1 **Application of phase change materials for thermal energy storage in concentrated solar**
2 **thermal power plants: A review to recent developments**

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10 **ABSTRACT**

11 The objective of this paper is to review the recent technologies of Thermal Energy Storage (TES)
12 using Phase Change Materials (PCM) for various applications, particularly Concentrated Solar Thermal
13 Power (CSP) generation systems. Five issues of the technology will be discussed based on a survey to
14 the state-of-the-art development and understandings. The first part is about various phase change
15 materials (PCM) in thermal storage applications and recent development of PCM encapsulation
16 technologies. The second is the current status of research and application of latent heat storage systems
17 in CSP plants. The third is the mathematical modeling and numerical simulations to the phenomenon of
18 latent heat thermal storage. The fourth is about the issues of integration of a PCM-based TES unit into
19 a power generation system and the operation. The last part is a discussion about the cost issues and
20 comparison between sensible and latent heat TES systems. The surveyed information will be very
21 helpful to researchers and engineers in energy storage industry and particularly solar thermal power
22 industry.

23
24 **KEYWORDS**

25 Concentrated Solar Power (CSP), Thermal Energy Storage (TES), Phase Change Material (PCM),
26 latent heat.

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1. Introduction

According to the 'World Energy Outlook 2014' issued by International Energy Agency (IEA), global energy demand will increase by one third from 2011 to 2035, and energy-related CO₂ emission will rise by 20%, to 37.2 Gigaton if fossil fuels are used as usual [1]. To alleviate the associated environmental problems, reduction of the use of fossil fuels by developing more cost-effective renewable energy technologies becomes more and more contingent. Among various types of renewable energy sources, solar energy takes a large proportion [2].

Solar Photovoltaic (PV) power generation and Concentrated Solar Thermal Power (CSP) are the two main technologies for solar energy harvest. A CSP system may use a solar power tower, parabolic troughs, or linear Fresnel reflectors to concentrate sunlight and produce intense heat which is carried away by a heat transfer fluid (HTF) to send to the thermal power plant (or called as power block) for power generation [3]. Solar PV systems directly convert solar energy to electricity by using solar cells [4]. The energy conversion efficiency of a commercial grade PV is relatively low compared to CSP systems, although the cost of PV panels are getting more and more reduced due to the advancement of the technologies. The biggest disadvantage of PV-based power production is the inability of power dispatch due to the challenge of electrical energy storage [5]. Being able to provide electrical power at nighttime using large quantity of stored thermal energy, a CSP system is obviously more capable to dispatch power than that of a PV-based solar power system. A CSP with thermal energy storage (TES) system becomes the first choice to provide flexibility for grid electricity supply and service at a large scale (>100MW) because of large capacity of thermal storage for power generation [6,7].

Spain is currently the largest producer of CSP electricity, with 50 CSP plants and a total capacity of 2.304GWe. USA has 19 CSP plants in operation with a total installed capacity of 1.640GWe up to July 2015 [8]. Countries like Algeria, Iran, Egypt, and Morocco have commercial power plants with CSP integrated with natural gas combined cycles, also called as integrated solar combined cycle (ISCC). Other countries having good solar resources like United Arab Emirates, Australia, China, India, Iran, Israel, Italy, Jordan, Mexico, and South Africa also have CSP programs and commercial demonstration projects at different stages of construction and/or operation [8,9,10]. Most recently, a number of different types of CSP plants are under construction which will make a total of more than

2.42 GW in the USA [8]. The International Energy Agency (IEA) estimates that, globally, a CSP capacity may grow to 147 GW in 2020 and reach 1,089 GW by 2050 [11].

A TES system is critically needed for CSP to smooth out the short-term transients and to extend the daytime operation to nighttime [12]. Also, of various energy storage technologies, a TES has many advantages, such as lower capital costs and high round-trip efficiency, compared to mechanical or chemical energy storage technologies. The TES system incorporated into the Solar Two project in Daggett, California, has a reported round-trip efficiency greater than 97% [13-15].

A TES system may directly store hot HTF and pump it out at the same temperature for energy discharge, which offers the highest energy and exergy efficiencies. Since the cost of most HTFs is high, most TES systems use a cheap thermal storage medium that needs heat transfer between the storage medium and HTF. This type of TES systems must have three components, the thermal storage medium, the HTF, and the containment system. The containment system holds the storage medium and also facilitates the heat exchange between the storage medium and HTF for energy charge and discharge, and it requires a good thermal insulation from atmosphere. The use of the HTF is to supply and extract heat to/from the storage medium. Fluids serving as HTFs in commercial CSP plants include air, water/steam, mineral/synthetic oils, and inorganic molten salts [16,17]. Desirable characteristics for HTFs should include low freezing point, good thermal stability at wide range of temperatures, low viscosity, high heat capacity, as well as acceptably low corrosion rate to metal alloys of containers and pipes holding the HTF. Low cost of HTFs is another critical criterion for industrial application [18,19]. For operating temperatures up to 550 °C, sodium and potassium eutectic nitrate salts are currently used as HTFs. These salts are also used as thermal storage media for solar trough CSP system where expensive synthetic oil is used as HTF. Other than the limitation of the working temperature, the shortage of market supply of nitrate salts worldwide is another issue, for example, 30 times of the current mining production of nitric salts from the largest mines in Chile and Peru is required to meet the need of CSP installation as targeted by IEA for 2050 [20]. To address these issues, alternative HTFs and thermal storage media made from inexpensive and abundant materials are intensively investigated. For example, researchers in an ongoing Multi-University Research and Investigation effort funded by the U.S. Department of Energy's SunShot program use chloride salts eutectic mixture (NaCl-KCl-ZnCl_2) as a potential HTF for future CSP applications [21].

The storage media's sensible heat, latent heat, or combination of both, or in the form of reversible chemical reactions [22] are all possible to be utilized for thermal storage. Reference [23] presented a classification of energy storage materials. In the current CSP industry, thermal-chemical energy storage has not yet been used due to both technical and economic challenges. Most of the studies conducted on storage materials have concentrated on sensible and latent heat storage. Studies conducted to compare latent heat (from phase change materials-PCMs) and sensible heat thermal storage have shown that a significant reduction in storage volume can be achieved using PCMs. Studies reported by Morrison and Abdel-Khalik [24] and Ghoneim [25] show that to store the same amount of energy from a unit area of collector, rocks (sensible heat storage) require more than seven times the storage mass of Paraffin 116 Wax (P116-Wax), or five times the storage mass of medicinal paraffin, or more than eight times the storage mass of $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$.

Latent heat thermal energy storage (LHTES) system using PCMs is a process near isothermal that can provide significantly larger storage capacity compared to sensible heat thermal energy storage (SHTES) at the same temperature range. Isothermal storage is an important characteristic because the variation of fluid temperatures of solar field inlet and exit are constrained by the solar field equipment and also the thermal power Rankine cycles [26]. As the storage capacity of a LHTES system is governed largely by the phase change latent heat which is typically several ten times bigger than the sensible heat, it is possible to have smaller and lower cost thermal storage system.

To date, synthetic oils and molten salts are the most widely used sensible heat storage materials in commercialized CSP systems. LHTES system using PCMs for CSP plants is still under active research and development. In the present review, discussions will focus on LHTES systems.

To better understand the state-of-the-art technology of LHTES systems in CSP plants, this paper presents surveys and discussions on five subjects: 1) various PCMs for different thermal storage applications; 2) current status of research and application of LHTES system in CSP plant; 3) mathematical modeling and numerical simulation to LHTES system; 4) integration and seamless operation of CSP using thermocline LHTES system; and 5) cost analysis of thermocline LHTES system.

2. Various PCMs for different thermal storage applications and recent development of PCM encapsulation technologies

2.1. Introduction to PCMs for different thermal storage applications

A number of studies have been reported [27-30] on using different types of PCMs for LHTES. Those PCMs generally known for thermal storage application include organic compounds, inorganic salts and their eutectics, as categorized in Fig. 1. Organic compounds used for PCM include paraffin waxes, esters, acids and alcohols; inorganic materials include salt hydrates, eutectics of inorganic salts, and metals and their eutectics [28,29]. Those PCMs from organic compounds generally have low melting points and can only be used for room-heating thermal storage. For high temperature thermal storage, molten salts have been widely considered by researchers [31]. Nevertheless, since molten metals and alloys are considered as HTFs in nuclear power plants [32], they are also viewed as possible HTFs as well as PCMs for thermal energy storage in CSP systems [27,33,34].

Fig.1 Classification of PCMs. [35]

From the working temperature point of view, Hoshi et al. [36] categorized those materials with melting points below 220 °C as 'low' temperature materials, melting temperatures up to 420 °C as 'medium' temperature materials, and melting point greater than 420 °C as 'high' temperature materials suitable to CSP thermal storage. They collected the latent-heat energy storage capacity of PCMs for

various materials with melting points in the range from 300 K to 1200 K as given in Fig. 2. Specifically for inorganic materials such as fluoride salts, chloride salts, carbonate salts, sulfate salts, bromide salts, nitrate salts, and three eutectic salts. Fig. 3 showed the latent-heat-energy storage capacity with melting point ranging from 500 K to 1300 K. It is seen that the melting point of single material tends to increase in the order of nitrates, chlorides, carbonates, and fluorides.

Fig.2 Latent-heat-based heat storage capacity of various PCMs.[36]

Fig.3 Latent-heat-based heat storage capacity of various molten salts.[36]

The product of density and the latent heat of PCM is the energy storage capacity during the phase transition process. Some detailed data of the surveyed PCMs are given in Tables 1 to 3. Table 1 shows that LiCl-LiOH (wt.37%-wt.67%) has the highest energy density during the phase transition among these

seven different types of PCMs [37,38]. In Table 2, the melting temperatures of the PCMs range from 220 °C to 400 °C, which perfectly matches the operating temperature range of Rankine cycle. It is obvious that NaNO₃, NaOH, KNO₃, NaCl-KCl (58:42 wt.), and KOH are all good candidates for LHTES system. Table 3 demonstrates some PCMs potentially for high temperature applications, as needed for higher thermal efficiency in a CSP system [39]. As observed in Table 3, NaF-MgF₂ (75:25 wt.%) with melting temperature at 650 °C is a good candidate for high temperature LHTES application.

