Chapter

Development of Latent Thermal Energy Storage Heat Exchangers to Utilize Renewable Energies with Thermal Form

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Abstract

The latent thermal energy storage (LTES) technology has advantages of high thermal energy storage density, system volume saving, and easy installation, which is of great significance for improving the flexibility of thermal energy supply in the background of renewable energy utilization. The process of storing/releasing thermal energy of LTES systems mainly relies on heat exchangers, one special device for exchanging heat between heat transfer fluids (HTFs) and phase change materials (PCMs). The inherent liquid-solid phase change process of PCMs in the device makes this kind of heat exchanger urgently needed for more efficient design and optimization. In this chapter, working materials, device types, design forms, heat transfer enhancement methods, and some actual applications for heat exchangers are introduced. The present problems of the heat exchanger development are also discussed. The purpose of this chapter is to attempt to help the readers obtain key knowledge and design points for potential better applications of the LTES heat exchangers.

Keywords: phase change material, heat transfer fluid, heat exchanger design, device type, latent thermal energy storage

1. Introduction

Latent thermal energy storage (LTES) is a process of using liquid-solid latent heat to store energy in thermal form (including heat and cold thermal energy) and then release it to the thermal energy systems. This is a typical intermittent and unsteady energy utilization process suitable for balancing and reducing costs for thermal energy usage occasions. In recent years, with the urgent trend of mitigating climate change and promoting green sustainability, the proportion of renewable energy is constantly increasing. The end users have put forward higher requirements for the flexibility of energy supply. Among the many forms of energy usage used by end users, thermal energy is crucial. For instance, in China, thermal energy, which is mostly used for ensuring thermal comfort in buildings (heating and cooling), accounts for 15% of the total social energy consumption. Globally, according to statistics, thermal energy covers 50% of the total energy consumption and is responsible for 40% of the CO_2 emissions. Consequently, it seems that the development of thermal energy storage technology that combines with renewable energy is important for accelerating thermal energy utilization toward green sustainability. Based on this, it is forecast by the International Renewable Energy Agency (IRENA) that the global thermal energy storage market will triple in size by 2030, and the capacity of thermal storage devices will increase to over 800 GWh in the next 10 years [1]. Therefore, in order to achieve an approximate effect of direct thermal energy usage for the end users, the LTES technology has received widespread attention. The scenarios of LTES applications can be divided according to the required temperature range, which is shown in **Figure 1**. It can also indicate that this technology has a wide range of application demands and applicability.

The storage and release of thermal energy in LTES devices mainly rely on the heat transfer process between the mediums. Therefore, these devices can be considered as a special kind of heat exchanger. The design, optimization, and control methods for traditional heat exchangers are also applicable to the LTES heat exchangers. The difference is that they are composed of PCMs, encapsulations, and HTFs. Consider for a moment the heat transfer process within a shell-and-tube LTES heat exchanger, such as that shown in **Figure 2(c)**. The HTF flows in the tube to pass heat through the wall of the tube. Subsequently, the PCM inside the shell is frozen or melted. The liquid-solid interface of PCM dynamically and continuously changes along with the tube

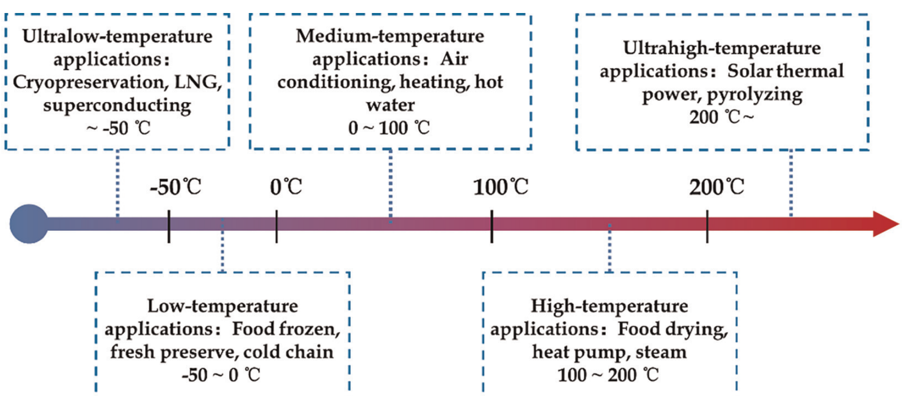

Figure 1.
Application scenarios and temperature ranges of LTES devices.

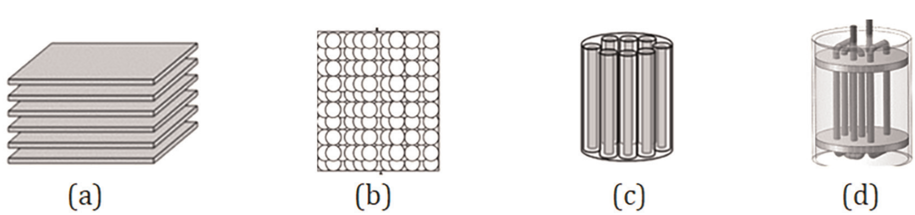

Figure 2.
Basic forms and characteristics of LTES heat exchangers: (a) plate type; (b) sphere type; (c) tank type; (d) casing tube type.

path. Yet the problem of determining the heat transfer in this situation, however difficult it appears to be, is a task that must be undertaken. The HTF flow in the tubes seems more tractable, but it, too, brings with it several problems that are not as simple as flows in a tube with a flat internal surface for the effect of the phase change process outside the tube. This kind of heat exchanger, similarly to the others, presents a kind of microcosm of internal and external heat transfer problems. These issues extend to the applications mainly reflected in the non-uniformity of the working process, such as:

a. The longest duration in the final stage of frozen or melting process;

b. The low efficiency for the overall heat transfer process due to low thermal conductivity of PCM;

c. Thermal stratification and phase separation caused by the poor fluidity of the liquid PCM.

The above are also urgent issues that need to be addressed for the research and development of this type of heat exchanger.

Our aim in this chapter is to present the analysis of a few basic concepts and to show progression toward increasing applications for LTES heat exchangers. We begin this undertaking with the fundamental problem of the materials.

2. Materials

The LTES heat exchanger consists of PCM, encapsulation containment, and HTF. Generally, in order to ensure the stability of PCM for cycling, the PCM is confined in encapsulation containment from several milliliters to several liters. The HTF flows within fluid channels that are composed of the outer side of the containments. The main material characteristics and selection criteria of these different functional parts in the heat exchangers are described below.

2.1 Phase change material

The term PCM specifically refers to materials that can produce liquid-solid phase transition in heat transfer process. The temperature at which the phase change happens is called the phase change temperature (PCT). The selection of the PCM is an essential step at the initial design stage of the LTES heat exchanger, which determines the storage capacity and eventually affects the device's final application. It is widely accepted that the desired requirements for PCMs are:

a. An appropriate operating temperature range depending on the application;

b. High energy density;

c. High thermal conductivity;

d. Low degree of subcooling;

e. Corrosion resistance;

f. Chemical and physical stability;

g. Not poisonous, toxic, flammable, or explosive;

h. Small vapor pressure and volume change;

i. Low cost and available in large quantities.

