Review of latent thermal-energy storage systems for solar air-conditioning systems

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Abstract

Solar air-conditioning is an important approach to satisfy the high demand for cooling given the global energy situation. The application of phase-change materials (PCMs) in a thermal storage system is a way to address temporary power problems of solar air-conditioning systems. This paper reviews the selection, strengthening, and application of PCMs and containers in latent thermal storage system for solar air-conditioning systems. The optimization of PCM container geometry is summarized and analyzed. The hybrid enhancement methods for PCMs and containers, and the cost assessment of latent thermal storage system are discussed. The more effective heat transfer enhancement using PCMs was found to mainly involve micro-nano additives. Combinations of fins and nanoadditives, nanoparticles and metal foam are the main hybrid strengthening method. However, the thermal storage effect of hybrid strengthening is not necessarily better than single strengthening. At the same time, the latent thermal storage unit has less application in the field of solar air-conditioning systems, especially regarding heat recovery, because of its cost and thermal storage time. The integration of latent thermal storage units and solar air-conditioning components, economic analysis of improvement technology, and quantitative studies on hybrid improvement are potential research directions in the future.

Keywords: Solar air-conditioning; Phase-change material; Hybrid enhancement; Latent thermal storage.

1. Introduction

The global energy situation is an important problem, and a global solution is needed to solve this problem. The combination of a highly stressed environment with a shortage of fossil fuel and climate change suggests a rapid transition towards a more sustainable energy infrastructure. Several countries, including the United States [1], Indonesia [2], and China [3] encourage the use of renewable energy and energy conservation methods. Financial subsidies are [4-7] offered to encourage both corporations and end-users to choose renewable energy options. Figure 1 shows that the installed renewable energy capacity in China [8] has increased, mainly owing to new public policies. The installed solar energy capacity grew fastest from 2009 to 2016. In 2016, the installed solar-power capacity was 76.31 million kW, ~81% higher than the previous year. Solar energy has a great long-term potential among renewable energy resources.

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For the cooling applications, the development of solar energy as a renewable energy has recently received unprecedented attention [9-11]. Solar cooling has great potential because of the high global need, environmental and energy saving benefits, and typically high availability of sunlight when cooling is needed. In essence, solar air-conditioning systems (SACSs) use solar energy instead of conventional energy to supply heat for a conventional cooling cycle. The key technology of SACS is not solar energy but the air-conditioning system itself. Air-conditioning systems capable of utilizing low-grade heat energy such as absorption, adsorption, and ejection systems have been known before the 1930s [12]. However, these cooling systems were of limited practical use because of their high cost and low efficiency when electricity-driven steam compression refrigeration systems became available [13]. After the 1970s, the energy crisis facilitated the development of SACS, especially the absorption refrigeration technology [14]. Current techniques that use solar energy for cooling are illustrated in Figure 2. SACSs are typically based on photoelectric conversion or photothermal conversion. Air-conditioning, refrigeration and other cooling demands can be performed using different SACS types, such adsorption, absorption, and ejection. Today, solar absorption cooling technology has reached the stage of large-scale industrial production. It is the best-developed form of SACS, followed by adsorption cooling [15]. Asia became the largest market for thermally driven chillers, thanks to the installation of large-scale solar-energy-driven cooling systems in India and China [16]. Solar thermal-cooling systems are already used by thousands of residential and commercial users.

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Although solar air-conditioning has become an established industry, the intermittent nature of solar energy still restricts its performance and reliability [17]. The energy-storage system, perhaps the most important component in a SACS, helps mitigate the temporal or local differences between solar energy supply and demand. Therefore, theoretical and experimental studies on energy storage have a great impact on the development of SACSs. Energy storage for SACS has two purposes: (1) Heat storage - storing the excess heat absorbed from solar collectors and recovered heat losses from other systems. (2) Cold storage - accumulate the extra cooling capacity stored by chillers (cold storage use). Most energy storage systems usually use water as the storage medium, i.e., these devices are large and heavy, making them unsuitable for many applications. Phase-change materials (PCMs) can help break though the current limitations of SACS, because of their high storage capacity and an almost constant operating temperature. Therefore, PCMs are widely used in solar energy storage system, especially in the shell of solar buildings [18-20], solar water collector [21, 22], and HVAC systems [23].