Table 1 Inorganic PCMs with melting temperature between 100 °C and 280 °C

Compound (wt. %)	Melting point (°C)	Latent heat (KJ/kg)	Density (kg/m ³)	Energy density (KJ/m ³)	Thermal conductivity (W/m·K)
MgCl ₂ ·6H ₂ O [37-40]	117	168.6	1450 (liquid, 120 °C) 1569 (solid, 20 °C)	244470 (liquid, 120 °C) 264533 (solid, 20 °C)	0.570 (liquid, 120 °C) 0.694 (solid, 90 °C)
NaNO ₃ -KNO ₃ , (50:50) [40,41]	220	100.7	1920	193344	0.56
KCl-ZnCl ₂ , (68.1:31.9) [40-42]	235	198	2480	491040	0.8
LiCl-LiOH, (37:67) [43,44]	262	485	1550	751750	1.10

Table 2 Inorganic PCMs with melting temperature between 280 °C and 400 °C

Compound (wt. %)	Melting point (°C)	Latent heat (KJ/kg)	Density (kg/m ³)	Energy density (KJ/m ³)	Thermal conductivity (W/m·K)
ZnCl ₂ [40,41]	280	75	2907	218025	0.5
NaNO ₃ [40,41]	308	199	2257	449143	0.5
NaOH [40,41]	318	165	2100	346500	0.92
KNO ₃ [40,41]	336	116	2110	244760	0.5
NaCl-KCl, (58:42) [40,41]	360	119	2084.4	248044	0.48
KOH [40,41]	380	149.7	2044	305987	0.5

Table 3 Inorganic PCMs with melting temperature above 400 °C

Compound (wt. %)	Melting Point (°C)	Latent Heat (KJ/kg)	Density (kg/m ³)	Energy Density (KJ/m ³)	Thermal Conductivity (W/m·K)
MgCl ₂ -NaCl, (38.5:61.5) [45-47]	435	351	2480	870480	N/A
Na ₂ CO ₃ -Li ₂ CO ₃ , (56:44) [45-47]	496	370	2320	858400	2.09

NaF-MgF ₂ , (75:25) [47,48]	650	860	2820	2425200	1.15
MgCl ₂ [41]	714	452	2140	967280	N/A
LiF-CaF ₂ , (80.5:19.5) [47,49]	767	816	2390	1950240	1.70 (liquid) 3.8 (solid)
NaCl [47,50]	800	492	2160	1062720	5.0
Na ₂ CO ₃ [47,50]	854	275.7	2533	698348	2.0
K ₂ CO ₃ [47,50]	897	235.8	2290	539982	2.0

1

2 Other than melting temperature and energy density, chemical stability, corrosion to
3 containers or capsule shells, and price are also important criteria determining the candidacy of a
4 salt for practical application. Zalba et al. [41] summarized the advantages and disadvantages of
5 organic and inorganic PCMs, and they concluded that inorganic PCMs have greater latent heat, but
6 with worse corrosion resistance and weaker thermal stability. Organic PCMs have very low
7 corrosion and much better thermal/chemical stability, but with a much lower latent heat and
8 thermal conductivity. Table 4 summarizes the requirement for PCMs as thermal storage materials.

9

10 *Table 4 Requirement for PCMs as energy storage materials. [41]*

<i>Thermal properties</i>	<i>Physical properties</i>	<i>Chemical properties</i>	<i>Economic properties</i>
1. Phase change temperature fitto application	1. Low density variation	1. Stability	1. Cheap and abundant
2. High change of enthalpy, melting point is near thetemperature of use.	2. High density	2. No phase separation	
3. High thermal conductivity inboth liquid and solid phases.	3. Small or no subcooling	3. Compatibility with containermaterials	
		4. Non-toxic, non-flammable, non-polluting	

11

12 It is important to note that the candidate PCMs should melt congruently and have
13 insignificant subcooling; otherwise, the storage capacity of the system will be reduced. Through
14 experimental investigations, Liu et al. [51] found that for PCMs made from carbonate salts, the
15 freezing temperatures are usually lower than the melting temperatures, which indicates that those
16 PCMs have higher degrees of subcooling. Compared to carbonate salts, chloride candidates CH1

(52MgCl₂-48NaCl, wt.%) and CH2 (64MgCl₂-36KCl, wt.%) have much smaller degrees of subcooling. Subcooling is undesirable because it reduces the usability of PCMs and can also completely prevent heat recovery if it is too severe [52].

In most of TES applications, PCMs are normally encapsulated, the compatibility of PCM and capsule material is the first requirement. Misra and Whittenberger [53] did a pioneer work to study the compatibility of some fluorides with 30 kinds of constructional alloys. Two eutectic salts, 80.5LiF-19.5CaF₂ wt.% with melting point of 769°C and 37NaF-27CaF₂-36MgF₂ wt.% with melting point of 905°C, were studied at 25 °C above their melting point. The salts and metal material were placed either in a sealed quartz tube or in an open crucible of alumina in argon environment for 500 hours. They found that the depth of corrosion for Hastelloy B and N was 15–30 µm, and for steel RA-330 the maximum corrosion depth was 280 µm.

Recently, Gomez et al. from NREL [54] studied the corrosion of SS316 in three eutectic molten salts at around 500 °C. These salts are 80.69KNO₃-11.87KBr-7.44KCl wt.%, 60.00MgCl₂-20.40KCl-19.60NaCl wt.%, and 34.81NaCl-32.29KCl-32.90LiCl wt.%. While the first salt has very low corrosion to SS316, the other two salts can have significant corrosion to SS316. Qiu and Galbraith [55] investigated the chemical corruptions of a NaCl/NaF eutectic salt to the containers/capsule made from SS316 and Inconel 625 sample coupon at temperatures ranging from ambient temperature to 750 °C. The containers were filled with salt in a controlled-atmosphere glove box and were then sealed by electron-beam welding. After keeping at 750 °C for 2500 hours, the containers were cut open so that the materials of containers and coupon samples were analyzed and evaluated. At 100 hours corrosion test, both SS316 and Inconel 625 exhibited a very small amount of corrosion. The stainless steel container suffered a shallow inter-granular grain boundary attack, on the order of 1-2 µm in depth. The Inconel 625 surface formed an oxide complex, which was resistant to dissolution into the molten salt. At 2500 hours of corrosion, the surface morphology for both materials was largely unchanged, with the corrosion process having switched from an initial localized pattern, to a more uniform pattern. The corrosion depth measured at 2500 hours remained near 1–2 µm, suggesting that the corrosion rate decelerated. Both materials showed promise for compatibility with the chosen salts.

A careful survey was conducted about high temperature PCM encapsulation technology

and industrial suppliers. Only one data source [56] shows encapsulated PCM with phase change temperature upto 885 °C. Table 5 shows some collected thermo-physical properties of the series of encapsulated PCM products.

Table 5 Commercial available PCMs from PCM Products Ltd. [56]

PCM	Melting point (°C)	Latent heat (kJ/kg)	Density (kg/m ³)	Product materials
H300	302	130	1,900	PlusICE PCM High temperature range
H395	395	215	2,330	PlusICE PCM High temperature range
H430	430	125	2,160	PlusICE PCM High temperature range
H500	500	300	2,220	PlusICE PCM High temperature range
H535	535	130	2,320	PlusICE PCM High temperature range
H610	610	410	2,070	PlusICE PCM High temperature range
H650	652	300	2,450	PlusICE PCM High temperature range
H700	699	250	2,410	PlusICE PCM High temperature range
H755	755	466	2,160	PlusICE PCM High temperature range
H885	885	236	2,290	PlusICE PCM High temperature range

It must have effective heat exchange between PCM and heat transfer fluid in order to have high round-trip energy storage efficiency. Therefore, PCMs are typically contained such that either large heat transfer surface area or high convective heat transfer coefficient between PCM package and HTF is possible. Fig. 4(a) shows a shell PCM container [57] with HTF in a tube, Fig. 4(b) a cylindrical PCM container [58,59] with HTF flowing around, and Fig. 4(c) a rectangular plate PCM container [60,61] that HTF can flow around.

Fig. 4. PCM containers and configuration of PCM versus HTF. (a) Shell-and-tube container; (b) Cylindrical container; (c) Rectangular container. [62]

Methods of improving the heat transfer performance between PCM and HTF also include the increase of the thermal conduction inside PCM by adding highly thermal conductive particles, or metal fins to overcome the weakness of intrinsic low thermal conductivity of PCMs [47,63]. There are a lot of studies using finned tubes of various configurations [64-72]. Other approaches seen in the literature include: bubble agitation [73], carbon fiber brushes for increasing the thermal conductivity of PCM [74], insertion of a metal matrix into the PCM [2,75-77], dispersing high conductivity particles into PCM [78], micro/macro encapsulation of the PCM [79,80] or shell-and-tube packaging [81,82]. Figure 5 shows configurations of PCM packaging mentioned above for the purpose of heat transfer enhancement.

Fig. 5. PCM packaging configurations to enhance heat transfer. [62]

In all the technologies shown in Fig. 5, bubble agitation and carbon fiber brushes are probably the two that need more explanations. Velraj et al. [73] did experiments to study the heat transfer enhancement in a LHTES system using bubble agitation, as shown in Fig. 5 (iv). In their study a very small amount of water was poured into the tube. Molten paraffin was then added and the tube was evacuated by a vacuum pump. The vacuum was maintained such that the saturation temperature of the water inside the tube was nearly equal to the phase change temperature of the PCM. The intention was to create steam bubbles inside the PCM during the phase change that would promote the heat transfer. Fukai et al. [74] developed brushes made of carbon fibers to improve the thermal

conductivities of phase change materials, as shown in Fig. 6. The volume fraction of the fibers was accurately and easily controlled and that the fibers with a low volume fraction (<1 vol.%) were entirely dispersed in the PCMs. They used the brushes to improve the thermal responses in the PCMs packed into cylindrical capsules and experimentally demonstrated that the effective thermal conductivities of the fiber/PCM composites reach the maximum values as theoretically predicted.