Based on the above criteria, many kinds of pure materials have been selected and applied. According to their chemical nature, the materials can be classified into organic and inorganic substances with variable PCTs. Then, one can deduce that more than two pure substances can be mixed for the PCT adjustment by varying the content of the components, which often refers to a mixture of PCMs. Among them, the eutectic PCM is fabricated from more than two substances. It can utilize hydration to store or release thermal energy, which has advantages in terms of higher energy storage density. In addition, these pure or mixed PCMs have some natural limitations for widespread applications, mainly due to their corrosiveness, supercooling, and phase segregation. Innovative nano additive and composite PCMs have been developed, which have given the ability to decrease subcooling, nucleation time, thermal conductivity improvement, and leakage prevention.

Based on temperature ranges as mentioned in the above section, the commonly used PCMs are listed and discussed below.

2.1.1 PCMs for low-temperature applications

When the PCT is below 0°C, it can be considered that this type of PCM is used for cold thermal energy storage. They are widely applied in areas such as frozen food, fresh conserve, cold chain, and air conditioning during the summer season. Compared with other applied PCMs, these low-PCT PCMs are mainly composed of pure substances and simple solutions, which also make them very easy to be used. The commonly seen PCMs for low-temperature applications are listed in **Table 1**. The PCMs that correspond to the ultra-low-temperature range are mainly composed of volatile pure substances. In temperature range within −50 to 0°C, many types, including pure substances, metallic salts solutions and eutectic water-salt solutions, can be utilized. It may be worth noting that water has the largest latent thermal energy density compared to other PCMs [2]. The additives and components, in general, can reduce the latent heat, increase the cost of the PCM products, and deteriorate the cycling stability. Therefore, the effect of including components should be evaluated to ensure an overall enhancement in the performance of PCMs. For instance, the enhancement may focus more on PCT fabrication and thermal conductivity improvement.

2.1.2 PCMs for medium-temperature applications

When the PCT is distributed between 0 and 100°C, it can be considered that this type of PCMs is used for heat thermal energy storage. This temperature range usually corresponds to the range of atmospheric liquid water applications. Therefore, from the supply-side view point, the PCMs are suitable for storing low-grade waste heat, solar energy, and geothermal energy. In addition, at the end-use view point, they are

Material	PCT (°C)	Thermal conductivity ($W\ m^{-1}\ K^{-1}$)	Latent heat ($J\ g^{-1}$)
Nitrogen (N_2)	−209.85	0.163 (l)	25.80
Pentane (C_5H_{12})	−129.75	0.173 (l)	116.43
Methanol (CH_4O)	−97.15	0.210 (l)	99.25
Methyl ethyl ketone (C_4H_8O)	−86.65	0.170 (l)	117.05
Hexanone ($C_6H_{12}O$)	−55.45	0.160 (l)	148.70
Ethylene glycol/H_2O (50:50 wt%)	−37.10		41.59
39.6 wt% K_2CO_3	−36.50		165.36
22.4 wt% NaCl	−21.20	0.570 (l)	222–235
Diethylene glycol ($C_4H_{10}O_3$)	−10.40	0.200 (l)	247.00
n-Dodecane ($C_{12}H_{26}$)	−9.50	2.210 (l)	216.20
27.2 wt% $ZnSO_4$	−6.50		208–235.75
Caproic acid ($C_6H_{12}O_2$)	−4.00	0.150 (l)	146.18
Water (H_2O)	0.00	0.551 (l)	333.30

Table 1.
Properties of PCMs for low-temperature applications.

Material	PCT (°C)	Thermal conductivity ($W\ m^{-1}\ K^{-1}$)	Latent heat ($J\ g^{-1}$)
Formic acid	8	0.27 (l)	277
Acetic acid	17	0.19 (l)	192
Calcium chloride hexahydrate	30	0.53 (l)	125
Lauric acid	44	0.15 (l)	212
Stearic acid	54	0.17 (l)	157
Sodium acetate trihydrate	58	0.34 (l)	266
Palmitic acid	61	0.17 (l)	222
Paraffin wax	0–90		150–250
Acetamide	82	0.25 (l)	260
Magnesium nitrate hexahydrate	89	0.50 (l)	140

Table 2.
Properties of PCMs for medium-temperature applications.

suitable for releasing thermal energy applications such as household heating, automotive air conditioning, and battery cooling. The commonly seen PCMs for medium-temperature applications are shown in **Table 2**.

It can be seen in **Table 2** that the organic PCMs, which are fatty acids, sugar alcohols, carboxylic acids, amides, and alkanes, are mainly employed for medium-temperature applications. Compared with inorganic PCMs, they have attracted more attention from the perspective of real applications due to their advantageous properties such as non-toxicity, slight supercooling, and good cycling stability. However, the character for having carbon atoms in their structure generally has very low thermal conductivity (from 0.1 to 0.6 W m^{-1} K^{-1}), hence requiring new methods to enhance their heat transfer performance. Therefore, nanoparticles, nanosheets, nanofibers, nanotubes, nanowires, and nanorods have been added and evaluated for the improvement of thermal conductivity [3].

2.1.3 PCMs for high-temperature applications

The PCM with a PCT above 100°C, which corresponds to hot steam conditions, can be regarded as for high-temperature applications. This kind of PCM is widely used in areas of concentrating solar power and integrated thermophotovoltaic systems. With these PCMs, solar energy can be harvested and stored in the systems to be efficiently used at night for power generation. It has been reported that a heat-to-electricity efficiency greater than 50% can be achieved. The commonly used PCMs for high-temperature applications are shown in **Table 3**.

It can be seen that the PCMs corresponding to high-temperature applications are mainly composed of organic compounds (sugar alcohols <200°C), molten salts (>300°C), and metallic alloys (>500°C). Molten salt-based PCMs are usually low-cost and have high heat-storage density, although the major disadvantage is the corrosion of containers, pipes, and valves. In addition, there are carbonate-based PCMs can be applied at higher temperatures (around 1000°C) applications. They have the advantages of high melting temperature, high viscosity, and high latent heat, making them suitable for developing structured PCMs in high-temperature thermal storage areas.

Material	PCT (°C)	Latent heat (J g^{-1})
Erythritol	117	340
$LiNO_3$(34)-66KNO_3	133	150
Maleic acid	141	385
$LiNO_3$(58)-42KCl	160	272
$LiNO_3$(87)-13NaCl	208	369
$NaNO_3$(86)-14NaOH	250	160
Zn(52)-48Mg	340	180
NaCl(56)-44$MgCl_2$	430	320
$CaCl_2$(52.8)-47.2NaCl	500	239
KCl(45)-55KF	605	407
LiF(70)-30MgF_2	728	520
NaF(68)-32CaF_2	810	600
Si(56)–44Mg	946	757

Table 3.
Properties of PCMs for high-temperature applications.

