCM is melted [77]. That is because the temperature in the melted part, which is closer to the heat source, increases and consequently, the temperature difference in the interface of PCM and the heat source decreases. The temperature difference reduction between the heat source and heat sink reduces the rate of heat transfer to the PCM. Considering these characteristics, it must be tried to find proper designs for C-D processes for a PCM used in a particular application.

A main consideration for designing the C-D process is that whether the PCM charging is one of the consumers of the heat being supplied. If yes, part of the solar energy collected by the ETSC must be allocated for PCM charging. This means that the main consumer for which the system has been designed does not receive the full amount of thermal energy being generated by the collectors. Riffat et al. [63] have conducted an experimental study on an ETSC filled with PCM. They reported that the charging process of the PCM could affect the performance of the ETSCs. They have calculated the average thermal efficiency of the collector in subsequent time intervals. The duration of the first and second periods was considered to be equivalent to that required for PCM charging and discharging, respectively. They have obtained the average collector thermal efficiency for the ETSC without PCM and the PCM-filled ETSC to be 73% and 40% during the charging period, and 77% and 92% during the discharge period, respectively. Sharma et al. [138] have reported that when the solar energy is both used by the main consumer of the ETSC and the PCM, the performance of the system is lower than when the PCM discharging being the only supplier of the heat to the main application. Fig. 17 shows HTF output temperature, PCM temperature, and system thermal power output for a solar combined heat and power cycle designed by Cioccolanti [17]. The cycle included Fresnel lens collectors equipped with vacuum tubes and external PCM heat storage unit as the heat source.

Fig. 17 shows the effect of PCM charging on the thermal performance of an ETSC-PCM arrangement. As discussed earlier, by increasing the temperature of the PCM, more thermal energy is demanded for charging the PCM. According to this figure, without PCM, 25 kW output thermal energy was achievable, but when the HTF was also used for charging PCM, the output thermal energy decreased to less than 5 kW. In general, PCM charging step decreases the available thermal energy for the application. When increasing the size of the collectors is not considered, one solution to this problem is using auxiliary heat sources to charge the PCM. As Joemann et al. [135] have reported that for an ETSC-PCM equipped steam jet ejector chiller this solution would not only enhance the system performance but also lead to a smoother operation. However, using an external heat source for PCM charging is costly and requires more components, which also adds to the complexity of the system. Therefore, in most cases of ETSC-PCM systems reported in the literature, the PCM is charged up using the solar thermal energy collected by ETSCs. In doing so, different approaches have been used and reported in the literature, which will be further discussed in this section.

As a common design, ETSCs are mostly used to charge the PCM, and then the thermal energy is consecutively provided by the PCM discharging the stored heat to the intended application. There are applications such as cooking or domestic hot water supply with variable energy demands for which this consecutive operation approach can be appropriate. There are also some studies in the literature focusing on this approach in which the thermal energy demand was constant. Chopra et al. [15] have considered a separate charging and discharging operations for an ETSC filled with PCM inside its manifold with the aim of

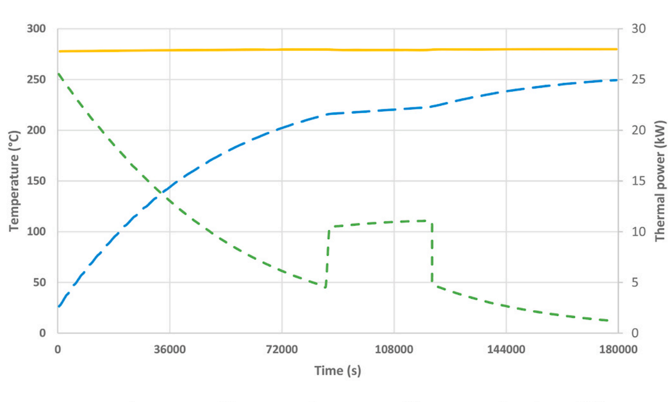

Fig. 17. HTF and PCM temperature and output thermal power during PCM charging step (data from Ref. [17] was used to regenerate the graph, with permission of reuse from Elsevier).

providing hot water. They have tested two different charging modes; i. e., full-day charging from 6:30 to 17:00 and half-a-day charging from 6:30 to 13:30. In each charging mode, the discharge operation began right after the charging step was done. Interestingly, they have reported that with such operation design, the half-a-day charging of PCM led to an increase in the overall thermal efficiency of the system by up to 10%.

Another approach investigated in the literature was using the collected solar energy for both PCM charging and direct supply of heat to the application simultaneously. Contrary to the consecutive approach in which the heat supply to the demand starts after the PCM is completely charged, in this simultaneous approach the thermal energy to the demand can be supplied while the PCM is being charged. Different outcomes have been reported in the literature on comparing the effects of consecutive and simultaneous C-D on the performance of ETSC-PCM.

Papadimitratos et al. [9] experimentally claimed that using the consecutive approach for operation of PCM in an ETSC-PCM arrangement resulted in a better overall performance than when the PCM charging and supply of heat to the demand are done simultaneously. However, Vempati [126] conducted a similar comparative study experimentally and reported quite an opposite result. According to their results, for the cases of only water heating, only PCM charging, simultaneous water heating and PCM charging, and water heating during the PCM discharging period only, overall efficiencies of 18.3%, 30.1%, 46.6%, and 65.68% were obtained, respectively. Abokersh et al. [67] also experimentally showed that for an ETSC-PCM water heater, with direct supply of heat to the demand while the PCM is simultaneously charged, the system performed more efficiently than a system in which the supply of heat starts consecutively after the PCM is fully charged. For an ETSC-PCM air dehumidification system, Mehla and Yadav [89] have reported that simultaneous charging of the PCM and supply of heat to the demand led to a poor performance during the first 2 h of operation during day time, and then their setup operated desirably until midnight. Then in another study on the same setup, they have compared the performance in two operation modes of simultaneous PCM charging and consecutive PCM discharging and [90] and have reported that the simultaneous mode showed a better performance than that obtained for the other arrangement. It must be noted that when the consecutive operation mode is selected, whilst PCM charging, the input solar energy is just consumed for PCM and not to supply the main energy demand. For instance, Mehla and Yadav [90] have tested both simultaneous and consecutive C-D. In their experiments, the ETSC-PCM energy output was available from the beginning of the experiment, i.e., 9:00 for the simultaneous C-D, and from 18:00 for the consecutive C-D. Hence, the consecutive arrangement also has some delays in supplying the thermal energy demand.