Fig. 6. Thermal energy storage units where brushes made of carbon fibers are inserted. [74]

The encapsulation of PCM has been given a lot of attentions during the recent time. If PCM is encapsulated into large number of capsules, either spheres or cylinders [83], the heat transfer area of PCM dramatically increases, which offers much better heat transfer when HTF flows through the capsule-packed bed. It has been reported that PCM stored in capsules with a radius of 10 mm offers a surface area of more than 300 square meters per cubic meter [84]. Depending on the techniques of encapsulation, capsules may have a size of several tens of millimeters to sub-millimeters. Metallic encapsulation is preferred if high temperature is the criterion, otherwise plastic encapsulation is commonly used for low temperature application. Encapsulation techniques have been reported in the works by RUBITHERM Technologies GmbH [85] and Climator Sweden AB [86].

Although making micro-encapsulated PCM is more challenging than that of making macro-encapsulated PCM, microencapsulation (of low temperature PCM using plastic shells) is still worth putting an effort, due to the fact that a substantially higher surface area to volume ratio is made possible when the capsule size goes down [62,87,88]. The difference of melting process of micro-encapsulated PCM with that of macro-encapsulated PCM was observed in the literature

[89]. Interestingly, there are also studies on the nano-encapsulated PCM for thermal energy storage [90-93]. Table 6 listed some surveyed detail of encapsulation and shell materials of capsules for PCMs.

Table 6 Manufacturers and their specifications of encapsulation of PCMs with maximum operating temperature above 100 °C

Manufacturer	PCM	Shell material	Container	Average container size	Applications	Operating Temperature	Reference
TEAP	Glauber's salt, soda ash, sodium acetate and paraffin wax	Aluminum, steel and polyethylene	Bottles, balls	25.4 mm	Storage and transport of food, medical equipment, storage, materials for textile	25°C–100°C	[94]
Rubitherm GmbH	Paraffin, salt hydrate in granulate, powder and compound forms	Aluminum, plastic	Box, bag	N/A	Storage and transport of food, medical equipment, storage, materials for textile	30°C–100°C	[85]
PCM Products Ltd.	Eutectics, salt hydrates, organic materials, and high temperature salts	Rubber, HDPE plastic	Tube, ball, pouches, plate	40 mm	International space station, automotive passive cooling, solar heating and heat recovery	90°C–885°C	[56]
Microtek Lab. Inc.	Paraffin	Polymer	N/A	17–20 µm 3–5 mm	Active wear clothing, woven and non-woven textiles, building materials, packaging, electronics	25°C–250°C	[95]

(Note: N/A means it is not reported on the company's website.)

2.2. Recent development of PCM encapsulation technologies

It is critical to ensure that the capsules having no leakage of liquid PCM when it is melt. Regin et al. [2], Nath [96] and Nomura [97] summarized the functions and requirements of materials to contain PCM: (i) meeting the requirements of strength, flexibility, corrosion resistance, and thermal stability; (ii) acting as a barrier to protect the PCM from harmful interactions with the heat transfer fluid surrounding PCM capsules; (iii) capsules are relatively small to have large surface-to-volume ratio, providing sufficient heat transfer surface area; (iv) providing structural stability and easy handling.

In order to make PCM capsules having the above characteristics, two different approaches can be adopted [96]. One is to make a PCM pellet of desired shape, either spherical or cylindrical and then apply a coating or a series of coatings which acts as a shell to hold the PCM inside. The other approach is to fabricate a shell (cylindrical or spherical) first and then fill in with PCM. The diagram in

Fig. 7 shows the two categories of PCM encapsulation technology.

Fig. 7 Schematic of Steps to Develop PCM Encapsulation. [96]

Due to the recent development of encapsulation technology, the size of PCM capsules can cover the range from 1-2 centimeters (macro-size) down to micrometers. Conventional PCM capsules are mostly in macro size. There are a number of published papers that reported various shell materials such as metals and plastics, and various shapes such as spherical [98 - 102] and cylindrical [99, 103 - 105]. Micro-encapsulation of PCM is a technology getting significant attention recently [106-111] for the advantage of getting larger surface area-to-volume ratio and also better adaptation to thermal expansion/contraction during phase change processes [106,107]. A number of papers reported the encapsulation methods, core PCM materials, shell materials, thermophysical properties, and capsule sizes of various micro capsules. Micro-interfacial polymerization [107] and in-situ poly-condensation [108-111] are the most popular micro-encapsulation methods. Medium to high temperature PCM encapsulation usually needs metal shells. Maruoka and Akiyama [112] proposed the encapsulation of using spherical metal shell, such as Cu and Pb with an electroplated Ni layer.

In summary, the technology of encapsulation of low-temperature PCMs is getting a significant development, in particular, the micro-encapsulated PCMs is becoming increasingly popular. The encapsulation of high-temperature PCMs is very challenging and thus is less popular despite its engineering importance. In the near future, it is expected that easy-producible encapsulated high-temperature PCMs with large thermal density for the purpose of CSP application will be developed.

3. Current status of research and application of LHTE systems for CSP plants

3.1. Brief introduction to CSP technologies with incorporation of energy storage

CSP technology dates back to 1970s, but most of the commercial CSP installations were only made in this decade, particularly in Spain and the USA [16,17]. Four well-known CSP technologies are: parabolic trough collectors (PTC), linear Fresnel reflectors (LFR), solar power tower (SPT), and parabolic dish systems (PDS). Among these technologies, PTC is the most common one, which takes more than 95% of the global CSP installations.

CSP technology has made great progresses recently. Only in 2014, there were five CSP plants in the world completed [113]. National Renewable Energy Laboratory (NREL) has a webpage giving details of all the CSP plants in operation around the world up to date [8]. Table 7 lists the detailed information of the CSP plants with TES systems in full commission operation since 2010 in USA and Spain.

Table 7. Summary of CSP plants in operation since 2010 in U.S. and Spain. [8]

Country	Project Name	Capacity (MW)	CSP type	HTF	Commission Date	TES	Storage Type	Operating Temperature
USA	Solana Generating Station	250	PTC	Therminol VP-1	2013	6 h capacity 2-tank indirect storage with molten salts	SHTES	293 °C–393 °C
USA	Crescent Dunes Solar Energy	110	SPT	Molten salts	2013	10 h capacity 2-tank direct storage with molten salts	SHTES	288 °C–565 °C
Spain	Andasol Solar Power Station	150	PTC	Dowtherm A/Thermal oil	2008 – 2011	7.5 h capacity 2-tank indirect storage with Solar Salt	SHTES	293 °C–393 °C
Spain	Arcosol 50	50	PTC	Biphenyl/Diphenyl oxide	2011	7.5 h capacity 2-tank indirect storage with Solar Salt	SHTES	293 °C–393 °C
Spain	Arenales	50	PTC	Diphenyl	2013	7 h capacity 2-tank indirect storage with Solar Salt	SHTES	293 °C–393 °C

Spain	Aste Solar Power Station	100	PTC	Dowtherm A	2012	8 h capacity 2-tank indirect storage with Solar Salt	SHTES	293°C–393°C
Spain	Astexol II	50	PTC	Thermal oil	2012	8 h capacity 2-tank indirect storage with Solar Salt	SHTES	293°C–393°C
Spain	Casablanca	50	PTC	Biphenyl/Diphenyl oxide	2013	7.5 h capacity 2-tank indirect storage with Solar Salt	SHTES	293°C–393°C
Spain	Extresol	150	PTC	Biphenyl/Diphenyl oxide	2010 – 2012	7.5 h capacity 2-tank indirect storage with Solar Salt	SHTES	293°C–393°C
Spain	Gemasolar Thermosolar Plant	20	SPT	Solar Salt	2011	15 h capacity 2-tank direct with Solar Salt	SHTES	290 °C–565 °C
Spain	La Africana	50	PTC	Undefined	2012	7.5 h capacity 2-tank indirect storage with Solar Salt	SHTES	293°C–393°C
Spain	La Dehesa	50	PTC	Biphenyl/Diphenyl oxide	2011	7.5 h capacity 2-tank indirect storage with Solar Salt	SHTES	298 °C–393°C
Spain	La Florida	50	PTC	Biphenyl/Diphenyl oxide	2010	7.5 h capacity 2-tank indirect storage with Solar Salt	SHTES	298 °C–393°C
Spain	Manchasol	100	PTC	Biphenyl/Diphenyl oxide	2011	7.5 h capacity 2-tank indirect storage with Solar Salt	SHTES	293°C–393°C
Spain	Termesol 50	50	PTC	Biphenyl/Diphenyl oxide	2011	7.5 h capacity 2-tank indirect storage with Solar Salt	SHTES	293°C–393°C
Spain	Termosol	100	PTC	Thermal oil	2013	9 h capacity 2-tank indirect storage with Solar Salt	SHTES	293°C–393°C

1 (Note: All information is from NREL website of Concentrated Solar Power Project Profiles.)

2

3 3.2. Recent developments of LHTES system in CSP applications

4 As indicated in Table 7, Solar SaltSHTESis utilized in most of CSP plants. Obviously,
5 LHTESusing high temperature PCM is not popular yet for commercialized CSP plants. The reason is
6 that the more challenging techniques of high temperature PCM encapsulation and heat transfer
7 enhancement are still undergoing research and development [2,96,114]. However, as observed from
8 Table 7, if PCM is adopted as the storage media in commercialized CSP plants, the operating
9 temperatures will be the same from 293 °C to 393 °C based on the Rankine power cycle. It is also
10 worth noting that PCM with higher melting temperature is always desirable in CSP plants with higher
11 operating temperature (>600 °C) due to the requirement of higher energy conversion efficiency.

12 In the recent 10 years, however, there are still quite amount of research and development for high
13 temperature LHTES systems. The German Aerospace Centre (DLR) did intensive research
14 toinvestigate Sodium Nitrate (NaNO₃) as a latent-heat thermal storage medium in the temperature

range from 296 °C to 316 °C. They used NaNO₃ for thermal storage in a direct steam CSP plant. Acting as a heat transfer fluid, the steam generated in solar field has a pressure of around 100 bar that passes through a thermal storage tank and gives out heat for storage. Laing et al. from DLR[115] tested a prototype storage tank with 140 kg of NaNO₃ as storage media and steam as HTF, and seven steel tubes with aluminum fins were imbedded in the tank, as shown in Fig. 8. This is the shell-and-tube type of packing configuration. They operated the thermal storage system for 172 cycles (more than 4000 hours) from 296 °C to 316 °C, and proved no decomposition of the PCM and no degradation of the finned aluminum steam tubes.