2.2 Materials for heat transfer fluid

The HTF is used to deliver heat to the PCMs. In most cases, the reason for choosing fluids as HTFs is their excellent heat transfer performance compared to other mediums and controllability. The HTFs can be divided into three basic types based on their working modes: pure gas phase, gas-liquid phase, and pure liquid phase. For low-temperature applications, the gas-liquid phase flow of volatile media is mainly used; For medium-temperature applications, pure liquid phase or pure gas phase can be used. For high-temperature applications, it is common to use high-temperature and high-pressure gases, which also include gas-liquid phase transitions of the hot steam. The heat transfer performance of the HTFs is usually better than that of the PCM. Therefore, on the HTF side, the significance of heat transfer enhancement is not very prominent. However, the uniformity of the HTF flow and the input power consumption need to be considered in the design process due to the diversity and complexity of the flow channels within the devices. In addition, due to the connecting effect of the HTF between systems and the LTES devices, from a system perspective, the availability and convenience of the HTF material also need to be considered for system optimization. The commonly used HTFs are mainly refrigerants, water, water-based solutions, hot steam, and gases.

2.3 Materials for encapsulation containment

Encapsulation containment refers to confining PCMs in closed containers from several milliliters to several liters. It can be used as a standalone LTES unit or as a multiple-stacked LTES device. The encapsulations can be divided into microencapsulation, microencapsulation, and porous stable shaping. The microencapsulation is the most widely used PCM encapsulation technique. It packages large amount of PCM in a big size and protects the PCM from contamination, which can also help to enhance heat transfer by providing a large heat transfer surface and reducing thermal resistance due to limited thickness. The microencapsulation and the porous stable shaped techniques, on the other hand, create a larger surface area than the microencapsulation, improving the heat transfer, the mechanical stability, and the cycling stability for the actual applications. Materials for the encapsulation containment can be metallic, polymer, and ceramic. The key property of encapsulation containment is its mechanical stability [4]. However, other properties such as density, volatile organic compound emission, flammability, and permeability of the containment shell play a role when a specific application is considered. In the case of micro and nanocapsules, capsule size distribution and morphology, which affect the heat transfer performance of the whole device, also need to be considered.

3. Device types and variations

The structure types of LTES heat exchangers are usually divided into plate type, spherical stacking bed type, tank type, and casing tube type. In order to improve heat storage efficiency, variations from the basic types have also been developed. The details on the device types and the variations are as follows.

3.1 Basic types and features

Plate type: The geometry of the plate is cuboid; as shown in **Figure 2(a)**, the heat transfer fluid (HTF) flows through the plate for heat exchange. The advantages are small pressure drop, simple structure, easy to manufacture and low price. The HTF is located outside of the containment and can flow freely.

Spherical stacking bed type: The basic unit of the spherical stacking bed type is the spherical capsule, as shown in **Figure 2(b)**. The PCM is encapsulated in a spherical shell with a certain thickness and then placed in a storage tank. The HTF exchanges heat through the voids between spheres. The dispersed mode of the spheres has the advantages of a large unit heat transfer area, simple structure, and no leakage. The stacking methods of the spheres can be classified into structured and unstructured. Similar to the plate form, the HTF is located outside the package and can flow freely.

Tank type: This type of device adds the pipes to the energy storage tank, where the PCM is filled in the tank. As shown in **Figure 2(c)**, the HTF flows in the pipe and exchanges heat with the PCM. The number and diameter of pipes in the tank greatly influence energy storage efficiency. The pipes are arranged horizontally or vertically. The HTF is located in the package, and the flow area is limited.

Casing tube type: The advantages of the casing tube include its compact structure and its large heat transfer area, as shown in **Figure 2(d)**. The space of the outer wall surface of the PCM is limited by an outer wall surface. The casing structure can be divided into horizontal and vertical structures according to the placement direction in a tank, and the body radius is the main factor affecting its performance. The HTF is located in the packaging and has a limited circulation area.

In the viewpoint from the surface structure of heat transfer interface (HTI) on the PCM side, the HTI can be divided into three different classifications as shown in **Figure 3**, i.e., flat surface type without surface microstructures, extended surface type with additional areas, and direct contact type that without solid walls as shown in **Figure 3(c)**. In detail, the flat surface HTI exhibits weaker overall contact capability due to its small contact area. The contact capacity of the extended HTI is higher than that of the flat surface HTI. For the direct contact HTI, the contact capacity performs best for the deformed contact interface.

The flat surface HTI comprises a flat surface interface that can be formed for the encapsulation of PCM with plates, spheres, tanks, and casing tubes. As the flat surface HTI does not include small local interface structures, the overall convective heat transfer coefficient can be calculated with respect to the total area of the HTI at the PCM side:

$$U = \frac{\varphi}{A \cdot \Delta T} \tag{1}$$

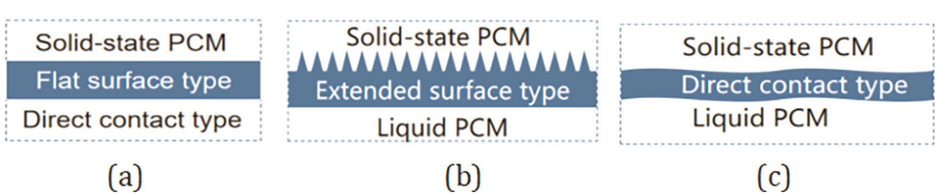

Figure 3.
Classifications of the HTI: (a) flat surface type; (b) extended surface type; (c) direct contact type.

$$\Delta T = \frac{\Delta T' - \Delta T''}{\ln\left(\frac{\Delta T'}{\Delta T''}\right)} \tag{2}$$

$$\varphi = \underset{HTF}{\dot{m}} C_{HTF}(T_{in} - T_{out}) \tag{3}$$

Eq. (1) represents a general calculation formula for the overall heat transfer process of all kinds of heat exchangers. Furthermore, this equation can describe the heat transfer process from the perspective of time averaging. Eq. (2) calculates the logarithmic mean temperature difference of the overall heat exchange process. The inlet temperature of HTF in Eq. (2) is usually maintained constant for the actual applications. The outlet temperature of the HTF can be calculated by Eq. (3). Generally, the temperature change at the outlet is small during the heat transfer process; therefore, a constant heat transfer flow rate is assumed [5]. By using Eqs. (1)–(3), the heat transfer performance of the LTES heat exchanger with different types of HTI can be compared.

3.2 Variations of the device structure

In order to strengthen the heat transfer for the LTES heat exchanger, the improvement of contact ability between the PCM and the HTI is usually adopted. It can be derived from two basic variations, i.e., HTI extension and direct contact. The extended surface HTI improves the heat transfer process by increasing the contact area of the flat HTI. Differently, the direct contact method strengthens the heat transfer process through the deformable direct contact HTI between PCM and HTF.

3.2.1 The extended surface HTI

The surface extension of the HTI is a widely applicable heat transfer improvement method for almost all of the basic types of LTES heat exchangers. From a general viewpoint, for heat exchangers, the evaluation of the extended surface heat exchangers involves the use of the convective heat transfer coefficient and Nusselt number ratio [6]. However, the Nusselt number of the LTES heat exchangers, owing to the small thermal resistance of HTI and a variable thermal resistance on the PCM side, cannot be precisely calculated. Therefore, the ratio of the overall heat transfer coefficient is used to clarify the enhancement performance in this section. The corresponding equations are listed below:

$$\frac{U}{U_0} = \frac{Q \cdot A_{PCM0} \cdot \Delta T_0}{Q_0 \cdot A_{PCM} \Delta T} \tag{4}$$

$$U = \frac{1}{\frac{1}{\mathrm{h}_{HTF}} + \frac{\delta_{wall}}{\lambda_{wall}} + R_{PCM}} \tag{5}$$

3.2.2 Direct contact HTI

The term "direct contact" refers to exchange heat between one medium and another material directly. In other words, for the heat transfer process, the PCM and the HTF share the same HTI, and the HTI often shows a dispersed style (such as droplets and bubbles). The physical property variations through the HTI are discontinuous. Meanwhile, the HTI shows obvious instantaneous deformation and complex structural characteristics. Therefore, the area of the HTI is difficult to obtain precisely. However, the overall convective heat transfer coefficient cannot be directly calculated without the precise determination of the heat transfer area. Based on this, researchers developed an estimation method that evaluates the mean size of the contact area. The details are described as follows.