Overall, the literature generally supports the simultaneous PCM charging and heat supply to the demand as the preferred arrangement in terms of efficiency. Focusing on this approach, some studies proposed solutions for operation of the system under a more controlled condition to further improve its performance [61]. Cioccolanti et al. [17] have proposed a controllable charging and discharging design for an external PCM tank as the thermal storage unit of an ETSC driven combined heat and power system. In their design, the PCM was only charged when there was surplus solar thermal energy supplied by the collectors over the demand of the main application, and then the PCM could be triggered when thermal energy supplied by the collector was not sufficient to meet the demand by itself. Using a numerical modelling approach, they showed that by applying such a controlling strategy the effective operating time of the system in year could be up to 3100 h (i.e. more than 35% of the year), producing 5110 kWh and 53,670 kWh of electrical and thermal energy, respectively. By taking advantage of this control strategy, they have achieved an almost constant electrical efficiency of 6.2% throughout the year. In another numerical study Tascioni et al. [18] have focused on a similar vacuum tube based trigenerative system. They have taken advantage of a fuzzy logic to optimise the involvement of PCM in the whole process. Their optimised C-D control led to a 5% increase in the overall electrical efficiency, and a 30% decrease in the system heat losses. Furthermore, Arteconi [139] employed this system for a residential building and reported that it could save 9% of the building's total energy costs. By optimising the C-D timings, Ghorbani et al. [116] have achieved 10 h of operation for a 72 kW solar (ETSC) absorption chiller in the absence of sunlight, which was quite an impressive operating time for a PCM heat source.

Zhang et al. [100] suggest that by controlling the timings for operating the PCM in charging and discharging modes, the performance of the ETSC-PCM arrangements could be enhanced considerably. This is whilst in such cases, auxiliary heating devices are still required. With an uncontrolled C-D operation, Zhang et al. [23] have experimentally supplied only 40% of the energy demand for floor heating of a building in a cold climate, by using an ETSC-PCM system. However, using a similar ETSC-PCM for space heating, Luo et al. [140] could supply up to 60% the daily required thermal energy by employing a controlling strategy for charging and discharging of the PCM in this system. In another example, by controlling PCM C-D operations, Luu et al. [61] have achieved a design for an ETSC-PCM system that did not need a hot water tank (as in conventional systems) for a 24-h supply of hot water. They found that by integrating an optimally controlled ETSC-PCM to a single fossil fuel-based boiler an annual saving of 97.4% in fossil fuel consumption could be achieved.

Hmadi et al. [20] have claimed that by using an optimum PCM C-D control method, an ETSC system can supply the entire heating and cooling demands of a building. They used an externally PCM integrated high solar combi-plus design to produce the heating, cooling, and domestic hot water energy demand of a building using ETSCs. Through a numerical model, they reported that an optimum ETSC-PCM system under controlled charging and discharging conditions can supply the total thermal energy demand of a two-floor building with a total area of 300 m^2. Shabgard et al. [94] have also reported similar numerical results for an optimum design of such system. However, they claimed that the system could supply up to 87% of the typical thermal energy demand of a residential building and an auxiliary heat source is still required to fill the 13% gap between supply and demand.

4.4. Design and specifications of the collectors

The specifications of an ETSC can expectedly influence its design and performance when it comes to its integration with a PCM unit. The amount of heat collected by a particular ETSC as well as its heat loss and cost are directly determined by its size [98]. However, according to the numerical results presented by Sekret and Feliński [79], the rate of thermal energy provided by an ETSC-PCM arrangement has a nonlinear relation with the size of the ETSC used in the system. Allouche et al. [97] have claimed that by increasing the size of the thermal storage mediums (i.e. the PCM unit), the effect of the collector area is even pronounced more. Liu et al. [92] also had a similar conclusion. They have concluded that that the required size for the PCM linearly increases by increasing the area of the collectors.

The tube diameter was another geometrical parameter, studied by Li and Zhai [77] numerically as indicated by Fig. 18.

According to Fig. 18, for a PCM-filled ETSC, the PCM temperature rises faster and melts quicker in smaller tube diameters. For the inner tube diameter of 42 mm, the PCM reached its melting point in less than an hour and melted completely in about 7 h. But for a tube with 64 mm diameter, it took more than 1.5 h for the PCM to reach its melting point, and after 10 h the PCM was not still fully melted. Li and Zhai [77] have reported that tubes with smaller diameters show a better performance because they can transfer the incident solar thermal energy to the PCM more uniformly. Their results were obtained numerically and yet need to be further investigated and validated experimentally.

There are also some studies on other designs of ETSCs. For example, Feliński and Sekret [71] have used a PCM-filled all-glass ETSC with heat pipes for water heating purpose. They added a compound parabolic

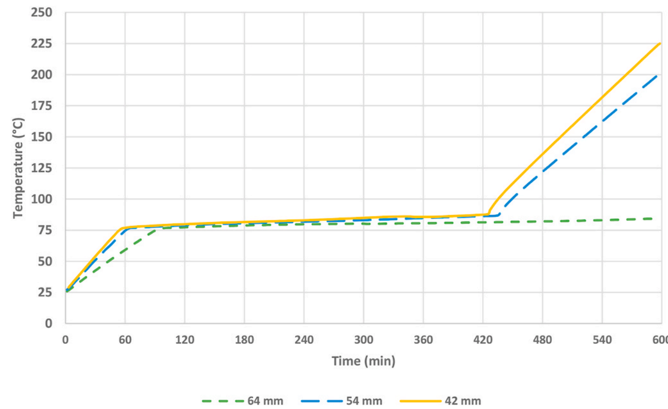

Fig. 18. Temperature of PCM inside a heat pipe type ETSC with time in different ETSC tube diameters (data from Ref. [77] was used to regenerate the graph, with permission of reuse from Elsevier).

concentrator (CPC) to their experimental setup to improve its thermal efficiency. After the addition of this the CPC, the backside of the ETSC that was not facing the sun, could also receive the solar irradiance reflected by the CPC. Hence, more amount of solar energy could be collected by ETSC from different sides, and then more energy could be stored in the PCM accordingly. Just by adding the CPC component, they obtained 39% more thermal energy supplied by the system for domestic hot water production.

Another parameter that directly affects the performance of ETSC-PCMs is the main energy source, i.e., solar irradiance. While there have been some studies indicating that ETSC-PCMs systems operate more efficiently in areas with a higher level of solar irradiance [17,137], some other studies claimed the opposite due to increased heat losses triggered by higher thermal energy generated [76]. It has been reported that the effect of solar irradiance on charging behaviour of PCM is even more than the effect of ambient temperature [82,141].

Wu et al. have [47] experimentally showed that adding PCM inside an ETSC offers more improvements in areas with lower solar radiation; this is while they emphasised that higher irradiance is still preferred for solar thermal systems in which no PCM is utilised. As is reported in their study, for a solar irradiance less than 300 W/m^2 the addition of PCM inside ETSC led to collecting13.5% more solar thermal energy by the system. On the contrary, by a numerical study, Sayegh et al. [79] have claimed that the most heat losses of a PCM-filled ETSC happened at lower solar irradiance.