Fig. 8 Schematic of the NaNO₃ test module with steel fins attached on the steam tube,[115]

The storage module in Fig. 8 was then scaled up to a unit having 14 tons of NaNO₃ by Laing et al. [116]. The PCM modules were combined with two concrete sensible thermal storage modules in a direct steam generation facility in Spain under real operation conditions, and the two concrete sensible thermal storage modules were used to store the heat for preheating and superheating of the water/steam, as shown in Fig. 9. Such a test facility demonstrated the sandwich concept of enhancement of heat transfer as a possibility to achieve high discharge power even at elevated temperatures, in spite of the low heat conductivity of PCMs. After 172 cycles in the temperature range from 25 °C to 400 °C, no degradation of PCMs was detected.

Fig. 9 Overview of a three-part thermal energy storage system for Direct Steam Generation (DSG) combining sensible and latent heat storage. [116]

Adinberg et al. [117] tested a reflux heat transfer storage (RHTS) system with PCM, as shown in Fig. 10. The concept of reflux heat transfer storage is based on the reflux evaporation–condensation occurring in the intermediate HTF. In their experiments, the discharge and charge heat exchangers were placed at the top and the bottom of the storage unit, and the charge heat exchanger was also immersed in the liquid intermediate HTF. They used Sodium Chloride (NaCl) as the PCM and sodium metal as the intermediate heat transfer medium for a storage temperature of 800 °C. A metal alloy Zn-Sn (70-30wt%) and the eutectic mixture of 26.5% biphenyl and 73.5% diphenyl oxide were experimentally investigated as the PCM-HTF system for producing high-temperature superheated steam in the temperature range of 350°C-400°C [117]. Although the proposed Zn-Sn (70-30 wt%) PCM is much more expensive than any of the molten salts, RHTS applications can probably be rewarding as the end result of a significantly improved thermal storage performance based on outstanding chemical stability, superior thermal conductivity and high heat transfer.

Fig. 10 Schematic diagram of the reflux heat transfer storage concept [117].

A TES system employing multiple PCMs with different melting temperatures is another attractive heat transfer enhancement technology. In this type of system, a few modules containing different PCMs with different melting temperatures are connected to each other in series. The multiple PCMs in shell-and-tube units should be in the flow direction that the melting temperature decreases in the charging process and increases in the discharging process as illustrated in Fig. 11 [118].

Fig. 11. Sequence of multiple PCMs in shell and tube latent heat storage unit [118]

Michels and Pitz-Paal [119] designed and tested a vertical shell-and-tube heat storage system filled with three high temperature PCMs, KNO_3 (PCM-1), eutectic KNO_3/KCl (PCM-2), and NaNO_3 (PCM-3). Fig.12 shows the schematic of the experimental setup and a picture of multiple-PCM thermal storage unit. The experimental results showed that around 92% of the PCM in the multiple-PCM storage unit was completely molten at the end of charging and around 67% was completely solidified at the end of discharging. In the single storage unit containing NaNO_3 as the PCM, almost 100% of the PCM was completely molten at the end of charging but only 2% was completely solidified at end of discharging. They found that multiple-PCM storage unit can offer a higher utilization of the possible phase change, and a more uniform HTF outlet temperature and higher exergy efficiency.

Fig. 12. Schematic diagram of experimental set up and a picture of multiple PCM storage system [119]

Due to the complexity of LHTES system, parametric study to LHTES system has to be conducted first in order to further improve the thermal storage efficiency of latent heat storage system. Since 2005, only one research paper reporting the parametric study for high temperature LHTES system. Guo and Zhang [120] conducted parametric study to assess how the thermal storage performance is affected by the geometry, thermal and boundary conditions in a shell-and-tube LHTES system. Their computational results illustrated how the heat transfer and discharge time were affected by the changes in geometry of the aluminum fins, tube radius, boundary conditions, and thermal conductivity of the PCM. It is expected that more thorough investigations including the thermal properties of PCM and the operating parameters of thermal storage system will be conducted.

The SunShot program from Department of Energy of the U.S. has funded a number of projects to develop high temperature PCM-based LHTES system for CSP plants. It is hoped that a better PCM-based LHTES system will be applied in commercialized CSP plant in the future, after conducting thorough parametric studies, solid systematic optimization, and pilot-scale system tests.

3.3. Analysis of energy storage efficiency of LHTES system

The performance of a TES system can be evaluated through an energy storage efficiency. As far as LHTES systems are concerned, the efficiency is a measure of how effectively the heat can be stored or

recovered. Hence, the efficiency of a LHTES system can be determined as charging efficiency or discharge efficiency or overall (complete cycle) efficiency.

Many investigators have analyzed the efficiency of LHTES systems. These investigations were either for a charging or a discharging process separately, or the complete working cycles of the system. The influence of various design and operating parameters on the efficiency has been studied.

Seeniraj et al. [121] investigated the thermal performance of a shell-and-tube LHTES unit. The thermal performance was studied using a quantity which is the ratio between the total heat stored and the maximum latent heat that can be stored.

If the HTF in a thermal storage system can be withdrawn at the temperature that it was originally stored, then the system has the highest energy storage efficiency from the thermodynamics point of view. Based on the work of Li et al. [122], the energy delivered in the required time period from a latent heat storage system is always less than that of the energy charged to the tank. If the required heat discharging period is $t_{\text{ref,discharge}}$, then a round-trip energy efficiency can be defined as:

$$\xi_{\text{trip}} = \frac{\int_0^{t_{\text{ref,discharging}}} \rho_f C_f [T_f(z=H, t) - T_L] dt}{\rho_f C_f (T_H - T_L) \cdot t_{\text{ref,discharging}}} \quad (1)$$

where the numerator represents the energy discharged from the storage tank, and the denominator represents the energy charged to the tank in the same time period as that of discharging.

Other than the round trip energy efficiency, energy storage efficiency may be defined by accounting the energy inside the storage system at the beginning and end of energy charging and discharging. Based on the enthalpy distributions h_r of PCM at the end of charge/discharge, Xu et al. [123] defined the energy storage efficiency:

$$\xi_{\text{storage}} = \frac{\int_0^H [h_r(z, t = t_{\text{ref,charging}}) - h_r(z, t = t_{\text{ref,discharging}})] dz}{\int_0^H [h_r(z, t = t_{\text{ref,charging}})] dz} \quad (2)$$

It is important to note that the thermal performance of LHTES system is assessed using only energy, which is based on first law of thermodynamics to identify the ways to improve the quantity of heat stored/recovered. However, the primary purpose of a thermal energy storage system is not to store the energy, rather to store useful work. As a consequence, energy analysis does not reflect the quality of energy stored/recovered. This inadequacy can be overcome, if an analysis based on second law of

thermodynamics is carried out for LHTES system, which will be introduced in next section.

3.4. Exergy analysis of LHTES system

Exergy analysis is a method that uses the conservation of mass and energy principles together with the second law of thermodynamics for the design and analysis of energy systems. It can reveal whether or not it is possible to design more efficient energy systems by reducing inefficiencies [124]. The exergy analysis method can provide information on the quality of the energy transferred in LHTES systems [124].

In 1980s and 1990s, Bjurström and Carlsson [125] as well as Adebisi and Russell [126], determined an optimum melting temperature for the PCM that would maximize the second-law efficiency during charging. Both studies concluded that maximum exergy would be recovered from the HTF when the melting temperature of PCM is equal to the geometric average of the environment temperature and the temperature of the hot HTF during charging. De Lucia and Bejan [127] accounted for the effect of natural convection during PCM melting, and they found the same expression for the optimal temperature as in Refs. [125] and [126].

There are quite amount of research papers discussing exergy analysis to LHTES systems since 2010. Jegadheeswaran et al. [128] presented a thorough review of the exergy analysis of LHTES systems. Keshavarz et al. [129] and Li et al. [130] investigated multiple PCMs in cascaded configurations in order to either minimize the entropy generation during an entire charging/discharging cycle, or to maximize the exergy extracted during discharging. Mahfuz et al. [131] performed energy and exergy analysis for a CSP plant located in Shiraz, Iran. They analyzed the exergy efficiency to show the possible improvement of efficiencies by integrating PCM. It was found that the exergy efficiency was only about 10% without using PCMs, but the exergy efficiency can be improved to 30% if PCM was adopted as the storage medium. Shabgard et al. [132] performed a combined heat transfer and exergy analysis to quantify the performance of a LHTES system. In order to maximize the exergy extracted from the storage system, a specific melting temperature must be used in conjunction with a specific charging time period and a specific HTF inlet temperature during discharging. For a typical molten salt PCM, the optimal melting temperatures corresponding to charging HTF inlet temperatures of 560°C and 800°C are 475°C and 715°C, respectively.

Nithyanandam and Pitchumani [133] studied the performance of an EPCM-TES (encapsulated PCMTES) system and a HP-TES (TES with embedded heat pipes) for Rankine cycle and s-CO₂ (supercritical carbon-dioxide) power cycles. For a CSP plant operating on s-CO₂ power cycle, the exergetic efficiencies of the EPCM-TES were simulated at tank heights of 10 m and 20 m, with different tank radius and radius of PCM capsules. Fig. 13(a) and (b) show that the exergetic efficiency of EPCM-TES is higher with larger storage tank radius at a fixed mass flow of HTF and capsule radius. The decrease in EPCM-TES tank radius leads to an increase in HTF velocity, resulting in a decrease in the residence time of the HTF in the tank. Consequently, the exergetic efficiency is low for cases with small tank radius. Fig. 13 (c) and (d) show the exergetic efficiency of EPCM-TES system working on steam powered Rankine cycle. In general, lower values can be observed due to the relatively low temperature of HTF flow for Rankine cycle. The highest exergetic efficiency of 98.1% is obtained for EPCM-TES system at tank height of 20 m and radius of 20 m filled with capsules in radius of 0.5 cm. This is low compared to 99.4% from as-CO₂ cycle.