First, the Galileo and the Reynolds numbers are calculated by using the physical parameters of PCMs and HTF:

$$\mathrm{Ga} = \frac{d^3 \cdot \rho \cdot (\rho_d - \rho_{PCM}) \cdot g}{\mu^2} \tag{6}$$

$$Re = \left(2.33 \cdot Ga^{0.018} - 1.53 \cdot Ga^{-0.016}\right)^{13.3} \tag{7}$$

Second, due to the interference of the dispersed phases in the direct contact type, the Prandtl number is introduced. Then, the Nu that represents the ratio of convective heat to conduction heat can be obtained by Eq. (9):

$$Pr = \frac{\mu \cdot C_{PCM}}{\lambda} \tag{8}$$

$$Nu = 2 + 0.65 \cdot \mathrm{Re}^{0.5} \cdot \mathrm{Pr}^{\frac{1}{3}} \tag{9}$$

The overall convective heat transfer coefficient can then be obtained as follows:

$$Nu = \frac{U \cdot d}{\lambda} \tag{10}$$

The diameter of the dispersed phases must be specified when calculating the Eq. (10). The diameter values can be denoted and predicted from the literatures for the calculations. What is more, in terms of evaluating the accessibility for direct contact type, calculation of the surface area density is also needed. It can be obtained by estimating the mean diameter values. In addition, the below equations can also be used to obtain the surface area by estimating the heat transfer coefficient for the direct contact HTI:

$$\varepsilon = \frac{T_{\mathrm{in}} - T_{out}}{T_{\mathrm{in}} - T_{PCM}} \tag{11}$$

$$\varepsilon = 1 - \mathrm{e}^{-NTU} \tag{12}$$

$$NTU = \frac{UA}{\dot{m}C} \tag{13}$$

3.3 Heat transfer performance of LTES heat exchangers

3.3.1 Evaluation and analysis of the flat HTI type

Usually, we can compare and analyze the heat transfer performance of the LTES heat exchangers by using parameters such as the overall convective heat transfer coefficient, surface area density, and heat transfer efficiency. The essential difference between the four basic types is the accessibility between PCM and HTF [7]. Thus, the surface area density represented by the area-to-volume ratio is used for the quantification of accessibility. A literature review of the data and the calculations of LTES heat exchangers with flat HTI is conducted in this section. The results of heat transfer coefficient and surface area density are extracted to form the upcoming **Figure 4**, which gives a direct look into the heat transfer performance with different LTES heat exchangers.

It can be seen in **Figure 4** that the overall convective heat transfer coefficient almost linearly increases with the increase in surface area density for all the cases. From comparisons between different device forms, the same variation trend can also be observed. The plate from the LTES heat exchanger comprises different numbers of parallel plates. The HTF flows between the plates. However, the plate form usually has a large aspect ratio, which exhibits a slight discreteness along the length direction. In addition, this form is usually applied when air is used as the HTF and the air flows in an interpenetration channel. Therefore, the overall convective heat transfer coefficient and the surface area density of the plate form are distributed in the lower left zone in **Figure 4**.

For the spherical stacking bed form, the size and the filling approach of the spherical capsule are the main factors affecting the energy storage efficiency. Many researchers have conducted experiments and simulations to prove this. The results indicate that when the volume of the tank keeps the same, the overall convective heat transfer coefficient of the heat exchanger is limited by the size and the number of filled spheres. The reason for this phenomenon is that the surface area density of the filled spheres has varied according to size and number. Furthermore, the nonstructural distributions (without arranged positions for the spheres) with the same number and size of the spheres can provide higher overall heat transfer coefficients than the structural distributions. The reason is that the nonstructural is more dispersed than the structural distributions. Overall, the spherical stacking bed form is conducive to the dispersed heat transfer process of the PCM and can better improve the heat transfer performance. Therefore, in **Figure 4**, it has a larger heat transfer performance than the plate form.

For the tank form, the number of pipes, the pipe layout direction, the pipe diameter, and the pipe outlet position are the main factors affecting the energy storage process. Researchers also conclude that the larger the pipe diameter, the better the heat transfer performance can be obtained. In **Figure 4**, the overall convective heat transfer coefficient of the tank form is generally higher than that of the spherical

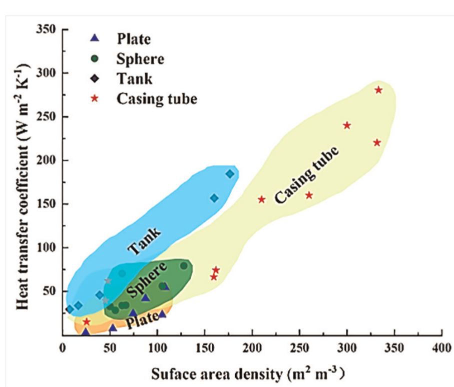

Figure 4.
Surface area density and corresponding overall convective heat transfer coefficient for different LTES heat exchangers with flat HTIs.

stacking bed type. This is because the HTF in the tank form is constrained inside the PCM by the pipe wall, which increases the accessibility of the PCM and the HTF. Therefore, inspired by this, it is more beneficial to improve the heat transfer performance by adding the HTI into the PCM.

Similarly, the HTF of the casing tube form is limited inside the PCM by pipe walls. The highest corresponding heat transfer performance can be seen in **Figure 4**. Unlike the tank form, the PCM in casing tube form is also limited by an outer shell wall. According to the literature review, the radius ratio of the shell to tube is usually smaller than the tank form, which provides a higher surface area density than the other forms.

3.3.2 Evaluation and analysis of surface extension HTI type

It is a widely used enhancement method to expand the heat transfer area on the PCM side for the LTES heat exchanger improvement. Based on the development principle of the LTES heat exchangers, it is found that the most common methods for surface extension are adding fins, embedding heat pipes, and adopting gradient-sized surfaces. To distinguish the performances before and after extending the surfaces, the ratio of surface area density is adopted. This value represents the extent strength to which the LTES devices can be improved after strengthening. Similarly, the heat transfer coefficient ratio is also used to represent the heat transfer enhancement. In addition, considering the evaluation of the heat transfer enhancement effect, the only difference between the tank and casing-tube structures is the outer shell wall. Both heat transfer enhancement methods are mainly aimed at the expansion of the outer wall of the inner tube. Therefore, the casing tube and tank forms are combined in the analysis; the comparison results are shown in **Figure 5**.