Studies on latent thermal-energy storage mainly focus on the mining and preparation of PCMs with excellent storage and improved heat transfer properties [24-26]. Some comprehensive reviews are available on the application of PCMs for heating, ventilation, and air-conditioning systems. Abduljalil et al. [27] reviewed the use of PCMs in air-conditioning systems. The article systematically summarized the applicable PCM in air conditioning system. The influence of the internal structure of PCM container on the heat storage efficiency was summarized. The influence of the geometric parameters of the PCM container was neglected. Li et al. [28] summarized the available cold storage materials for air conditioning and focused on the use of phase-change slurry. Zhai et al. [29] discussed PCMs for cold storage in air-conditioning systems, especially composite PCMs. Pintaldi et al. [30] reviewed appropriate PCMs and design schemes for use in SACSs. The paper focused on LTESSs in the high temperature (>100 °C) cooling systems. Khan et al. [31] reported latent thermal storage methods for solar absorption air-conditioning systems and concentrated mainly on the PCMs used in single-effect absorption air-conditioning systems. Omara and Abelnour [32] introduced different methods for integrating PCMs into air-conditioning systems. In addition, the application of PCMs in improving energy saving of air-conditioning systems is discussed. The review focuses more on the effect and improvement of the PCM side on the latent thermal storage performance of air-conditioning systems and less on the PCM container side. However, the abovementioned studies are neither systematic nor sufficiently comprehensive, and include overlaps. These reviews do not simultaneously summarize the studies on cold and heat storage in SACSs, which is needed to discuss the diversity of latent thermal energy storage system (LTESS) designs for different application scenarios. Moreover, most studies emphasized the role of PCM in the latent thermal storage unit, but ignored the PCM container.

This paper aims to review the enhancement methods and current status of available PCMs and their containers from the heat (including thermal power and heat recovery storage) and cold applications of LTESSs in SACSs. The aspects emphasized in this review are described as follows:

- Material selection and performance optimization of PCM and its container

- Economic evaluation of enhanced technology and LTESSs.

The outline of this paper is as follows:

1. Section 1 briefly summarizes the contributions and limitations of other reviews on LTESSs in SACSs.
2. Section 2 presents applicable PCMs, and their selection methods and improvement strategies.
3. Section 3 describes the categories, key design considerations, and enhancement strategies of latent thermal storage containers.
4. Section 4 discusses the use of LTESSs in SACSs with respect to heat and cold storage.
5. Section 5 discusses the hybrid enhancement of PCM and its containers, and the economic evaluation of LTESSs in SACSs.
6. Finally, Section 6 reports the main findings of this paper and suggestions for future research.

2. PCMs for solar air-conditioning systems

PCMs used in SACSs have the potential to store energy during off-peak periods and reuse the energy during the peak times, thus reducing and transferring peak loads [33]. PCMs have been used for thermal storage since the 1880s [34]. Since then, most studies focused on finding PCMs with improved properties [35]. In this chapter, the selection method and improvement for PCMs in SACS are reviewed.