The studies that have discussed the effects of solar irradiance on the performance of ETSC-PCMs are limited to what has been presented here. Overall, contradicting effects are reported in the literature, and it is not possible to suggest a general behaviour for this parameter based on the few number of available studies. Hence, a full understanding of the effects of solar irradiance on the performance of ETSC-PCM remains to be a gap in the literature.

4.5. Heat transfer fluid

Although the type of heat transfer fluid (HTF) used in the system is an important parameter to consider [128], most of the studies reported in the literature are focused on the role of the HTF flow rate for a given HTF. HTF transfers the collected thermal energy to the primary energy consumer, which can be the intended application or even the PCM placed in the system for storing the energy. Although the employment of PCM reduces the effects of variations of HTF flow rate [21], the effect of this parameter can still be significant in some operating condition or designs of the ETSC-PCM systems [110].

In two studies on the same experimental setup, Abdulateef et al. [109,110] have studied the effects of HTF flow rate on charging and discharging operations of an external PCM-filled triplex tube heat exchanger. They have considered three different HTF flow rates of 16.2, 29.4, and 37.4 min/kg and reported that the middle value led to the fastest charging time [110]. However, during the discharge operation, the highest HTF flow rate showed the best performance [109]. Same results were reported by Chopra et al. [15] and Li et al. [42] too. They reasoned that higher HTF mass flow rates increase the convection heat transfer rate between the PCM and HTF.

Li et al. [142] had the conclusion that higher HTF flow rates generally decrease the maximum operating temperature of the ETSC-PCM and increase its thermal efficiency. The reason for the increase in thermal efficiency is that HTFs at higher flow rates can carry more thermal energy per unit of time [125]. On the other hand, HTFs at higher flow rate have shorter exposure to the heat source and thus less increase in their temperature is expected [125]. In other words, by increasing the flow rate, the rate of transferring heat to the HTF increases too; however, the thermal energy is distributed into a larger mass of HTF, which results in lower HTF temperature rise [125]. This behaviour is observed by other researchers as well. Through an experimental study in different conditions on an ETSC with PCM integrated inside its manifold, Mehla et al. [85,89–91] have reported the exact same results of lower output temperature and higher thermal efficiency by increasing the flow rate of the HTF. Similarly for a PCM-filled heat pipe type ETSC, Chopra et al. [66] by comparing the flow rates of 8, 16, and 24 l/h, have obtained the average daily energy efficiency of 62.80%, 69.65%, and 78.37% and exergy efficiency of 19.98%, 22.34%, and 23.15%, respectively. They have reasoned that in higher flow rates, because of the lower HTF temperature, the heat losses from HTF to the ambient minimises and consequently the overall energy and exergy efficiency of the collector will be increased.

For an ETSC equipped with an external PCM unit, the experiments by Agarwal and Sarviya [125] have obtained a 23% increase in discharging time by a 50% decrease in the HTF flow rate. Likewise, for another PCM-in-manifold design, Naghavi et al. [53] experimentally and Bazri et al. [86] numerically reported such behaviour. Experiments on PCM-filled ETSCs by Abokersh et al. [67] and Tyagi et al. [22] on U-tube type and Huang et al. [82] on heat pipe type also indicated higher efficiencies for the system at higher HTF flow rates. Based on the available data in the literature, the effects of flow rate on the amount of thermal energy collected by the HTF and the output temperature of the system are shown in Fig. 19 and Fig. 20, respectively.

As shown in Fig. 19, the experiments conducted by Agarwal and Sarviya [125] have obtained 50% more thermal energy output after increasing the HTF flow rate by 100% from 1.5 g/s to 3 g/s. The numerical results provided in Fig. 20 suggest that during almost all the operation time, the output temperature is higher at lower HTF flow rate. Even more than 10 °C temperature difference is reported between the flow rates of 50 l/h and 80 l/h. Feliński and Sekret [46] have transferred more solar thermal energy by increasing the HTF flow rate of a PCM-filled heat pipe ETSC. They have also reported that at lower flow rates, increasing the flow rate has more effect on improving the output thermal energy. However, it has also been suggested that increasing the flow rate of the HTF at nighttime could lead to a negative impact on the performance of the system [35]. Agarwal and Sarviya [125] have mentioned that although the increase in HTF flow rate increases the overall thermal efficiency of an ETSC-PCM system, it can have a negative impact on the thermal performance of the primary application to which the heat is supplied. This is because in some cases, such as drying applications, the HTF can require more contact time to transfer its thermal energy to the system. On the other hand, Arkar et al. [98] have claimed that for building heating applications, higher HTF flow rates will increase the overall thermal efficiency of the building.

Although most of the studies in the literature have reported that increasing the HTF flow rate would enhance the performance of the ETSC-PCM system, there are a few studies out there that have experimentally obtained an opposite behaviour. Wang et al. [143] have reported for an externally PCM-equipped ETSC that using higher flow rates of HTF could lead to higher output temperatures. They have taken advantage of fins inside the PCM container to improve the heat transfer rate and have employed the consecutive C-D method. Alajo [96] have obtained higher thermal efficiency for another ETSC with external PCM unit. Their setup included a water storage tank, which was filled by the water passed through the PCM tank. Their results were obtained for a simultaneous PCM C-D.

Apart from the lower HTF output temperature, the literature has also reported some other challenges associated with increasing the HTF flow rate. The heat transfer between HTF and PCM requires enough time to complete thermal charging and discharging of PCM [72]. Hence, with incomplete charging a PCM cannot deliver its full capacity to store thermal energy and thus the benefit of using a PCM unit is not fully pronounced. Interestingly, the experiments by Nagappan et al. [101] contradicts with the reports by Essa et al. [72] and by only considering the charging mode of an external PCM unit, they observed that increasing the HTF flow rate led to storing more thermal energy in the PCM. Therefore, it can be concluded that for every ETSC-PCM design, there must be an optimum HTF flow rate, and moving away from this optimum value can lead to a decrease in the performance of the system. By considering a wide range of HTF flow rates, Chopra et al. [74] have

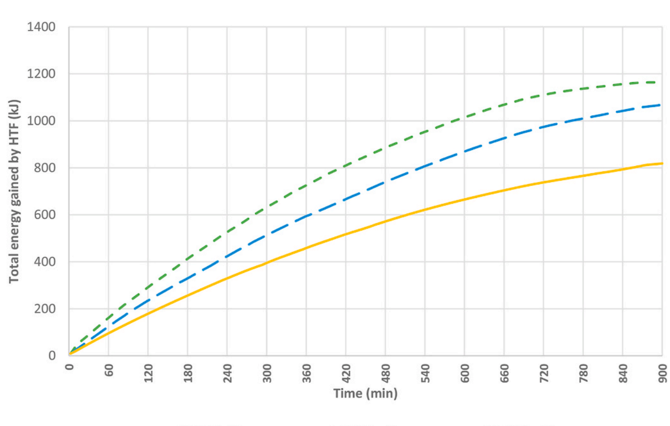

Fig. 19. Cumulative amount of energy transferred from ETSC-PCM to HTF during PCM discharge, in different HTF flow rates. ETSC is equipped with an external PCM unit and the consecutive charge, and discharge method is tested. HTF is air with an inlet temperature of 30 °C and enters a food dryer after passing through the PCM unit (data from Refs. [125] was used to regenerate the graph, with permission of reuse from Elsevier).