3.3.3 Evaluation and analysis of direct contact HTI type

The LTES heat exchangers with direct contact HTI type can be divided into two forms, top-down and bottom-up, based on the distributions of the HTF inlet. The HTF that is usually used is pure gas and pure liquid. It should be noted that the phase change (gas-liquid transition) of HTF can also significantly enhance the heat transfer

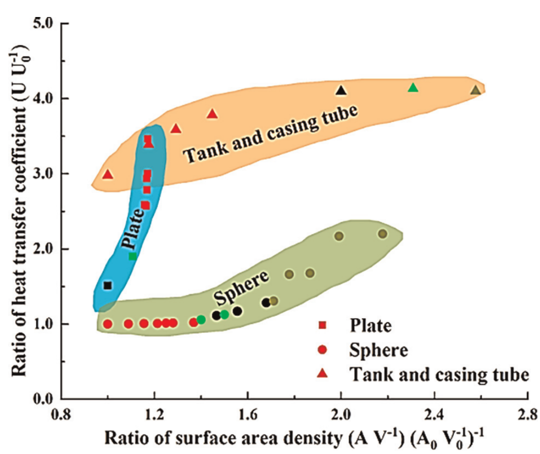

Figure 5.
Surface area density ratio and heat transfer coefficient ratio of different forms with surface extension HTIs.

performance for this type of heat exchanger. The direct contact HTI is formed by two or more immiscible media. Its structure and position are highly variable and are driven by the natural or forced flow of the HTF. Since the variation of HTI can highly improve the mobility of the liquid PCM, this type of heat exchanger has higher heat transfer performance than the others. The estimation of the average size of the HTI seems crucial for calculating the total convective heat transfer coefficient. However, few studies can accurately predict this value for the inherent complex mechanism of the HTI variation. Further studies are needed to quantitatively evaluate the heat transfer properties of the direct contact LTES heat exchangers. Another method for the evaluation of heat transfer performance is direct experiments, which are compared to indirect types. Researchers concluded that the maximum increase in the average rate of energy storage for direct contact type is 218%. Due to the removal of the fixed wall surface, the heat transfer coefficient at the interface between PCM and HTF can reach higher levels, beyond 1000 W m^{-2} K^{-1}.

4. Design methods

Usually, constructing models is a crucial step for the heat exchanger design. The developed models for heat exchangers can be divided into one-dimensional steady models, dynamic analytical models, and numerical models, which play indispensable roles in the heat transfer area. The modeling process for heat transfer issues is not only a component of scientific research but also a cornerstone in solving practical problems in engineering practice. For the LTES heat exchangers, the design also relies on the development of the heat transfer model. Therefore, in this section, the design methods are described by developing the specific models, which can also provide the guidelines for the actual device design.

4.1 One-dimensional steady model

The study of system behavior under equilibrium or stable conditions is crucial for the ease of implementation of the LTES heat exchanger design. Common types of one-dimensional models include static steady-state models, which mainly focus on the equilibrium state at specific time points. It is worth noting that static steady-state models are usually simpler, but provide valuable insights into system behavior.

4.1.1 Construction of one-dimensional model for LTES heat exchangers

When constructing steady-state models, it is essential to ensure that the model's parameters and assumptions align with real conditions. Conducting sensitivity analysis is crucial to understanding the model's response to changes in parameters. Furthermore, the significance of the one-dimensional model lies in its ability to serve as a references for the long-term performance of systems, providing a foundation for strategy formulation and decision-making. Therefore, in practical applications, model results should be compared with actual observational data to validate their accuracy and reliability.

4.1.2 Modeling of equations

In a one-dimensional model, equations typically articulate the equilibrium conditions among various variables in a system under steady conditions. With a relatively fixed heat transfer area, the state parameters encompass the temperature variation of PCM and the cold/hot supply performance.

Its mathematical representation is based on the mean effectiveness-NTU (number of transfer units) method. When the working fluid within the heat exchanger undergoes a phase change, the effectiveness of the heat exchanger can be expressed as follows [8]:

$$\varepsilon = 1 - e^{-NTU} \tag{14}$$

When utilizing PCM, effectiveness is formulated as the ratio of the actual released heat energy to the theoretical maximum released heat energy. The NTU is associated with the properties of the working fluid without phase change and is determined by the mass flow rate, heat capacity, and total thermal resistance. The NTU at any given time can be expressed as follows:

$$NTU = \frac{UA}{\dot{m}_h C_h} = \frac{1}{R_T \dot{m}_h C_h} \tag{15}$$

Taking the example from the authors' research of a latent heat energy storage panel assisted by embedded heat pipes (HP), the total thermal resistance (R_T) is a function of six thermal resistances shown in **Figure 6** and defined by Eq. (16):

$$R_{Total} = R_f + R_{c1} + \mathrm{R}_{ew} + R_{cw} + R_{c2} + \mathrm{R}_{pcm} \tag{16}$$

The following equations shown in **Table 4** are used for the calculation of the total thermal resistance. It should be noted that under steady-state conditions, the total thermal resistance of the HPs is formed by the thermal resistance of the HP wall and the wick. The thermal resistance of the vapor flow can be neglected.

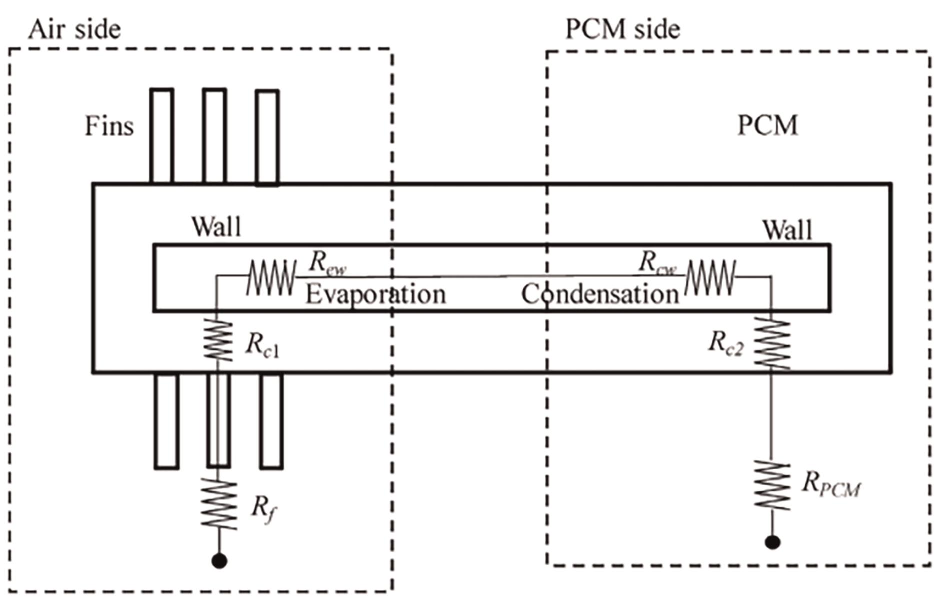

Figure 6.
Thermal resistance model of the heat exchange process.

Thermal resistance	Equations
R_{c1}	$R_{c1} = \ln(r_o/r_i)/(2\pi k_{wall}L_e)$
R_{ew}	$R_{ew} = \ln(r_i/r_v)/(2\pi L_e K_{eq})$
R_{cw}	$R_{ew} = \ln(r_i/r_v)/(2\pi L_c K_{eq})$
R_{c2}	$R_{c1} = \ln(r_o/r_i)/(2\pi k_{wall}L_c)$
R_f	$R_{c1} = 1/\left(A_f\eta_f\eta_n h_f\right)$
R_{PCM}	$R_{PCM} = \ln(r_m/r_o)/(2\pi k_{PCM}L_c)$

Table 4.
Referenced equations for the calculation of thermal resistances.