2.1 Applicable PCMs in LTESSs of SACSs

Solid–liquid PCMs are widely used in SACS owing to their low phase transition temperature and small volume change. Solid–liquid PCMs can be further divided into organic, inorganic, and eutectic PCMs, as shown in Figure 3. Their properties are shown in Table 1. The ideal PCMs for SACS should have the properties shown in Table 2. Unfortunately, very few PCMs satisfy all the requirements. Therefore, it is necessary to find the best suitable PCMs considering the requirements of the specific system. This selection process forms the core of effective LTESS design. In general, the PCM is mainly selected based on the required melting temperature range. Table 3 shows the suitable temperatures for cold and heat storage levels in SACSs. However, it is not sufficient to determine the PCM only based on the melting temperature. Thermal conductivity and specific heat are considered to ensure a high storage density and high efficiency of the system [27]. The volume change rate of PCM should also be considered to optimize the system design [28, 31]. Table 4 shows the PCMs considered for use in the LTESS field in SACSs.

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2.2 Selection methods

The traditional selection method involves the use of charts to compare and select the thermophysical data obtained from a literature search. However, this method has many disadvantages. Because a large number of PCMs are available or under development for SACSs, it is difficult to find the best suitable PCM. Because of the lack of suitable and complete thermophysical data, manual selection makes the process time-consuming, difficult, and error-prone. In contrast, the selection can be more comprehensive, user-friendly, faster, and accurate by using a database [58]. A database also makes it easier to find and evaluate materials with similar properties that can also be considered for the task.

Material databases can be divided into offline and online databases. In the 1970s and 1980s [59], storage media mainly consisted of CD-ROMs when computers were used. Hence, numerical offline databases such as Mat. DB and CMS systems were common at that time [60]. With the availability of internet, modern databases are mostly accessed online. The more famous commercial databases are MatWeb and NIMS. Refs [61] and [62] summarized a large number of databases that can be used to select PCMs.

However, dozens of potential materials may still be available for a given scenario. Therefore, it is necessary to rank and analyze the candidates using a consistent evaluation system. Because each candidate has several measurable indicators, this type of selection problem is more suitable for multicriteria decision-making (MCDM). MCDM is divided into multiobjective decision making (MODM) and multiattribute decision making (MADM) [62]. A popular MODM tool is the Ashby method [63]. Because of the limitation of the used principle, the Ashby method is mainly used for the preselection of PCMs [62]. Commonly used MADM methods for PCM selection include both the hierarchical analysis method (AHP) and ranking performance technique (TOPSIS) [63-67]. Xu et al. [68] found the most suitable PCM for a solar lithium bromide absorption refrigeration system using MADM in combination with AHP and TOPSIS by targeting a specific temperature range and considering the volume constraints for PCM. Yang et al. [69] introduced a comprehensive evaluation index model that uses both AHP and the entropy information method. The group also used TOPSIS to select the optimal PCM for a ground source heat pump system. The model considers the individual design and is very flexible. MCDM is an economical and convenient alternative technology to sort and filter PCMs.

Although electronic PCM material selection represents an important step forward, there is still room for improvement. First, the organization responsible for the database should update and supplement all the material data sufficiently and frequently. Second, the software should also provide information about possible material handling methods, defects, previous uses (examples), and possible future uses, in addition to basic physical properties. However, the complete collection of data depends on the software developer.

2.3 Selection of PCM strengthening methods

Most of the PCMs discussed above have some disadvantages that limit their use in SACSs, such as a low thermal conductivity and supercooling. These problems directly affect the storage and release efficiency of PCMs, thus limiting the long-term operation of the system. Therefore, a PCM should be optimized to achieve good heat storage performance. Table 5 shows some of the problems associated with PCMs and the corresponding solutions. Table 6 shows the PCM enhancement methods applied to LTESSs in SACSs. Table 6 reviews the control variables, evaluation indicators, recommended parameters, and promotion effects of the improvement methods reported in the studies.

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To improve the thermal performance of LTESSs, extensive studies have been conducted on the thermal performance enhancement technology of PCMs in the past decades [28-31]. As shown in Table 6, the heat transfer enhancement method used in PCMs is used mainly to reduce the thermal resistance of PCMs by adding high thermal conductivity materials to the PCM, such as expandable graphite [72, 93, 94], nano-scale metal [75] and metal oxide [91].