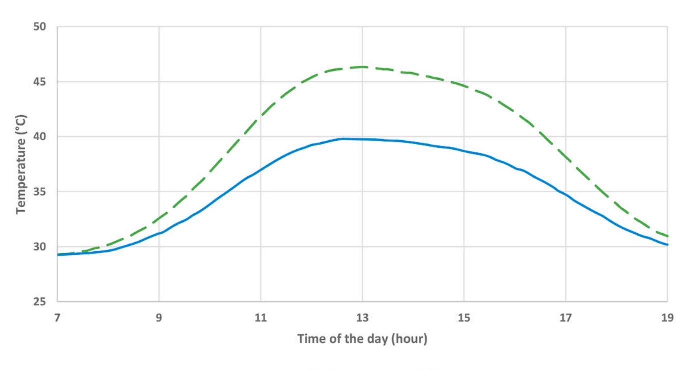

Fig. 20. HTF outlet temperature obtained numerically for a PCM-inside manifold ETSC in two flow rates of 50 and 80 L per hour. The considerations in the model: the collector is used for water (HTF) heating under high intensity of solar irradiance, the manifold is filled with PCM and PCM is fully charged, HTF is heated up just by PCM discharge (data from Refs. [86] was used to regenerate the graph, with permission of reuse from Elsevier).

experimentally obtained similar results. They have tested water flow rates of 8 l/h, 12 l/h, 16 l/h, 20 l/h, and 24 l/h for a PCM-filled heat pipe type collector and have obtained the maximum temperature rise for the flow rate of 12 l/h and the maximum collector thermal efficiency at the HTF flow rate of 20 l/h. However, their experiments were conducted in different days and the slight differences in the availability of sunlight has had some effects on their final results too.

Currently, there have been few numerical studies conducted on finding optimum HTF flow rates in different designs. For two different externally PCM-integrated ETSC systems, Iranmanesh et al. [41] and Cheng et al. [102] have numerically evaluated different flow rates of air and water as the HTF, respectively. Iranmanesh et al. [41] have reported that in the range of 0.025–0.09 kg/s, the HTF flow rate of 0.05% must show the best heat storage performance. The results of the study by Cheng et al. [102] suggested that in HTF flow rate range of 50–250 l/h, the most desirable ETSC-PCM performance could be achieved by the value of 200 l/h. Through an experimental study, Feliński and Sekret [46] have interestingly claimed that for a PCM-filled heat pipe ETSC and per every 1 m^2 of ETSC aperture area, the water (HTF) flow rate of 0.02 kg/s showed the best thermal performance. However, they have only considered three values of 0.02 kg/s.m^2, 0.03 kg/s.m^2, and 0.06 kg/s.m^2 for a given arrangement, making it difficult to generalise their finding for other ETSC-PCM systems.

4.6. Operating temperature

4.6.1. Heat transfer fluid temperature

For an externally PCM equipped ETSC Al-Abidi et al. [107] have experimentally proven that compared to the HTF flow rate, the temperature difference between the HTF and PCM could have more effects on the overall performance of an ETSC-PCM system. By varying the HTF flow rate and its inlet temperature to the PCM unit, they could achieve up to 58% and 86% less PCM charging time, respectively. It must be noted that the HTF temperature was raised using an auxiliary heater placed between ETSC and PCM unit. Thus, the temperature of the inlet HTF to the PCM unit was independent of HTF flow rate.

It is widely known that the heat transfer rate increases by the temperature difference between the heat source and the heat sink [101]. Depending on the ETSC-PCM configuration, the HTF can be the heat source of the PCM or its heat sink. When PCM is integrated inside the ETSCs or their manifold, the HTF will act as the heat sink, and thus, by lowering the HTF temperatures the heat transfer rate from the ETSC to the HTF increases. Also, as indicated by the experiments conducted by Bai et al. [76] as well as the numerical results obtained by Li et al. [42], at lower HTF temperatures the PCM is discharged at a faster rate. On the other hand, Xie et al. [65] have claimed through a numerical study that the HTF temperature has a negligible effect on the performance of an ETSC filled with PCM. However, they have only considered a particular design (a solar cooker) in which the HTF itself was the primary energy consumer remaining inside the ETSC rather than flowing through it. In general, for the cases with PCM integrated inside ETSCs, lower HTF inlet to the collector temperature showed a better heat transfer performance. The HTF inlet temperature directly affects its exit temperature from the collector as well, and the latter must match the application temperature requirements. Therefore, finding a proper HTF inlet temperature to achieve the best performance while meeting the system's requirements is an optimisation task by itself.

When a PCM is integrated with an ETSC as an external unit, the PCM unit in most cases, receives the thermal energy from the HTF and releases it to the application or the process that the system has been designed for. Hence, the HTF would be the heat source for the PCM, and it is expected to show a better performance at higher temperatures. There have been some studies in the literature investigating the effect of HTF temperature when entering the PCM units in such cases. Agarwal and Sarviya [125] share the same opinion as presented here and have experimentally obtained 20% faster PCM charging time increasing the in HTF inlet temperature by 10 °C. On the other hand, Feliński and Sekret [46] experimentally, and Li et al. [142] numerically have reported that higher HTF inlet temperatures could lead to higher heat losses and consequently lower thermal efficiencies of the system.

4.6.2. Melting point of the phase change material

Considering the variable nature of solar irradiance, PCM selection is a vital part of designing a desirable ETSC-PCM system [69]. One of the most important criteria in selecting a PCM is its melting point that must be matched with temperature requirements of the intended process or the application by the end-user [15,65]. Feliński and Sekret [69] have suggested that for water heating purposes, a PCM with a melting point of about 60 °C can be a proper choice. But for floor heating applications, Wang et al. [7] have proposed the employment of PCMs with a melting point in the range of 35–40 °C. For externally integrated PCM designs, the PCM melting point must be higher than the application temperature requirements. According to Zhou et al. [14], this is 5–10 °C, and according to Wang et al. [7], this has to be 15–20 °C higher than the operating temperature of the application for which the ETSC-PCM is designed.