From these equations, it can be observed that the effectiveness varies with the change in the radius of the molten PCM layer. Thus, the average effectiveness of an individual unit can be defined as:

$$\overline{\varepsilon} = \int_{r_m=r_0}^{r_m=r_{\max}} \frac{\varepsilon dr_m}{r_{\max} - r_0} \tag{17}$$

Subsequently, the average performance of cold and hot energy supply can be obtained:

$$\overline{q} = \overline{\varepsilon}\dot{m}c_p(T_{\text{inlet}}\text{-T}_{\text{PCM}}) \tag{18}$$

4.2 Dynamic analytical model

The application of dynamic models in the design is aimed at a more comprehensive understanding of the heat exchangers dynamically. In contrast to the static models that focus on the system's equilibrium state at a specific moment, dynamic models, by modeling along the time dimension, can capture the dynamic characteristics of the device over time, providing explanatory power for both long-term trends and instantaneous changes. Common dynamic modeling approaches usually involve the development of differential and integral equations. The differential equations focus on the continuous-time evolution of the heat transfer process. The integral equations involve the accumulation of system states. Dynamic models can also be categorized into linear and nonlinear models. The linear dynamic models assume that the system's behavior can be described through linear relationships, whereas the nonlinear dynamic models offer more flexibility in handling nonlinear effects within the system, providing a closer representation of real scenarios.

4.2.1 Construction of dynamic analytical model

When constructing dynamic analytical models, special attention must be given to the selection of model parameters and the establishment of initial conditions, as they significantly impact the predictions. Furthermore, conducting analyses on the stability and sensitivity of the model is a crucial step to ensure that the results possess reasonable explanations under varying conditions.

4.2.2 Modeling of equations

In dynamic analytical models, it is essential to initially establish the system's state variables and the relationships between these variables. This can be accomplished through the formulation of differential equations and calculus expressions. In this section, an example of LTES heat exchanger development using bubble flow from the author's research is used to explain the modeling method. When dealing with phase transition processes characterized by unfixed heat transfer interfaces, the utilization of dynamic analytical models can facilitate the swift derivation of simulation outcomes.

In the mathematical representation of dynamic analytical models, the differential equation of energy conversion is [9]:

$$\rho_{Ps}\gamma\frac{dV_{Ps}}{dt}+\rho_{Ps}C_{Ps}\frac{dV_{Ps}}{dt}\Delta T=\dot{m}_hC_h(T_{in}-T_{out}) \tag{19}$$

The calculation of ΔT adopts the logarithmic mean temperature difference method, expressed as:

$$\Delta T=\frac{T_{in}-T_{out}}{\ln\left(\frac{T_{in}-T_P}{T_{out}-T_P}\right)} \tag{20}$$

Consistent with the method of calculating NTU using steady-state models, the NTU at any given time can be represented as follows:

$$NTU=\frac{UA}{\dot{m}_hC_h}=\frac{1}{R_T\dot{m}_hC_h} \tag{21}$$

Taking the direct contact phase change process as an example, the intricate and diverse nature of the contact interface structure necessitates the establishment of state parameters from an overall process perspective. The state variables encompass changes in the volume of the PCM and the outlet temperature throughout the phase transition. Simultaneously, in order to solve this model, certain objective and subjective assumptions have been proposed.

The dimensionless relationship between volume and contact area with HTF during PCM phase transition is assumed as:

$$\frac{dA}{dA\cdot A_0}=\frac{dV}{dt\cdot V_0} \tag{22}$$

$$UA_0=\frac{1}{R_{T0}} \tag{23}$$

Connect volume and thermal resistance based on the volume assumption can be obtained by:

$$\frac{1}{R_T}=\frac{V}{V_0}\cdot\frac{1}{R_{T0}} \tag{24}$$

To derive the mathematical expression for NTU, Eq. (24) is substituted into Eq. (19), facilitating a dynamic analysis of the heat transfer process in the direct contact LTES heat exchanger:

$$NTU = \frac{1}{\dot{m}_h C_h} \cdot \frac{1}{R_{T_0}} \cdot \frac{V}{V_0} \tag{25}$$

Once the solution to the dynamic analysis model is obtained, it can be applied to predict the future behavior of the system or analyze its response under different conditions. This aids in a comprehensive understanding of the system's dynamic characteristics, offering guidance for optimization in design and control.

4.3 Numerical model

The application of numerical models in the fields of heat exchanger development aims to address complex mathematical equations or encountered practical problems, which are often too difficult to be solved by the analytical models. The major development methods of the numerical models include the finite element method, finite difference method, and finite volume method. The finite element method is primarily used for structural mechanics and fluid dynamics issues, while the finite difference method is commonly employed for the numerical solution of partial differential equations. On the other hand, the finite volume method gives wide application in fluid dynamics and heat transfer problems. Each method has its applicable scope and advantages, and the choice of an appropriate numerical approach depends on the characteristics of the problem and the requirements of the solution. It is noteworthy that there is a trade-off between the accuracy and computational efficiency of numerical models. Generally, the more refined the model, the greater the computational resources required. Therefore, establishing a suitable numerical model necessitates a balance based on the complexity of the problem and the availability of computational resources.

4.3.1 Construction of numerical model for the LTES heat exchangers

In the construction of numerical models, consideration of parameter selection, grid partitioning, and time step setting is of paramount importance. These choices directly impact the accuracy and the stability of the numerical model. Furthermore, the comparison with actual data and model validation are indispensable steps to ensure the reliability of the numerical model.

4.3.2 Modeling of equations

Numerical models often rely on differential equations, employing numerical methods such as finite element, finite difference, or finite volume techniques to approximate the solutions of these equations. The common numerical model formulas for heat transfer process of the LTES heat exchangers are as follows [10].

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \left(\rho \vec{u} \right) = 0 \tag{26}$$

Special attention should be given to grids in regions with density variations, where the density is defined as $\rho = \alpha\rho_l + (1-\alpha)\,\rho_s$. Here, α represents the volume fraction of the liquid phase, defined as:

$$\alpha = \frac{V_L}{V_{cell}} \tag{27}$$

Momentum equation:

$$\frac{\partial \vec{u}}{\partial t} + \nabla \cdot \left(\vec{u}\vec{u}\right) = -\frac{1}{\rho}\nabla p + \nu \nabla^2 \vec{u} + \beta\rho g\left(T - T_f\right) \tag{28}$$

The parameter T_f represents the reference temperature for buoyancy-driven flow. The second viscosity term is negligible and can be safely disregarded in the model solution [11]. The shear stress can be imposed on the calculation domain through the first term on the right of Eq. (28). The grids in the density-varying region are influenced by the volume fraction α, giving rise to forces arising from density differences with surrounding grids. Consequently, the macroscopic motion of the solid PCM can be directly driven by the stress term.