Fig. 13 Exergetic efficiency at conditions of different combinations of tank radius and capsule radius. (a) tank height of 10 m, and (b) tank height of 20 m for s-CO₂ cycle. (c) tank height of 10 m, and (d) tank height of 20 m for a Rankine cycle. [133]

If the melting temperature of PCM is fixed, in order to maximize the exergy performance, a good inlet temperature of HTF should be selected. During charging, higher inlet temperature of HTF leads to higher temperature difference between HTF and PCM, which also results in higher entropy generation. This conclusion was proven by Kousksou et al. [134] when they analyzed a packed-bed encapsulated PCM storage system. As a result, one may conclude that in order to minimize entropy generation, the HTF inlet temperature should be as close as possible to the melting temperature of PCM. However, smaller temperature difference results in lower heat transfer rate and the charging rate. Hence, the selection of HTF inlet temperature may be a compromise between the required charging rate and exergy performance. Ereç and Dincer [135] have calculated exergy efficiency for a shell-and-tube storage module, and they have found significant increase of exergy efficiency due to increase in HTF inlet temperature during discharging.

The exergy performance of LHTES system is also found depending on mass flow rate of HTF. According to the conclusions from Kousksou et al. [134,136] and Ereç and Dincer [135], the temperature difference between inlet and outlet temperature of HTF decreases as Re number increases. Smaller temperature difference would reduce the entropy transfer due to heat transfer between HTF and PCM. Therefore, the net exergy can be increased by increasing Re number, although there is an increase in pressure drop irreversibility.

Fig. 14 Comparison of energy recovery for cases using PCM and sensible heat storage method. Sensible heat storage allows high exergy recovery and high energy density simultaneously.

[137]

In 2013, Bindra et al. [137] reported that for a packed-bed storage system, SHTES can provide higher exergy recovery than LHTES under similar high temperature conditions. In their study, similar properties and operating conditions of HTF were applied. Particle size and shape for sensible heat storage material and PCM encapsulated material were chosen to be identical. The results of this comparative analysis are presented in Fig. 14, which shows that with sensible heat higher energy density and higher exergy recovery can be simultaneously achieved; whereas with PCM it is difficult to achieve both simultaneously. They also concluded that a PCM method is particularly useful if the heat is needed at a temperature near the melting temperature. Xu et al. [138] found similar phenomenon when they calculated and compared the thermal storage efficiency for a packed-bed TES system using different storage media.

Nevertheless, one cannot simply conclude that LHTES system is not as good as SHTES system, since systematic optimizations to LHTES system is needed to approach high efficiency. For example, based on Nithyanandam and Pitchumani's analysis [133], the round-trip exergy efficiency of LHTES system can approach 95%, which is pretty close to the target set by DOE SunShot program. Nithyanandam and Pitchumani's work [133] is the first publication which demonstrates the exergy efficiency after the storage system is optimized. It is expected that more studies will discuss a fair comparison between systems using LHTES and SHTES.

4. Mathematical modeling and numerical simulation to latent-heat thermal storage

The heat transfer between the PCM and a HTF during the thermal charging and discharging processes needs to be analyzed in order to understand the time-dependent temperature variation of HTF when the stored heat is retrieved for utilization. In this section, mathematical models describing the heat transfer between PCM and HTF will be presented. Numerical methods and procedures of solution to the relevant governing equations will also be briefly discussed.

A one-dimensional mathematical model about the heat transfer between packed bed of encapsulated PCM and HTF is summarized here for readers to get a basic understanding. Thereafter, efforts and studies for more accurate and sophisticated modeling will be introduced.

As shown in Fig. 15, the thermal storage tank is packed with capsules of PCM, and heat transfer

fluid flows through the packed bed. With no melting process considered, Schumann [139] proposed a group of governing equations early in 1929 for the heat transfer between packed bed of rocks and a HTF. For the heat transfer in melting process, we need a supplementary equation for the energy balance in the PCM. The following assumptions are necessary for the one-dimensional mathematical modeling.

- 1) There is a uniform radial distribution of the flow and filler material throughout the storage tank.
- 2) Assume that the capsules have only point contact between each other and therefore heat conduction between capsules is negligible.
- 3) In the HTF, compared to the convective heat transfer the heat conduction in the axial direction is ignorable.
- 4) When the capsules have Biot numbers less than 0.1, the lumped heat capacitance method is basically applicable to the transient heat conduction in the capsules. For capsules with larger Biot number, a modified lumped capacitance method will be applied to, which is accomplished simply by introducing a modified heat transfer coefficient for the convection heat transfer between the fluid and the capsules.
- 5) It is assumed that the PCM is homogenous and isotropic, and there are no impurities inside the phase change material, resulting in the melting process being isothermal.
- 6) Heat loss from the storage tank to the surroundings is negligible.
- 7) The onset of natural convection in liquid PCM during phase changing process is determined by the Rayleigh number (Ra). Due to the small size of encapsulated PCMs and its consequence of restricted moving capacity of liquid phase PCM inside the capsules, the Rayleigh number of liquid PCM is sufficiently small for neglect of natural convection, which is the case in the present study. However, it is worth noting that if the natural convection is significant, a common way to consider the effect of heat transfer improvement inside PCM is to introduce an effective thermal conductivity to consider both the conduction and natural convection, which is discussed at the end of this section. As a result, the 1D model introduced in this section also preserves the capability of considering the natural convection in encapsulated PCM during the phase changing process.

Fig. 15 A differential control volume of the packed bed of capsules

When there is no phase change, the energy balance equations for the HTF and the capsules due to the heat exchange between capsules and HTF are as follows:

$$\frac{hS_s}{\rho_f C_f \varepsilon \pi R^2} (T_s - T_f) = \frac{\partial T_f}{\partial t} + U \frac{\partial T_f}{\partial z} \quad (3)$$

$$hS_s (T_s - T_f) = -\rho_s C_s (1 - \varepsilon) \pi R^2 \frac{\partial T_s}{\partial t} \quad (4)$$

where h is the heat transfer coefficient between the capsules and the HTF, S_s is defined as the heat transfer surface area of capsules per unit length of the storage tank, ε is the porosity of the packed bed, U is the flow velocity the HTF passes through the packed bed, R is the radius of the storage tank.

Based on the Colburn factor relation [140], the heat transfer coefficient in a packed-bed thermal storage system can be found from reference [141]: $h = 0.191 \dot{m} \text{Re}^{-0.278} C_f \text{Pr}_f^{-2/3} / (\varepsilon \pi R^2)$, where

$\text{Re} = 2R \cdot \dot{m} / ((1 - \varepsilon) \rho_f v_f \pi R^2)$, $\text{Pr}_f = v_f \rho_f C_f / k_f$, $\dot{m}$ is the mass flow rate, R is the radius of the storage tank, ε is the porosity of the packed system.

When a location is experiencing melting process, the energy equations of the HTF and the PCM becomes [142]:

$$\frac{hS_s}{\rho_f C_f \varepsilon \pi R^2} (T_m - T_f) = \frac{\partial T_f}{\partial t} + U \frac{\partial T_f}{\partial z} \quad (5)$$

$$hS_s (T_m - T_f) = -\Gamma \rho_s (1 - \varepsilon) \pi R^2 \frac{d\Phi}{dt} \quad (6)$$

where the melting point is known as T_m , latent heat of the melting is Γ , and the percentage of melting

is Φ (with melting starting point as $\Phi=0$ and melting completion point as $\Phi=1$).

A more general enthalpy-based 1D transient model was proposed by Tumilowicz et al. [143] through introducing enthalpy of the PCM capsules. The governing equations include Eq. (3) and the following enthalpy equation for the capsules:

$$\frac{\partial \bar{h}_s}{\partial t} = \frac{-h_s (T_s - T_f)}{\rho_s (1 - \varepsilon) \pi R^2} \quad (7)$$

The relationship between the enthalpy and the temperature of the capsules is defined by the equation of state as follows:

$$T_s = \begin{cases} \frac{(\bar{h}_s - \bar{h}_{s_ref})}{C_{s_s}} + T_{s_ref} & \bar{h}_s < \bar{h}_{s_melt} \\ T_{s_melt} & \text{for } \bar{h}_{s_melt} \leq \bar{h}_s \leq \bar{h}_{s_melt} + \Gamma \\ \frac{(\bar{h}_s - (\bar{h}_{s_melt} + \Gamma))}{C_{s_l}} + T_{s_melt} & \bar{h}_{s_melt} + \Gamma < \bar{h}_s \end{cases} \quad (8)$$

The solution to the above equations only needs initial temperature conditions of fluid and solid in the tank and the time-dependent inlet fluid temperature.

Approaches of analytical solution assisted with numerical computation to the above equations have been well described in the work of Van Lew et al. [144] for thermal storage with no melting, and the work of Tumilowicz et al. [143] for the case with melting process.

The above mathematical modeling was developed referring to the configuration of HTF flowing through a packed bed of spherical capsules of PCM. This methodology of modeling can be easily extended to the cases that the PCM is encapsulated into a plate, a cylinder, or a cylindrical shell, as shown in Fig. 16, if an equivalent porosity is introduced by counting the volume of HTF and the total volume of the storage tank.

(a) Packed solid flat plates with HTF passing through the channels in a tank

(b) Packed solid cylinders with HTF passing along in a tank

(c) Solid thermal storage material with HTF tubes passing through in a tank

Fig. 16 Three other typical solid-fluid configuration in thermal storage systems

(solid thermal storage material; HTF) [145]

If the thermal conductivity in capsules and the convective heat transfer coefficient between capsules and the HTF cannot satisfy the requirement of Biot number less than 0.1, as required in the assumption (4) for the one-dimensional mathematical modeling, a modified heat transfer coefficient

will be introduced to replace h in the governing equations (1) to (5). Expressions of the modified heat transfer coefficient h_{eff} for spherical capsules, and the three types of capsules in Fig. 12 are available in the work by Xu et al. [146].

One-dimensional modeling has been the major tool mostly used to predict thermal storage involving melting and solidification processes for packed-bed PCMTES system. A summary of recent studies using one-dimensional modeling is given in Table 8.