Freeman et al. [10] have reported that while the PCM melting point must be selected to be in an appropriate range, usually lower quantities of PCMs are required in systems for which PCMs at higher melting points are used [3]. It is noteworthy that more heat has to be supplied to PCMs with higher melting points and the collectors should also operate at higher temperatures accordingly. The collectors operating at higher temperatures are usually less efficient than those operating at lower temperatures [14]. Therefore, it is critical to choose an optimum operating temperature for given application to make sure that the system operates at the best possible overall efficiency. This optimum value depends on many other parameters including, the integration type, the system design and its application, the collector and PCM specifications, and even the climate condition under which the system operates. Despite the importance of this topic, there have been very few studies devoted to the optimisation of the PCM melting point for application in ETSC-PCM systems.

4.7. Fin-enhanced containers for phase change materials used with solar thermal collectors

It is widely known that fins can improve the heat transfer rate by increasing the heat transfer area [103]. Hence many studies have included fins in the PCM unit of the system [21,52,106,108,110]. Employment of fins also helps create a more uniform heat transfer behaviour inside the PCM [15]. Mat et al. [108] have obtained 43% faster rate of melting for a PCM used inside the tubes of an ETSC system, by adding fins inside the tubes. By contrast, the experiments of Abokersh et al. [81] have shown that the utilisation of fins has increased the collector efficiency only during discharging operation. In their study on a PCM-filled U-tube ETSC water heater, they have achieved 14% higher efficiency for an un-finned design compare to a finned design during the charging mode. However, in another study on the same setup Abokersh et al. [67] have reported that the overall efficiency of a finned PCM container, in both charging and discharging steps, was higher than that of an un-finned one. A similar conclusion was made by Al-Abidi et al. [106] who have numerically indicated that the employment of fins can significantly improve the PCM performance during discharging operation as well as charging mode.

The main difference between the two studies by Abokersh et al. [67,81] is that the consecutive and simultaneous C-D were tested in the former [81] and latter [67] studies, respectively. In the former study, for such behaviour, they mentioned that natural convection is the main heat transfer mechanism inside the melted part of PCM, which is closer to the heat source. Thus, the fins act as thermal resistance between the heat source and the melted part of PCM. But they have not justified why contradictory results are obtained by the same setup in another experiment. It seems the main reason was the specific fin configuration they have employed inside ETSC. The schematics of the fin design in their work is shown in Fig. 6. Normally, fins are designed in a way that they are perpendicular to the heat transfer surface and go deep into the heat transfer medium. But in their setup, the fins are placed on the intersection of the PCM and ETSC components. In such a fin configuration, the specifications of the heat transfer medium can affect the usability of the fins. However, despite the higher collector efficiency reported for their un-finned design during PCM charging, Abokersh et al. [81] have obtained more extended operation time and more stable collector temperature output by employing the fins. Hence, employment of fins enhances the overall performance of ETSC-PCMs.

Wang et al. [143] have also studied the concept of introducing fins in ETSC-PCM arrangements. They have experimentally designed a heat pipe ETSC-PCM system with fins on its different parts. In this design, the heat pipe, PCM tank, and the air duct connected to the PCM tank were equipped with fins. The main novelty of their work was the installation of fins on the condenser section of the heat pipes. This part of heat pipes is typically placed inside the ETSC manifold. Fig. 21 shows the schematic of their finned heat pipe design.

Installation of fins on the heat pipes' condenser sections has been practised by other researchers as well [15,76]. Some studies have focused on how and where the fins can be installed on ETSC-PCMs, and some others have focused on specifications of the fins themselves. For an externally integrated PCM unit equipped with fins, Al-Abidi et al. [106] have numerically investigated the effects of fins number, length, and thickness on the PCM performance. According to their results, the number of fins is the most effective parameter affecting the performance of the PCM. They have also reported that compared to fins thickness, fins length has more influence on PCM C-D performance. There are also some other parameters including the fins material, orientation, and spacing that have been reported to be effective on the heat transfer performance of ETSC-PCMs [53].

5. Performance indicators for PCM-integrated evacuated tube solar collectors

There are four main performance indicators used in the literature to assess and compare ETSC-PCMs, namely, collector thermal efficiency, PCM charging efficiency or heat storage efficiency, overall thermal efficiency, and solar fraction. The last two parameters are defined for performance assessment of the whole system, including the end-user and the ETSC-PCM arrangement.

The behaviours of both the collectors and the PCM unit vary continuously during ETSC-PCM operation. Hence the performance modelling of the system can either focus on its instantaneous performance of the system at a given time or its overall average performance over a given period. However, the latter approach is usually used for evaluating the performance of ETSC-PCM systems. In doing so, the energy efficiency of solar thermal collectors can be calculated using the following general equation [144]:

$$\eta_{col.} = \frac{Q_{out}}{Q_{in}} \tag{10}$$

where $\eta_{col.}$ is the collector thermal efficiency, Q_{out} is the amount of useful thermal energy produced by the collector (kJ), and Q_{in} is the amount of incident solar thermal energy received by the collector (kJ). Eq. (10) can be rewritten in the following form [142]:

$$\eta_{col.} = \frac{m_{HTF}\overline{\Delta h}_{HTF}}{A_c\int_0^t Gdt} \tag{11}$$

where m_{HTF} is the total mass of HTF (kg) leaving ETSC over a selected period of $t(s)$, $\overline{\Delta h}_{HTF}$ is the average enthalpy difference (kJ/kg) of HTF when entering and leaving the collectors, and $\int_0^t Gdt$ is the total incident irradiance received by the collector (kW/m^2). Based on the design and components of the collector, Eqs. (10) and (11) must be modified. In most cases, there is an HTF following through ETSC tubes or its manifold and hence [75,97]:

$$Q_{out} = m_{HTF}c_{p,HTF}\overline{\Delta T}_{HTF} \tag{12}$$

where $c_{p,HTF}$ is the specific heat of HTF ($kJ/kg.^{\circ}C$), and $\overline{\Delta T}_{HTF}$ is the average temperature difference ($^{\circ}C$) of the HTF when entering and leaving the collectors. When there is a PCM component, such as PCSs, passing through ETSC and assuming that all the PCM is melted, Q_{out} would be equal to the energy stored in PCS. The amount of stored energy can be calculated using Eq (7). If an external PCM unit is employed, it will not directly affect the collector efficiency; hence, the effect of external PCM unit will already be taken into consideration in the inlet and outlet temperatures of the HTF.