Energy equation:

$$\frac{\partial h}{\partial t} + \nabla \cdot \left(\vec{u}h\right) = \nabla \cdot \left(\frac{\lambda}{\rho}\nabla T\right) - L\frac{\partial \alpha}{\partial t} \tag{29}$$

Here, h represents enthalpy; λ is the thermal conductivity of the PCM; L is the latent heat of the PCM. The second term on the right side of Eq. (29) accounts for the rate of latent heat change resulting from the solid-liquid phase transition within the grids of the density-varying region.

5. Application cases

5.1 The low-temperature application

The transportation of liquefied natural gas (LNG) is a typical application scenario that can be combined with low-temperature cold thermal energy storage. A large amount of cold thermal energy needs to be released to recover the LNG to the normal atmospheric temperature condition for the end users. Recovering and utilizing this cold thermal energy is of great significance for optimizing the energy consumption of the entire industrial chain. However, it is difficult to achieve a large temperature difference under low-temperature conditions, while maintaining a stable working condition. Therefore, using an LTES heat exchanger to recover and store LNG cold energy becomes rational for real applications. For example, **Figure 7** illustrates the situation of an LNG refrigerated truck, where the LTES heat exchanger serves as a cold storage unit (CSU) integrated with the fuel system of the truck. A large amount of low-temperature cold thermal energy is released during the gasification process and stored for cooling the refrigerated space on the truck. Due to the non-continuous operation of the truck, fluctuations in the cold supply can also be reduced when the LTES heat exchanger is utilized. For the system operation of the refrigerated truck, the LNG is stored in a tank and then released by controlling the valves. It flows into

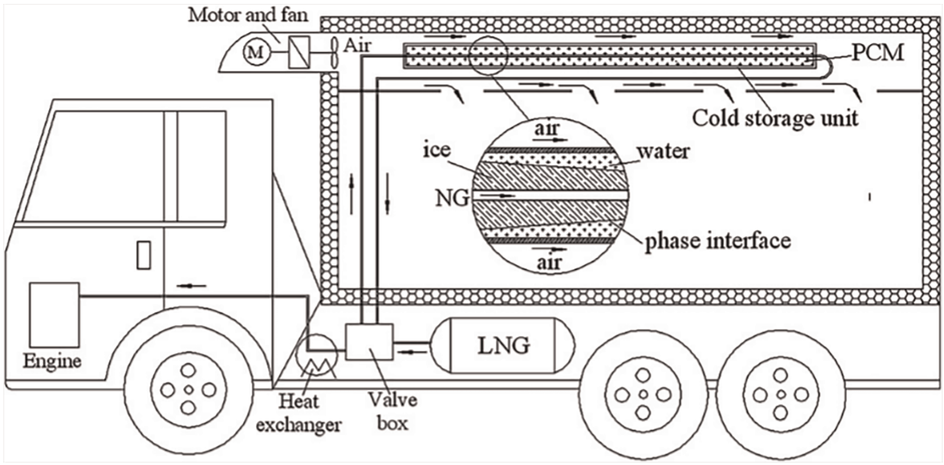

Figure 7.
Schematic diagram of LNG refrigerated truck integrated with the LTES heat exchanger [12].

the CSU to absorb heat from the encapsulated PCM. LNG changes from liquid to gas when passing through the CSU and eventually flows into the vehicle engine for combustion. Due to the low temperature of LNG, which is approximately −162°C, this type of LTES heat exchanger exhibits typical characteristics of large temperature differences and high HTF flow rates. Therefore, the triangular corrugated fins are used to improve the heat transfer process in the application case. The maximum cooling time (or the most effective use of cold thermal energy) can be reached when the aspect ratio of the triangular fins is 0.75. The economical effect can also be realized by using the LTES heat exchanger to store/release cold thermal energy compared to the traditional refrigerated truck.

5.2 The medium-temperature application

A typical scenario for applying the LTES heat exchanger with medium temperature is the heat pump system. The air source heat pump (ASHP) heating technology utilizes the heat energy in the air to provide heating and hot water for end users, which is more energy-efficient and environmentally friendly than traditional heating methods. However, the ASHPs are limited by ambient temperatures during operation, especially in cold regions, where their performance significantly decreases, thus restricting their development. To address the issue of low efficiency of ASHPs in outdoor low-temperature conditions, the LTES heat exchanger combined with solar thermal energy and the ASHP is proposed. The LTES heat exchanger has the advantages of small volume and convenient use, which makes it suitable for applications in small-scale heating scenarios, such as winter heating in rural residences. A typical proposed system can be seen in **Figure 8**. The system consists of solar collectors, hybrid thermal energy storage tanks, circulating pumps, and heat pump systems. When there is sufficient solar radiation outdoors, the thermal energy can be stored in the tank. At night, the thermal energy serves as a heat source for the heat pump, which is conducive to improving the system’s energy efficiency and reducing operating costs. The thermal energy storage tank uses RT25 paraffin as the PCM, which has the advantages of high latent heat, large energy storage density, non-toxicity, and non-corrosiveness. The heat exchanger inside the tank adopts a tube-in-tank device

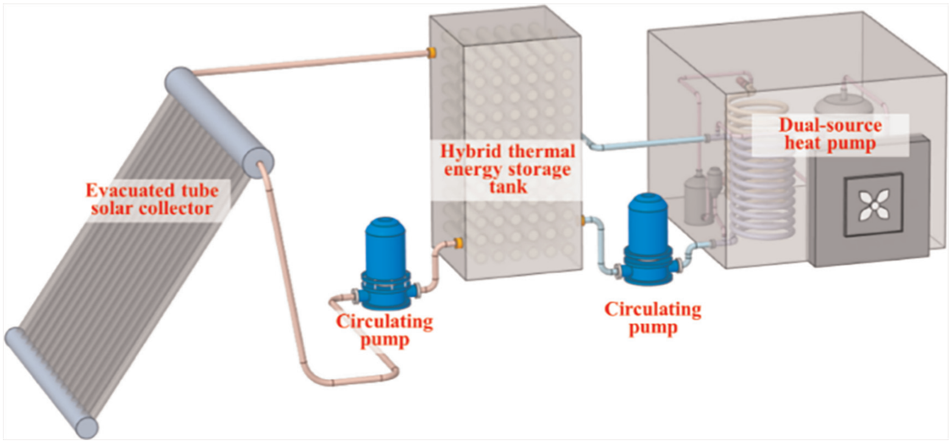

Figure 8.
System composition diagram of the LTES heat exchanger combined with solar thermal collector and ASHP [13].

type. It is estimated that, in northern China, the shortest investment payback period for this system is 5.5 years, which helps to reduce the economic costs of the heat pumps.

5.3 High-temperature applications

In the field of high-temperature thermal energy storage, the thermal storage of power systems has always been a focus of attention. In recent years, electricity production has gradually shifted from conventional thermal power plants to renewable energy sources (RESs). However, the energy generation rate of RESs is closely tied to weather conditions. Due to the high dependence of RESs on nature, the capacity rate is difficult to control. Energy storage systems (ESSs) have attracted attention as they can mitigate the instability of natural resources. In large-scale ESS applications, thermal energy storage systems are favored for their direct utilization of thermal energy. They can store excess heat energy by heating thermal storage mediums. Due to the favorable thermophysical properties such as moderate operating temperatures, high heat capacity, and chemical stability, molten salt has received widespread attention for the development of LTES heat exchangers for power systems. For example, in **Figure 9**, the molten salt TES system is developed to store high-temperature heat to achieve the purpose of power generation.