Table 8 Studies that used one-dimensional numerical model for spherical capsules of PCMs in latent heat storage systems

Reference	Model description	Numerical approach
[147] 2001	1D model for LHTES systems with encapsulated PCMs	Integral method.
[148] 2002	A simplified 1D model. Storage tank has a numbers of layers of packaging. Convection in liquid phase of PCM was treated by using an effective thermal conductivity.	A marching technique in which the phase change problem inside the spherical capsule is coupled with the energy balance equation between the spherical boundary and the working fluid.
[149] 2005	1D model to study the effects of capsule diameter and void fraction on the performance of heat storage	Implicit finite volume method, second order accuracy.
[84] 2009	1D model using equations similar to those of Schumann. Enthalpy equation was used for phase change of PCM inside the capsules.	Explicit, first order finite difference method.
[150] 2011	1D model. The PCM capsules behave as a continuous medium.	Implicit finite difference method.
[151, 152] 2014	1D model, simulated mass and energy transport inside a latent heat thermocline tank. The model was integrated into a system-level model.	First-order implicit finite volume method. The convective terms was discretized with the quasi second-order local extrema-diminishing scheme.
[143] 2014	Enthalpy-based 1D model was developed to track the solid-fluid interface. Lumped capacitance method was applied using an effective heat transfer coefficient to consider the internal heat conduction of capsules.	Method of characteristics, explicit, trapezoidal rule.
[153] 2014	1D model. Used temperature-dependent correlations to obtain the thermophysical properties for the HTF and considered heat loss through the tank wall.	Implicit finite volume method. Upwind scheme for convective terms.

10

For different PCM packaging schemes, such as in the forms of cylinders, tubes, or plates, the heat transfer between PCM package and HTF may also be analyzed using two-dimensional or three dimensional modeling. These models may treat the entire thermal storage container as a zone of porous media that HTF flows through, or may treat PCM zone and HTF zone with reasonable details and load

1 of computations using comprehensive 3D CFD study. References that used two-dimensional and
2 three-dimensional modeling for the analysis of the heat transfer and energy storage are summarized in
3 Table 9 and Table 10.

4

5 *Table 9 Two-dimensional thermocline modelling work for LHTES*

Reference	Model description	Numerical approach
[154] 2005	A mathematical model of transient heat transfer in a shell-and-tube latent thermal energy storage unit, with a developed algorithm for non-isothermal phase transition	Finite difference method, velocity and pressure fields of HTF using SIMPLER algorithm, convection–diffusion terms treated by the power-law scheme.
[155] 2005	A numerical model for packed flat plate TES system, and graphite matrix embedded with the PCM to enhance heat transfer	Finite difference method, implicit scheme.
[156] 2005	A comprehensive 2D porous-medium transient model for cold storage with coolant flowing in a packed-bed encapsulated PCM thermal storage system	Implicit finite difference method, second order central difference scheme for diffusion term, and Power law scheme for convective terms, SIMPLER for velocity-pressure coupling.
[104] 2006	The heat transfer characteristics of the melting process inside a horizontal cylindrical capsule for paraffin wax PCM have been investigated numerically.	Finite difference approach and a fixed grid scheme based on the technique of enthalpy method
[157] 2009	Transient numerical model of shell-and-tube latent thermal storage system with natural convection	Implicit finite difference method, a uniform size and constant time steps.
[158] 2010	A comprehensive numerical 2D model for melting with natural convection in a square cavity, the energy balance associated with the phase change is represented by the temperature transforming model.	Implicit finite volume method, the consistent update technique (CUT) algorithm was applied to couple velocity-pressure, the central difference scheme for both the convection and diffusion terms.
[159] 2014	A comprehensive transient 2D model for charge/discharge cycles by considering the natural convection. The temperature variation in the tank is axisymmetric, and the temperature varies radially inside the encapsulated PCM.	An implicit method, with the convective-diffusive fluxes in the HTF governing equation discretized using the power-law scheme, and the diffusive fluxes in PCM governing equation discretized using central differencing scheme.
[160] 2015	A Comprehensive transient and two-dimensional numerical model with porous medium (Note: the packed bed with spherical PCM is assumed to be a continuous and homogeneous porous medium.)	ANSYS Fluent 13.0 was applied, pressure based solver, SIMPLE pressure–velocity coupling scheme, second order upwind scheme.

6

7 *Table 10 Works using three-dimensional thermocline modeling for LHTES systems*

Reference	Model description	Numerical approach
[161] 2007	A 3D transient CFD model; the interpolating cubic spline function method was used to determine the specific heat in each time step of the temperature calculations.	Implicit finite difference method, the standard Gauss elimination method was used to solve the system of equations.

	(Note: it is a packed flat plate storage system in a thermal insulated ventilation duct.)	
[162] 2009	A comprehensive 3D numerical simulation, 3 separated groups of governing equations, for the PCM, the shell, and the HTF, with thermodynamic analysis, first law and second law efficiency. (Note: it is a single spherical PCM capsule surrounded by the heat transfer fluid.)	ANSYS Fluent 6.3 was used, pressure based solver, and the enthalpy-porosity method was applied to track the solid-liquid interface.

1

2 It is worth noting that all the numerical models listed in Table 8-10 have been validated, and they
3 all have good agreements with experimental data. As a result, these numerical models are encouraged
4 to be applied in thermal storage applications if PCMs are adopted as storage materials.

5 Unlike the one-dimensional model, the lateral-direction heat conduction of the HTF and PCM is not
6 neglected in the two-dimensional and three-dimensional model. As a result, the axisymmetric or
7 symmetric model with comprehensive simulation was commonly employed in two-dimensional model,
8 without assuming fully developed flow condition. Due to the complexity of numerically simulating
9 the flow and heat transfer in porous mediums (storage tank filled with encapsulated PCMs), there are
10 only a couple of research papers investigated the energy delivery and extraction using comprehensive
11 3D CFD study. Zukowski [161] performed a 3D comprehensive simulation for latent storage system
12 incorporated with cubic encapsulated PCM using an in-house code, and the interpolating cubic spline
13 function method was applied to determine the value of specific heat capacity of PCM in each time step,
14 which can automatically track the melting and solidification of PCM capsules. MacPhee and Dincer
15 [162] presented what appears to be the first CFD analysis for spherical encapsulated PCM inside a
16 latent thermal storage tank. ANSYS Fluent 6.3 was applied with a pressure-based solver, and the
17 enthalpy-porosity method was utilized to track the solid-liquid interface. More comprehensive
18 three-dimensional CFD studies are expected in the future. For example, if the temperature difference
19 between the surface of PCM and the inner wall of container is significant, the radiation heat transfer
20 inside each PCM capsule cannot be neglected. As discussed before, by using the same effective heat
21 transfer coefficient, the radiation heat transfer can also be included and accurately simulated. The
22 reason for applying constant thermal-physical properties of PCM is to simplify and reduce the
23 computational loads. Also indeed, the variation of the properties in a narrow temperature range of 150
24 °C is not significant. Among many thermal-physical properties of PCM, density, specific heat capacity

and thermal conductivity are three most important properties. Temperature dependent properties will provide more accurate simulation results for a LHTES system.

It is important to note that the natural convection of the liquid phase PCM is an important factor to the heat transfer in PCM. At the beginning of the melting process, conduction is the dominant energy transfer mode. The importance of natural convection gradually increases as the melted region grows and the liquid-solid interface curves, thus augmenting the melting process. Rayleigh number (Ra), $Ra = g\beta(T_p - T)L_\infty^3 / (\nu\alpha)$ is a key dimensionless parameter to determine the onset of natural convection, where g is the local gravitational acceleration; β is the thermal expansion coefficient of liquid phase PCM; T_p is the external surface temperature of PCM capsules; L_∞ is the characteristic length-scale of convection, and usually it will be chosen as the thickness of liquid layer; ν is the kinematic viscosity of liquid phase PCM; α is the thermal diffusivity of liquid phase PCM.

In the works listed in Table 9 and 10, Kousksou et al. [156] did not consider natural convection in PCM capsule during phase change heat transfer processes. However, different from the approach used by Kousksou et al., Felix Regin et al. [104] considered the conduction inside PCM capsules as the dominant energy transfer mode, and used an equivalent thermal conductivity to merge the natural convection effect in the thermal conductivity of the liquid by using a relation:

$$\bar{k}_{eq_liquid} = \bar{k}_{eq} \cdot k_{liquid} \quad (9)$$

where the overall equivalent conductivity $\bar{k}_{eq}$ was defined as the ratio of total heat transfer rate to heat transfer rate by conduction ($\bar{k}_{eq} = Nu / Nu_{conduction}$), and k_{liquid} is the thermal conductivity of liquid PCM, and $\bar{k}_{eq_liquid}$ is the mean equivalent thermal conductivity that merges natural convection.

Adine & El Qarnia [157] and Zukowski [161] also processed the effects of natural convection during melting process by using an effective thermal conductivity of the liquid phase of the PCM. The thermal conductivity of the PCM is given by the following expression:

$$k_p = f_l k_e + (1 - f_l) k_s \quad (10)$$

where f_l is the liquid fraction, k_s is the thermal conductivity of PCM in solid phase, and k_e is the effective thermal conductivity of the liquid phase PCM, which takes into account the effect of

natural convection on the heat transfer during melting. The expression of k_e is giving by the following correlation:

$$k_e = Ck_l Ra^n \left(\frac{\delta}{l} \right)^m \quad (11)$$

where k_l is the thermal conductivity of PCM in liquid phase, Ra is the Rayleigh number, C is a constant of 0.05, n is a constant of 0.25, δ is the PCM liquid thickness, l is the PCM thickness, and m is also a constant of 1.0.

Wang et al. [158] considered the effects of natural convection inside a 2D square cavity filled with PCM, and the modeling of melting was simplified by considering melting as a process occurring within an artificial mushy zone associated with a finite temperature range from $-\delta\theta$ to $\delta\theta$, so that the latent heat was formally considered by a finite thermal capacity and source term.