For the collectors with a direct flow of HTF inside the ETSC, an empirical relation is used as below [10,61,96,142]:

$$\eta_{col.} = \eta_{col.,0} - a\frac{\overline{T}_{HTF} - \overline{T}_a}{\int_0^t Gdt} - b\frac{(\overline{T}_{HTF} - \overline{T}_a)^2}{\int_0^t Gdt} \tag{13}$$

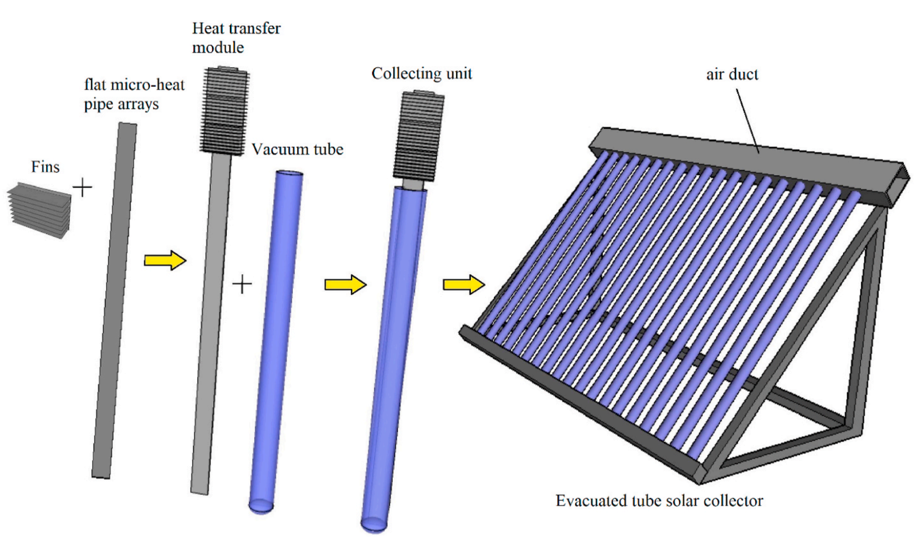

Fig. 21. Schematic of fin installation on a heat pipe type ETSC [143] (with permission of reuse from Elsevier).

where $\eta_{col.,0}$is the collector nominal efficiency without losses, $a$and $b$are thermal loss coefficients, $\overline{T}_a$is the average ambient temperature ($^\circ C$), and:

$$\overline{T}_{HTF} = \frac{\overline{T}_{HTF,o} - \overline{T}_{HTF,i}}{2} \tag{14}$$

where $\overline{T}_{HTF,o}$and $\overline{T}_{HTF,i}$are the average outlet and inlet HTF temperatures ($^\circ C$). The values of $\eta_{col.,0}$, $a$and $b$are determined by having the specifications of ETSC.

Another performance indicator that has been used in a few studies is named heat storage efficiency or PCM charging efficiency. By definition, heat storage efficiency is the ratio of the amount of thermal energy stored in PCM to the maximum possible amount that could be stored [116]. Heat storage efficiency is though calculated by Eq. (15) as follows [57]:

$$\eta_{PCM} = \frac{Q_{st.}}{A_c \int_0^{t_{ch.}} G dt} \tag{15}$$

where $Q_{st.}$is the amount of thermal energy stored in the PCM during the charging period (kJ), $t_{ch.}$is the duration of charging (s), and $G$is the solar irradiance collected by ETSC (kW/m^2). The amount of Q_{stored}can be obtained using Eq. (16):

$$Q_{stored} = fMq_{PCM,latent} \tag{16}$$

where $f$is the fraction of PCM that is in liquid state after passing $t_{ch.}$, and $M$is total mass of PCM (kg) [57].

The relations for solar fraction and overall thermal energy efficiency are dependent on the application or process the system has been designed for. For cooling applications, instead of thermal efficiency, mostly COP is used as the key performance indicator. Because there is a wide range of possible applications for ETSC-PCMs, only the main definition of solar fraction is presented here. Eq. (17) [145] shows how solar fraction can be calculated:

$$SF = \frac{Q_{sol.}}{Q_{sol.} + Q_{Aux.}} \tag{17}$$

where $SF$is the solar fraction, $Q_{sol.}$is the amount of thermal energy demand supplied by the ETSC-PCM system (kJ), and $Q_{Aux.}$is the amount of thermal supplied by auxiliary heaters (kJ).

Because of broad differences in the design of ETSC-PCMs studied in the literature, comparing their performance indicators is often challenging and may not provide a useful base for benchmarking them against each other. However, as a reference for performance assessment of ETSC-PCMs, the performance indicators data found in the literature are summarised in Table 4.

6. Research gaps and recommendations for future studies

The configuration of ETSC-PCMs has received a significant level of attention in the literature, and many interesting designs have already been proposed and investigated by different researchers. However, in many cases the need for an auxiliary heater for a continuous operation of the system was emphasised. But how the auxiliary heater must be coupled with ETSC-PCM systems have not received enough attention. Further studies are required to provide a clear picture on incorporation of auxiliary heaters with ETSC-PCMs, indicating how such an integration can be managed, what kind of heaters are the best candidates, what are the effective parameters in such systems, and what are the key considerations for a high performance ETSC-PCM coupled with an auxiliary heater. Moreover, economic factors are also the important aspects to be investigated for such systems.

One of the most efficient use of PCMs can be their employment as a waste heat recovery unit. There has been very limited number of studies on such designs [111], and their advantages, disadvantages, and potentials are yet to be comprehensively studied.

This comprehensive literature review is indicating that many studies have not reflected the ETSC-PCM operation performance in real working conditions because most of the studies are focused on consecutive PCM C-D. In many of the presented designs, the PCM must be fully charged first, before it starts releasing its stored thermal energy. In such designs, the primary heat source, which is the solar energy, is fully utilised for PCM charging before its heat is redirected to its intended application. Moreover, the main source is kept out of the loop for direct supply to the demand while the PCM is being discharged. Simultaneous C-D seems to be more feasible in realistic applications; however, there is a need for more detailed studies on this C-D approach. The results given in the literature [17,20,94,100,116,139,140] indicate that controlling the charge and discharge operations of PCM can significantly improve ETSC-PCM performance. Although auxiliary heat sources are required in such systems, high-performance energy systems are achievable by optimisation of C-D cycles. There have been very few numerical studies on C-D optimisation in the context of ETSC-PCM systems. The studies found during this review have only been conducted on the external ETSC-PCM configurations. Both experimental and numerical studies are required on the external and other ETSC-PCM configurations to obtain more accurate and reliable results and determine the optimum C-D designs.

Except for a few numerical studies, all the other studies have investigated the performance of ETSC-PCMs just during short periods, from few hours in a day to severall days in a season. Hence, their results are only valid for that specific period, and it cannot be concluded how the ETSC-PCMs perform throughout the year. This is critical to study such systems for a year-round operation as the variations of climate conditions can significantly affect the performance of both PCM and ETSCs throughout the year. Hence, to fully understand the performance of ETSC-PCMs, their yearly performance must be studied.