It is interesting that this device introduces bubble flow to enhance the heat transfer performance of the liquid molten salt during the charging process. The system mainly consists of molten salt tanks, electric heaters, heat transfer pipes, and an air injection system. During the energy storage process, excess electricity from the power grid is converted into heat by multiple electric heaters inside the molten salt tank. During the thermal energy release process, water is flowed into the tank through heat transfer pipes and heated to form the high-pressure steam for electricity generation via steam turbines. To enhance the heat transfer process, multiple serpentine heat transfer pipe bundles are installed inside the storage tank to ensure higher heat transfer rates during the storage and release processes. Additionally, the air injection system serves to further enhance heat exchange by inducing movement of the molten salt around the heat transfer pipes, transitioning the heat transfer mechanism from natural convection to forced convection. This greatly improves the efficiency of the TES system.

Figure 9.
Operation of the molten salt energy storage system: (a) static melting; (b) melting with air injection [14].

Therefore, the more efficient high-temperature LTES heat exchanger can effectively alleviate the imbalance between energy supply from the grid and user demand.

6. Conclusions

The LTES heat exchangers provide important advantages in green and sustainable improvement of traditional thermal energy systems by directly storing and releasing thermal energy. The main conclusions of this chapter are summarized below.

In terms of material selections, the basic requirements imposed upon PCMs have been formulated. Due to the diversity of specific applications and the unique characteristics of different types of materials, a large number of materials have been developed. The key properties, including thermal conductivity, PCT, latent heat, and cycling performance, have been extensively tested and validated. However, development and production of commercial materials for LTES heat exchangers are more labor-consuming and long-term processes that demand the attraction of board circles of scientists and experts of various specialties.

In terms of device types, improvements have been made to the HTI, resulting in rich forms of basic structures and improvements. Due to the low heat conductivity of PCMs, surface area density, which is used to present the accessibility of the PCM and the HTF, appears to be an important indicator of structural improvement parameters. In order to improve this parameter, microencapsulation, stable shaping method, and direct contact method are gradually receiving more attention. However, these studies also face important challenges that require further research, mainly focusing on multicycle penetration pollution, flow control, and durability of the heat exchanger.

In terms of LTES heat exchanger design, simulation methods from steady-state to dynamic and from one-dimensional to three-dimensional have been developed. There is also mature commercial software available for querying the physical properties of PCMs. However, it still lacks integrated design software for simulation models and physical properties simultaneously, which is mainly required to solve the integration problem of material property queries and also support calculation methods.

In terms of LTES heat exchanger applications, they already have a variety of applications for passive and active heating/cooling scenarios as a component or integrated part of cascaded thermal energy storage systems. More developments and studies about LTES heat exchangers have undoubtedly been directed to low-temperature applications such as district heating/cooling and drying processes. Meanwhile, a detailed investigation is necessary into other applications for high-temperature occasions that can enhance the thermal properties and suppress the supercooling characteristics of PCMs. To sum up, the LTES heat exchangers have been successfully applied in fields such as air conditioning, heat pumps, heating, cold chain, solar power generation, electronic component cooling, and aerospace. It is expected that this type of heat exchanger will gradually attain wider market penetration due to environmental requirements and renewable energy applications.

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Conflict of interest

The authors declare no conflict of interest.

Notes/thanks/other declarations

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References

[1] Nejat P, Jomehzadeh F, Taheri MM, et al. A global review of energy consumption, CO_2 emissions and policy in the residential sector (with an overview of the top ten CO_2 emitting countries). Renewable and Sustainable Energy Reviews. 2015;**43**:843-862. DOI: 10.1016/j.rser.2014.11.066

[2] Hua WS, Lv X, Zhang XL, Ji Z, et al. Research progress of seasonal thermal energy storage technology based on supercooled phase change materials. Journal of Energy Storage. 2023;**67**: 107378. DOI: 10.1016/j.est.2023.107378

[3] Magendran SS, Khan FSA, Mubarak NM, et al. Synthesis of organic phase change materials (PCM) for energy storage applications: A review. Nano-Structures & Nano-Objects. 2019; **20**:100399. DOI: 10.1016/j. nanoso.2019.100399

[4] Palacios A, Navarro-Rivero ME, Zou B, et al. Ding a perspective on phase change material encapsulation: Guidance for encapsulation design methodology from low to high-temperature thermal energy storage applications. Journal of Energy Storage. 2023;**72**:108597. DOI: 10.1016/j.est.2023.108597

[5] Mousa MH, Yang CM, Nawaz K, Miljkovic N. Review of heat transfer enhancement techniques in two-phase flows for highly efficient and sustainable cooling. Renewable and Sustainable Energy Reviews. 2022;**155**:111896. DOI: 10.1016/j.rser.2021.111896

[6] Li NQ, Wang JH, Klemeˇs JJ, et al. A target-evaluation method for heat exchanger network optimisation with heat transfer enhancement. Energy Conversion and Management. 2021;**238**: 114154. DOI: 10.1016/j.enconman. 2021.114154

[7] Yang L, Villalobos U, Akhmetov B, Gil A, Khor JO, Palacios A, et al. A comprehensive review on sub-zero temperature cold thermal energy storage materials, technologies, and applications: State of the art and recent developments. Applied Energy. 2021;**288**:116555. DOI: 10.1016/j.apenergy.2021.116555

[8] Tian S, Yang QF, Hui N, et al. Discharging process and performance of a portable cold thermal energy storage panel driven by embedded heat pipes. Energy. 2020;**205**:117987. DOI: 10.1016/ j.energy.2020.117987

[9] Tian S, Ma JH, Shao SQ, et al. Experimental and analytical study on continuous frozen/melting processes of latent thermal energy storage driven by bubble flow. Energy. 2024;**290**: 130244. DOI: 10.1016/j.energy. 2024.130244

[10] Arıcı M, Tütüncü E, Yıldız Ç, et al. Enhancement of PCM melting rate via internal fin and nanoparticles. International Journal of Heat and Mass Transfer. 2020;**156**:119845. DOI: 10.1016/j.ijheatmasstransfer. 2020.119845

[11] Faden M, König-Haagen A, Höhlein S, et al. An implicit algorithm for melting and settling of phase change material inside macrocapsules. International Journal of Heat and Mass Transfer. 2018;**117**:757-767. DOI: 10.1016/j.ijheatmasstransfer. 2017.10.033

[12] Tan HB, Li YZ, Tuo HF, et al. Experimental study on liquid/solid phase change for cold energy storage of liquefied natural gas (LNG) refrigerated vehicle. Energy. 2010;**35**:1927-1935. DOI: 10.1016/j.energy.2010.01.006

[13] Zhang SL, Liu SL, Wang JH, Li YL, et al. Analysis of a solar-assisted heat pump system with hybrid energy storage for space heating. Applied Thermal Engineering. 2023;**231**:120884. DOI: 10.1016/j.applthermaleng.2023.120884

[14] Che S, Kim J, Jeon J, et al. Thermodynamic analysis of molten salt-based single-tank thermal energy storage system with heat transfer enhanced by gas injection. Journal of Energy Storage. 2024;**77**:109959. DOI: 10.1016/j.est.2023.109959