Nithyanandam et al. [159] modeled the circulation of liquid due to buoyancy-driven natural convection currents during the melting of PCM using an enhanced effective thermal conductivity of the PCM melt front, $k_{p,eff}$, evaluated using the empirical correlation in [163], which covers both the conduction and convection regimes and is expressed as $k_{p,eff} = k_p \cdot Nu_{conv}$, where k_p is the molecular thermal conductivity of PCM and Nu_{conv} is calculated using [163]:

$$Nu_{conv} = 1.16 f(Pr) \left(\frac{D_o - D_i}{2D_i} \right)^{1/4} \frac{Ra^{1/4}}{(D_i/D_o)^{3/5} + (D_o/D_i)^{4/5}} \quad (12)$$

$$\text{where } f(Pr) = \frac{2.012}{3} \left[1 + \left(\frac{0.492}{Pr} \right)^{9/16} \right]^{-4/9}.$$

The correlation shown in Eq. (12) is valid for a wide range of Prandtl (Pr) number and Rayleigh number (Ra) of the PCM. The term $D_o - D_i$ in Eq. (12) represents the thickness of the liquid layer formed during melting of PCM. As we discussed before, since the thickness of the liquid layer is very small initially, heat transfer across the liquid layer occurs primarily by conduction although, ultimately, convection becomes important as the melt region expands. Therefore, heat transfer through the melting is calculated by evaluating a conduction heat transfer using k_p and an overall thermal conductivity

associated with the use of $k_{p,eff}$ for considering free convection in a spherical enclosure. The expression that yields the largest heat transfer rate was used in the computations in Ref. [159].

5. Integration and seamless operation of CSP using thermocline LHTES system

From a practical point of view, one way to have a good picture of thermocline system behavior is to simulate the annual performance of a CSP plant. Several numerical models for parabolic trough CSP plant that include thermal storage system have been developed by different organizations [164-168]. All these models only consider the conventional molten-salt two-tank storage system for which outlet/inlet temperatures are fixed. However, in a thermocline storage tank, the available thermal energy at maximum temperature is expected to decrease with subsequent charging/discharging cycles [169] due to a continuous increase of thermocline thickness. Moreover, thermocline thickness also increases during idle periods because of thermal diffusion [170], which decreases TES exergy and the potential useful power that can be extracted. Bayón and Rojas [171] illustrated the difference between both two-tank and thermocline sensible storage systems in terms of outlet temperature as a function of time for the particular case of an initial discharge process, as shown in Fig. 17. While the two-tank system provides maximum constant storage liquid temperature, T_{max} , during the whole discharging process until the end; liquid outlet temperature for a thermocline tank starts decreasing after a certain time, $t_{partial-discharge}$ down to the minimum temperature, T_{min} when full discharge time, $t_{full-discharge}$ is attained.

Fig. 17 Outlet HTF temperature profile as a function of time for initial discharge processes corresponding to both a two-tank storage system and a single thermocline sensible heat storage tank.

[171]

Due to thermocline degradation, the annual electricity yield of a plant with thermocline storage is always lower than the same plant with a two-tank storage system. In this way, Biencinto et al. [172] carried out an annual performance analysis for different charge and discharge operation strategies, in order to find out the best operation mode that minimizes the difference in annual yield between both systems. With respect to the annual electricity yield, the best strategy for discharge processes is a total extraction of thermocline region, feeding the power block, firstly, for electricity production and, secondly, for the next day preheating. This strategy is easy to implement in a parabolic trough CSP plant and does not require more fossil consumption than keeping the remaining energy inside the tank.

However, according to the basic temperature requirement of Rankine cycle, which is applied by most commercialized CSP plants for power generation, the HTF temperature at the exit of storage tank (herein called as output HTF temperature) needs to be maintained above a cutoff temperature during the entire time period of discharge, below which HTF will not be able to be used in the power cycle for electricity generation. In the past decade, several research works have been presented for the analysis of output HTF temperature of latent thermocline storage system.

Zanganeh et al. [173] presented a new TES configuration to stabilize the outflow temperature of a thermocline storage system incorporated with rocks and latent heat storage by adding a relatively small amount of PCM to the top of the packed-bed. In their numerical analysis, three different PCMs were adopted (PCM #1: 27NaF-73NaBr, PCM #2: 46LiF-44NaF-10MgF₂, PCM #3: 52LiF-35NaF-13CaF₂). Fig. 18 shows the outflow HTF temperature as a function of time during discharging of the 9th cycle for three PCM packing heights on top of the packed-bed of rocks (indicated as "Rocks + Material #"). Also shown is the solid curve for the packed bed of rocks without PCM (indicated as "Rocks only"). It was reported by Zanganeh et al. [173] that the outflow temperature during discharging can be kept constant around the PCM melting temperature by adopting PCM #2 and PCM #3, thereby eliminating the inherent temperature drop of TES based on sensible heat storage only. A PCM volume of only 1.33% of

the total storage volume is sufficient to accomplish stabilization, corresponding to 4.4% of the total energy stored as latent heat.

Fig. 18 Outflow air temperature as a function of time during discharging of the 9th cycle for various PCM's packing heights on top of the packed bed of rocks ("Rocks + Material #"), and for the packed bed of rocks without PCM ("Rocks only"). [173]

Wu et al. [150] studied the dynamic characteristics of TES system with spherical capsules packed bed during discharging process using a one-dimensional model. Paraffin was taken as phase change material and water was used as heat transfer fluid. There are three stages during the discharging process, namely, liquid cooling, solidification (liquid-solid phase change) and solid cooling, as shown in Fig. 19. It was observed that the temperature of PCM decreases rapidly until it reaches the solidification temperature. During the solidification process, the temperature of PCM remains uniform at the solidification temperature. Then, it decreases gradually to the inlet temperature of HTF at solid cooling stage. The time for total solidification at the middle location is about 160 min and at the outlet location is about 280 min. This is due to the fact that heat transfer decreases as the temperature difference between PCM and HTF decreases along the direction of HTF flow. So, it is clear that the closer to the outlet location, the longer time for complete solidification and discharging process.

Fig. 19 Temperature evolution of PCM and HTF for different locations. [150]

Unfortunately, Wu et al. [150] didn't pay attention to the cutoff temperature. In order to explore the relationship between the melting temperature of PCM and the cutoff temperature, the current authors performed numerical investigation, using a 1D enthalpy-based transient model [143] and the general volume sizing strategy [138]. In this analysis, two different PCMs were adopted (PCM-1: KOH; PCM-2: NaCl-KCl, 58-42 wt%), and the cutoff temperature was chosen as 360°C, which was the same as the melting temperature of PCM-2. Following the general volume sizing strategy, with a fixed storage tank diameter of 10m and a constant discharge time of 6 hours, it was found that PCM-1 can offer a storage tank height of 50.4m, while PCM-2 can provide 43.7m high of storage tank, and the outflow HTF temperature variation with discharge time is shown in Fig. 20, where the red dashed line indicates the cutoff temperature of 360°C.

(a) PCM-1: KOH

(b) PCM-2: NaCl-KCl, 58-42 wt%

Fig. 20 Output HTF temperature variation during the entire discharge time for two different PCMs following the general volume sizing strategy

As a consequence, if the cutoff temperature can be kept the same as the melting temperature of PCM, such a phase change material can offer a smaller storage tank volume, which will lead to a significant reduction of material and construction cost. With the provided many thermophysical parameters of latent-heat thermocline TES system, a parametric study is necessary, and more investigations will be presented in the near future.

6. Cost analysis for thermocline LHTES system

6.1. Cost of selected PCMs

On the basis of the data collected by Kenisarin in 2010 [174], the current authors searched the updated commodity prices of some commonly used industrial grade PCMs for CSP application, and most of the prices were quoted from suppliers up-to-date in June 2015, which are listed in Table 11. It is seen that lithium carbonate is the most expensive salt, followed by aluminum fluoride and potassium hydroxide; while sodium fluoride and sodium chloride have the lowest prices.

Table 11 Commodity prices for selected PCMs

PCM	Price, \$/kg	PCM	Price, \$/kg
NaF	0.05 [175]	NaNO ₃	0.38 [176]
KF	0.10 [177]	KNO ₃	0.85 [178]
MgF ₂	0.01 [179]	Ca(NO ₃) ₂	0.25 [180]
CaF ₂	0.50 [181]	NaCl	0.05 [182]
AlF ₃	1.20 [183]	KCl	0.27 [184]
Na ₂ CO ₃	0.18 [185]	MgCl ₂	0.35 [186]
Li ₂ CO ₃	5.71 [187]	BaCl ₂	0.41 [188]
K ₂ CO ₃	1.00 [189]	CaCl ₂	0.14 [190]
Na ₂ CO ₃	0.10 [191]	SrCl ₂	0.80 [192]
KOH	1.09 [193]	ZnCl ₂	0.98 [194]

*Table 12 Estimated prices for various salt mixtures**

PCM (wt%)	Price, \$/kg	PCM (wt%)	Price, \$/kg
42Ca(NO ₃) ₂ -15NaNO ₃ -43KNO ₃	0.53	61KCl-39MgCl ₂	0.30

54KCl-46ZnCl ₂	0.59	25KCl-27CaCl ₂ -48MgCl ₂	0.27
48NaCl-52MgCl ₂	0.21	5KCl-29NaCl-66CaCl ₂	0.12
32KCl-68MgCl ₂	0.32	28KCl-19NaCl-53BaCl ₂	0.31
33NaCl-67CaCl ₂	0.11	24KCl-47BaCl ₂ -29CaCl ₂	0.30
37MgCl ₂ -63SrCl ₂	0.63	32Li ₂ CO ₃ -35K ₂ CO ₃ -33Na ₂ CO ₃	2.21
47Li ₂ CO ₃ -53K ₂ CO ₃	3.21	40KCl-23KF-37K ₂ CO ₃	0.16
44Li ₂ CO ₃ -56Na ₂ CO ₃	2.57	17NaF-21KF-62K ₂ CO ₃	0.65
28Li ₂ CO ₃ -72K ₂ CO ₃	2.32	35Li ₂ CO ₃ -65Na ₂ CO ₃	2.06
51K ₂ CO ₃ -49Na ₂ CO ₃	0.56	22Li ₂ CO ₃ -16Na ₂ CO ₃ -62K ₂ CO ₃	1.89

* Costs are based on values in Table 11.

Based on the prices in Table 11 for single specie/material, the prices of various mixturePCMs are calculated and given in Table 12. It is noted that the prices of the PCM may vary due to the variation of market and supply situations.