Selection of PCM can significantly affect the performance of ETSC-PCM systems. As shown in Fig. 22, mainly due to their availability and stable performance, different grades of Paraffin have been used as the PCM in most of the studies reviewed. Utilisation of Erythritol, Acetamide, and Solar Salt has also been repeated in a few papers. Other PCMs such as salt hydrates and specific inorganic materials have been mostly investigated in one or two individual studies. There have been very few efforts to compare the effects of using different PCMs on the performance of ETSC-PCM systems. More studies are required on the selection of an optimum PCM for use in different ETSC-PCM configurations.

A well-known drawback of PCMs is their weak heat transfer properties (i.e. conduction), which also affects their performance in the context of an ETSC-PCM system. Various methods have been developed for enhancing PCM thermal properties; however, only a few studies on ETSC-PCMs have briefly mentioned the use of such techniques to obtain a high-performance integration. Considering various ETSC-PCM configurations and their potentials, there is a wide range of modifications on the PCMs in the context of ETSC-PCM systems that have not been studied yet. Based on the flexibility of the main integration type between ETSC and PCM, further studies can focus on taking advantage of various nanoparticles, encapsulation materials and methods, slurries, additional heat pipes, and etc.

HTF inlet temperature and flow rate make various impacts on the performance of ETSC-PCM systems, depending on the integration type and the configuration of the system. Too high values or too low values for HTF inlet temperature can impact the performance of the system negatively. Therefore, there is a need for studies providing guidelines on the optimisation of HTF flow rate and temperature.

Most of the studies on ETSC-PCMs have just investigated the effect of PCM characteristics on the performance of the whole system and the effect of varying the design parameters of ETSCs have received little attention. This is an important area to be investigated by future studies. Moreover, the effects of the system main source of energy, i.e. solar

Table 4
Efficiency data for different ETSC-PCM designs.

Main configuration	Performance		Material as PCM	Application	Study type	Ref.
	Indicator	Value				
PCM-filled U-tube ETSC	Collector thermal efficiency	48–57%	Mannitol-Graphite	Air heater	Experimental	[48]
	Overall thermal efficiency	21.90%	a commercial grade of Paraffin	Water heater	Experimental	[72]
		20–33%	ALEX WAX 600	Water heater	Experimental	[67]
		34–58%	Barium Hydroxide Octahydrate	Water heater	Experimental	[70]
		10–20%	a commercial grade of Paraffin	Air heater	Experimental	[22]
	Solar fraction	24–57%	ALEX WAX 600	Water heater	Experimental	[67]
PCM-filled heat pipe ETSC	Collector thermal efficiency	29–43%	a commercial grade of Paraffin	Domestic hot water (DHW)	Experimental	[69]
		51–63%	a commercial grade of Paraffin	Water heater	Experimental	[47]
		30–53%	Stearic acid	Water heater	Experimental	[66]
		79–87%	Stearic acid (67)	Water heater	Experimental	[74]
	Heat storage efficiency	51–64%	a commercial grade of Paraffin	Air heater	Experimental	[76]
		31–36%	a commercial grade of Paraffin	DHW	Experimental	[71]
		42%	a commercial grade of Paraffin	DHW	Experimental	[69]
		40.17%	Erythritol	–	Experimental	[77]
		39.98%	Not given	–	Numerical	[42]
	Overall thermal efficiency	34–42%	a commercial grade of Paraffin	Water heater	Experimental	[53]
	Solar fraction	47%	a commercial grade of Paraffin	DHW	Experimental	[69]
PCM unit inside ETSC manifold	Collector thermal efficiency	15.60%	Acetamide	Air heater	Experimental	[91]
		17.90%	Acetamide	Air heater	Experimental	[90]
	Heat storage efficiency	14–18%	Acetamide	Air heater	Experimental	[85]
		17.08%	Acetamide	Air heater	Experimental	[91]
		25–50%	Acetamide	Air heater	Experimental	[90]
	Overall thermal efficiency	36–58%	a commercial grade of Paraffin	Water heater	Numerical	[86]
		52–72%	Stearic acid	Water heater	Experimental	[15]
		58–75%	a commercial grade of Paraffin	Water heater	Experimental	[29]
		55–60%	a commercial grade of Paraffin	DHW	Numerical	[21]
		52–72%	Stearic acid	Water heater	Experimental	[15]
		58–75%	a commercial grade of Paraffin	Water heater	Experimental	[29]
		55–60%	a commercial grade of Paraffin	DHW	Numerical	[21]
		20%	Acetamide	Air heater	Experimental	[85]
	COP	0.96	Acetamide	Solar cooling	Experimental	[30]
	Overall exergy efficiency	19–25%	a commercial grade of Paraffin	Water heater	Experimental	[29]
		7.8–8.4%	Acetamide	Air heater	Experimental	[91]
		2%	Acetamide	Solar cooling	Experimental	[30]
PCM flow in manifold of a heat pipe ETSC	Overall thermal efficiency	50–77%	PC210	Water heater	Experimental	[75]
ETSC with external PCM unit	Collector thermal efficiency	45–50%	Dodecanoic acid	Air heater	Experimental	[143]
		58–62%	Not given	Solar cooler	Experimental	[137]
		60–65%	Acetanilide	Solar cooker	Experimental	[120]
		43%	RT82	Absorption refrigeration cycle	Numerical	[95]
		53–56%	Not given	Organic Rankine cycle (ORC)	Numerical	[142]
	Heat storage efficiency	70–98%	Numerous materials	Solar cooler	Numerical	[116]
	Overall thermal efficiency	23–29%	ALEX WAX 600	Water heater	Experimental	[81]
		46–65%	PureTemp 48	Water heater	Experimental	[126]
		63.60%	PT56	DHW	Experimental	[96]
		60–70%	Not given	Floor heating	Experimental	[23]
		5–7%	Not given	ORC	Numerical	[142]
		6.9–14.6%	Not given	ORC	Numerical	[59]
		30%	Acetanilide	Solar cooker	Experimental	[120]
		33–40%	RT50	Solar drying	Numerical	[41]
		43–83%	Not given	Solar drying	Experimental	[55]
		64–96%	Sodium Sulfate Decahydrate	Solar assisted heat pump	Experimental	[64]
	COP	0.87	RT11	Building heating and cooling	Numerical	[32]
		2.93–3.22	a commercial grade of Paraffin	Floor heating and cooling	Experimental	[141]
		0.043–0.193	RT15	Solar cooling	Numerical	[97]
		4.5–6.5	a commercial grade of Paraffin	Solar cooling	Numerical	[99]
		0.87–2.52	Not given	Absorption refrigeration cycle	Numerical	[3]
		5–10	Sodium Sulfate Decahydrate	Solar assisted heat pump	Experimental	[64]
	Solar fraction	63–66%	a commercial grade of Paraffin	Solar cooling	Numerical	[99]
		70%	RT15	Solar cooling	Numerical	[97]
		16–73%	PT56	DHW	Experimental	[96]
		63%	PX21	Air heater	Numerical	[98]