The storage material cost is formulated as: $[\rho_p(1-\varepsilon)C_p^* + \rho_f\varepsilon C_f^*] \cdot \pi R_t^2 H_t$ where C_p^* is the PCM cost per unit mass, such as tabulated in Table 12, and C_f^* is the HTF cost per unit mass. The cost of molten salt HTF in power tower CSP plant is around \$1/kg [195,196]. The cost of PCM encapsulation is usually measured in terms of cost/kg of capsule, and it also increases with the increase of capsule radius due to higher cost of heat treatment and processing. Also, the stronger buoyancy driven natural convection that will be prevalent inside the molten PCM of larger capsules during the melting process requires a thicker shell material [197].

6.2. Cost analysis of LHTES systems

In 2011, the US Department of Energy launched the SunShot Initiative and has put forth an aggressive R&D (research and development) plan to make CSP technologies cost-competitive with other energy generation sources on the grid by the end of the decade. The goal of the SunShot Initiative includes the LCOE (levelized cost of electricity) from solar power plants less than 6 ¢/kWh without subsidies, a round-trip annualized exergetic efficiency greater than 95%, storage cost less than \$15/kWh, by 2020, which would pave way for rapid and large-scale adoption of solar electricity.

Pacheco et al. [198] presented what appears to be the first cost analysis of a sensible thermocline storage system. Considering an indirect configuration, temperature differential of 84°C, HTF of ‘solar salt’, and storage medium of quartzite rocks, a cost of \$13,900,000 is calculated for a 688 MWh system,

corresponding to a capacity cost of \$20/kWh. EPRI [199] reported a much more thorough and detailed cost analysis procedure. Cost analysis of a molten salt thermocline storage system, ranging in capacity from 100 MWh to 3500 MWh was considered. It was reported that the capacity cost of a molten salt thermocline storage system ranges from \$246/kWh to \$34/kWh for the storage capacity ranging from 100 MWh to 3500 MWh. Strasser and Selvam [200] performed cost analysis for utility-scale of 2165 MWh packed-bed and structured-concrete thermocline storage systems, indicating that a packed-bed thermocline TES system is 12.5% less costly than a structured-concrete thermocline TES system (\$30/kWh vs. \$34/kWh).

Relatively few works of cost analysis have been published for thermocline LHTES systems. Nithyanandam and Pitchumani [133] presented a cost and performance analysis of concentrated solar power systems with integrated latent thermal energy storage, using a previously developed comprehensive transient 2D model [159]. In their analysis, two different types of latent thermal storage system, namely EPCM-TES (encapsulated phase change material thermal energy storage) and HP-TES (latent thermal storage system with embedded Heat Pipes) systems were evaluated with respect to the storage capacity cost and annual exergetic efficiency. Based on their systematic parametric analysis on various performance metrics, feasible operating regimes and design conditions, it was found that the minimum LCOE obtained from the parametric study and the design window is at 5.37 ¢/kWh, less than the SunShot 2020 target of 6 ¢/kWh for EPCM-TES system. Also, it was found that the maximum cost of heat pipes embedded in latent heat TES, which satisfies the SunShot requirements, is \$4/unit HP (heat pipe). The results provide first-hand information for optimum operation and design of the latent thermal storage systems for CSP plants.

Xu et al. [138] performed a simple cost analysis for the comparison between SHTES and LHTES, based on a previously developed 1D enthalpy-based transient model [143]. According to the general volume sizing strategy proposed by the authors [138,201], the storage media cost for four different systems (SHTES with granite rocks under 6h charge, LHTES with KOH under 8h charge, LHTES with KOH under 6h charge, LHTES with 58% NaCl - 42% KCl under 6h charge) were calculated and compared, for a parabolic trough CSP plant with 60 MW electrical power output at a thermal efficiency of 35%. The authors [138] reported the capacity cost of three different LHTES systems, which are much higher than the capacity costs listed in Ref. [200], and this is because the cost of Therminol VP-1

HTF is much higher than that of 'Solar Salts' HTF, for example the cost of Therminol VP-1 is \$26.3/kg, while the cost of Solar Salt is only \$0.5/kg. Using the prices from several different distributors mentioned by Strasser and Selvam [200], the cost analysis listed in Ref. [138] has been revised by replacing Therminol VP-1 with Solar Salts, and the updated capacity cost for each system is shown in Table 12. The results show that LHTES using salt (58% NaCl -42% KCl) with 6 h charge has the lowest capacity cost of \$20.5/kWh, which is about 43% less than that of SHTES using granite rock with 6 h charge. The capacity costs of LHTES of KOH with 8 h charge and LHTES of KOH with 6 h charge are at the same level of \$20.5/kWh. Comparing the thermocline energy capacity costs, it is found that LHTES has at least 35%, at most 43% reduction than that of SHTES. The capacity costs listed in Table 12 are still higher than the targeted capacity cost of \$15/kWh from DOE Sunshot program. Systematic optimizations to LHTES and SHTES systems are needed to achieve the goal.

Table 12 Capacity cost analysis of SHTES and LHTES

Cost contributor	Thermocline storage system (60 MWe, 35% thermal efficiency)			
	SHTES with granite rocks under 6h charge	LHTES with KOH under 8h charge	LHTES with KOH under 6h charge	LHTES with 58% NaCl - 42% KCl under 6h charge
Energy storage media	\$155,072.65	\$527,597.50	\$566,965.75	\$731,824.70
Storage tank	\$8,000,00	\$4,000,00	\$5,000,00	\$3,000,00
Foundation	\$3,000,000	\$3,000,000	\$3,000,000	\$3,000,000
Platform and steel	\$2,898,600	\$1,449,300	\$1,449,300	\$1,449,300
Insulation	\$2,062,800	\$1,062,800	\$1,062,800	\$1,062,800
Pumps and PCE	\$6,673,660	\$6,673,660	\$6,673,660	\$6,673,660
Piping and valves	\$2,177,830	\$2,177,830	\$2,177,830	\$2,177,830
Electrical	\$550,742	\$550,742	\$550,742	\$550,742
Instrument/controls	\$322,118	\$322,118	\$322,118	\$322,118
Construction costs	\$11,695,260	\$4,847,630	\$5,847,630	\$3,847,630
Constr. management	\$1,500,000	\$1,500,000	\$1,500,000	\$1,500,000
Installed cost	\$31,036,083	\$22,111,678	\$23,151,046	\$21,315,905
Capacity cost (\$/kWh)	\$30.1	\$20.5	\$22.2	\$20.8

In order to further analyze the levelized cost of electricity for LHTES system, according to the LCE (Levelized cost of electricity) calculator on NREL website [202], a rudimentary LCE cost analysis is provided in Table 13 for the four thermal storage systems listed in Table 12. In this cost analysis, a

1 fixed discount rate of 3%/year for system lifetimes of 25 years is assumed. The capacity factor is
2 assumed to be 60%, and the cost of operation and maintenance is also assumed to be a constant of
3 \$40/kWe-yr. Then based on the current electricity retail price and cost escalation rate in Southwest
4 region of US, the LCE for each system can be calculated, as shown in Table 13.

5

6 *Table 13 Levelized Cost of Electricity for a 60MWe CSP plant for SHTES and LHTES*

Cost contributor	Thermocline storage system (60 MWe, 35% thermal efficiency)			
	SHTES with granite rocks under 6h charge	LHTES with KOH under 8h charge	LHTES with KOH under 6h charge	LHTES with 58% NaCl - 42% KCl under 6h charge
Periods (Years)	25	25	25	25
Discount Rate	3%	3%	3%	3%
Capital Cost (\$/kW)	\$517.30	\$368.50	\$385.90	\$355.30
Fixed O&M cost,\$/kWe-yr	\$40	\$40	\$40	\$40
Variable O&M Cost (\$/kWh)	0.002	0.002	0.002	0.002
Capacity factor	43.6%	43.6%	43.6%	43.6%
Electricity Price (cents/kWh)	12	12	12	12
Cost Escalation Rate	2.3%	2.3%	2.3%	2.3%
Levelized cost of electricity, ¢/kWh	10.0	9.8	9.8	9.8

7

8 As shown in Table 13, the levelized cost of electricity for SHTES is 0.2¢/kWh higher than LHTES,
9 and all three LHTES system almost have the same LCE, but all of them are higher than the targeted
10 LCE of 6¢/kWh from DOE SunShot program. Once again, it indicates the necessity of optimizing the
11 thermal storage system before they are employed in practical applications.

12

13 **7. Concluding remarks and discussions**

14 The development of concentrated solar power systems has been focused on thermal performance,
15 reliability, and cost,of the system with thermal energy storage, as evident from a large amount of
16 research and publications through sustained, long-term support and investments by government
17 agencies and industries worldwide.Thermal storage in the form of sensible heat, or latent heat, or a
18 combination of both is considered in CSP industry. Studies conducted tocompare latent thermal storage
19 and sensible heat storage have shown thata significant reduction of storage tank volume can be
20 achieved usingPCMs.

21 This work surveys the state-of-the-art technologies of LHTES especially PCM encapsulation and

1 thermocline heat transfer of packed PCM capsules. First, some commonly-used phase change materials
2 were categorized based on the temperature ranges of application. A list of industrial manufacturers and
3 companies possessing encapsulation technologies is provided. Giving considerations to the heat
4 transfer enhancement approaches in latent heat storage system, details of numerical modeling of latent
5 heat thermocline heat transfer is provided. The relationship between PCM melting temperature and the
6 cutoff temperature (lowest HTF temperature acceptable by power plant) is discussed. Conclusions from
7 literature showed that if the cutoff temperature can be kept the same as the melting temperature of a
8 PCM, such a phase change material can offer a smaller storage tank volume, which will lead to a
9 significant reduction of material and construction cost. At the end, studies about the cost of PCM-based
10 thermal energy storage system is analyzed, by providing a list of prices of some phase change materials
11 and a cost analysis comparing SHTES and LHTES systems.

12 By developing and deploying more efficient CSP plants with TES systems, the sun's free and
13 clean energy can be harnessed to power homes, businesses, and communities around the world. This
14 will lead to reduction of harmful carbon pollution and keeping our global environment clean for the
15 future generations. It is expected that this review is beneficial to the fast developing LHTES
16 technologies for CSP industries.

17

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