(*continued on next page*)

Table 4 (*continued*)

Main configuration	Performance		Material as PCM	Application	Study type	Ref.
	Indicator	Value				
		82%	DX53	Floor heating	Experimental	[100]
		21–42%	Erythritol	Power plant carbon capture	Numerical	[34]
		45–80%	Erythritol	Power plant carbon capture	Numerical	[92]
	Overall exergy efficiency	75–90%	Magnesium Nitrate Hexahydrate	DHW	Numerical	[94]
		67–88%	Not given	Solar drying	Experimental	[55]
		40–66%	Eutectic mixture of Capric, Lauric, and Oleic acids	Solar cooling	Numerical	[102]
	ORC electrical efficiency	6.20%	Solar salt	ORC	Numerical	[17]
Vacuum tube-based parabolic trough collector with external PCM	Overall thermal efficiency	25.73%	a commercial grade of Paraffin	Solar still	Experimental	[73]
	Overall exergy efficiency	60.40%	a commercial grade of Paraffin	–	Experimental	[101]
Linear Fresnel reflectors equipped with vacuum tube and external PCM	Overall thermal efficiency	19–66%	Solar salt	ORC	Numerical	[139]
	ORC electrical efficiency	3–10%	Solar salt	ORC	Numerical	[139]
		5%	Solar salt	ORC	Numerical	[18]
ETSC and PCM as individual components	Heat storage efficiency	72–98%	Solar salt	Trigenerative ORC	Numerical	[60]
	Overall thermal efficiency	6–8%	Not given	Building heating and cooling	Numerical	[146]
		17.90%	a commercial grade of Paraffin	Solar still	Numerical	[62]
		50%	a commercial grade of Paraffin	Solar still	Experimental	[111]
	COP	0.15–0.45	Not given	Building heating and cooling	Numerical	[146]
		0.65–0.71	Solar salt	Trigenerative ORC	Numerical	[60]
	Solar fraction	27–55%	Not given	Building heating and cooling	Numerical	[146]
	Overall exergy efficiency	6.90%	a commercial grade of Paraffin	Solar still	Numerical	[62]
	ORC electrical efficiency	2–12%	Solar salt	Trigenerative ORC	Numerical	[60]

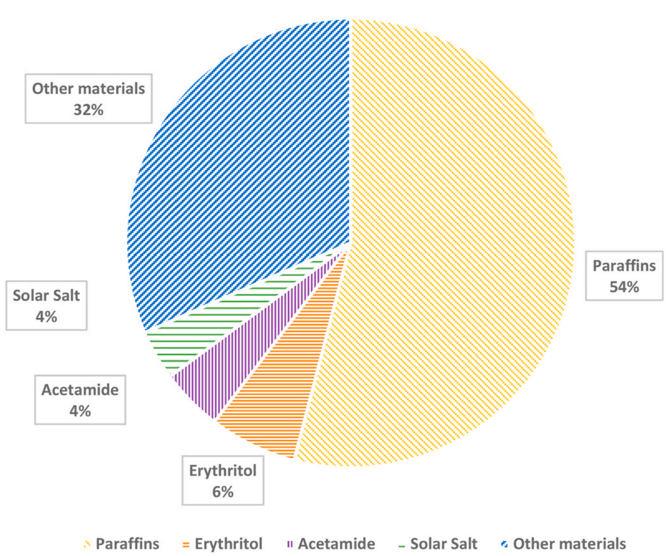

Fig. 22. Pie chart of materials employed as PCM in ETSC-PCMs.

irradiance, has not been fully realised yet. There have been very limited number of studies discussing this parameter and they have mostly reported contradicting results. Further studies would be highly regarded to determine which irradiance conditions or climates are better candidates for employment of ETSC-PCMs.

Finally, very few studies have considered the economic factors of ETSC-PCMs. This technology has not been commercialised yet. A major step toward its commercialisation is understanding its economic performance along with studying its technical feasibility, opportunities, and challenges.

7. Conclusion

In this paper, previous studies on ETSC-PCMs have been thoroughly reviewed. Different ETSC-PCM designs and configurations were presented, and their energetic performance was investigated. Directed by the literature, the effective design parameters were identified, and their impacts on ETSC-PCM performance were studied. Moreover, the research gaps were highlighted, and direction on future studies was provided accordingly.

The main purpose of integrating PCMs with ETSC systems is to maximise the benefit of solar thermal systems and reduce the impact of the solar energy intermittency on the smooth operation of the system. ETSC-PCMs have been widely studied from various perspectives, and almost all these studies have reported the PCM-integrated ETSCs to be promising solutions for various applications. This is while the capacity of ETSC-PCMs for commercialisation is yet to be fully realised. Except for a very few numerical studies, different ETSC-PCM designs presented in the literature were not able to completely meet the energy demand of their applications. Hence, auxiliary heaters were recommended to support ETSC-PCMs for achieving steady operation of the system while fully meeting the demand.

It has been found that the ETSC-PCM operation modes can be categorized as simultaneous or consecutive, based on the design of the PCM charge and discharge operation. Majority of the experimental studies reported in the literature were based on the consecutive mode and concluded that introducing PCMs can significantly extend the operating time of the processes/systems supported by the ETSCs. On the contrary, most of the studies that have investigated the simultaneous design have reported less increase in operating time, but more effective and stable delivery of solar thermal energy. Furthermore, a controlled charge and discharge approach has been employed by several studies, all of which have obtained a higher performance rather than simultaneous or a consecutive modes. Controlling these operations can be among the most effective solutions to achieve higher heat storage and release performance.

Overall, ETSC-PCM technology still requires further improvements. Besides, the need for studies on the techno-economic feasibility of ETSC-PCMs as well as more effective designs are required to eliminate or minimise the need for auxiliary heaters. It is important to also compare the performance of each ETSC-PCM designs by using different PCMs, as previous studies were mostly focused only on details of the proposed arrangements rather than the PCM. When there is enough information on the performance of different materials in ETSC-PCMs, a PCM selection guide can be developed. This will be a very useful tool for optimum design of ETSC-PCMs. Considering the positive impact of using simultaneous operation mode on the smooth and stable operation of ETSC-PCMs, these systems need further investigation to achieve better performance in terms of increasing their operating time. It is important to highlight the fact that very few studies have investigated the performance of ETSC-PCMs in real applications. For this technology to be successful, it is necessary to test it in real conditions and for real applications such as hot water supply for buildings. By doing so the practical challenges of such systems will be better understood and addressed, which are the key step towards their commercialisation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

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