Metals are considered to be good additives in the medium-temperature PCMs owing to their high thermal conductivity. However, metals easily react with PCMs. For example, nickel is incompatible with paraffin [95]. The thermal conductivity of expanded graphite and carbon fiber exceeds most metals. At the same time, they have excellent corrosion resistance and chemical stability. Therefore, the addition of graphite and carbon fiber additives in corrosive inorganic PCMs can play a two-fold role [93]. Oya et al. [72] compared the thermal properties of erythritol with expanded graphite, spherical graphite, and nickel particles. The theoretical effective thermal conductivity of 15 wt% expanded graphite and spherical graphite increased by about 640% and 210%, respectively. The strengthening effect of 15 wt% nickel particles is close to that of spherical graphite of the same concentration. The results show that graphite additives have a higher enhancement effect on the thermal performance of PCM than metal additives. However, the manufacturing technology of graphite additives is more complex than metal particles [73]. Nanoparticles have the potential to greatly improve the thermal conductivity of PCMs. This is because the addition of solid particles enhances the thermal conductivity of PCMs. In addition, the small-size effect of nanoparticles causes microconvection between the particles and liquid. However, a high concentration (0.05 wt%) of nanoparticles will hinder the convection heat transfer in the late melting stage of PCMs [92].

In summary, in quantitative studies of high thermal conductivity additives, there is a common question worth discussing—what is the appropriate quantity? For example, the addition of a metal powder can double the thermal conductivity of PCM. However, the density of metal is large, and the more the components, the more obvious the weight gain of the container, imposing a burden on the installation of the system. At the same time, the increase in additives will also increase the cost of system. Therefore, considering the size of the system, balancing the cost and benefit of thermal storage performance brought by high thermal conductivity additives can be more effective for engineering applications of LTESSs. This study [96] demonstrated an economic analysis of improvement technologies. The author measured the cost of expanded graphite in the latent heat storage unit. The results show that the use of expanded graphite can save steel and reduce the initial investment cost by more than 20%. Future studies can measure the long-term operating benefits of PCMs with strengthening strategies based on cost.

3. PCM storage containers for SACS

Unlike conventional heat exchangers, PCM storage containers have both fluid pipes and PCMs inside, enabling thermal transfer and storage concurrently. The successful application of PCMs also depends on the development of containers. Achieving the high thermal storage efficiency on the premise of meeting the cold or heat demand is the goal of LTESS design. The thermal storage efficiency of an LTESS is related to the melting and solidification characteristics of PCM that are mainly affected by the heat transfer mechanism (conduction and/or convection) [97]. The geometrical structure and gravity effect of a PCM container will affect the heat transfer mechanism of PCM, which can be quantified from the melting time and the motion of solid–liquid interface during the phase change. Therefore, the design of a properly structured PCM container is critical for improving the thermal storage efficiency of LTESS. In addition, the thermal conductivity of material of PCM container also affects the thermal conduction of phase change. And the corrosiveness and thermal stress of the material also affect whether the conduction can operate normally at a suitable temperature. This chapter mainly introduces the classification of PCM containers, selection suggestions for their materials and geometric structures, and the thermal transfer enhancement on the container side.

3.1 Classification of containers

The type of PCM storage containers varies with the operating temperature range [98, 99]. For low- and medium-temperature solar energy utilization, PCM storage containers for SACS can be divided into bulk storage and (small volume) encapsulation storage. Bulk storage is similar to heat exchangers with respect to the structure. It can be further divided into the following: plate, multitube, concentric tube, shell-and-tube, spiral tube [100]. The aim of structural diversification is to increase the heat transfer efficiency by increasing the heat transfer area. It should also be considered that the volume change of a PCM for bulk storage causes thermal stress, causing the deformation of equipment. Encapsulation storage refers to the arrangement of encapsulated PCMs in a tank in a particular way. The PCMs are encapsulated using hydrophilic polymer capsules as shell-covered core [101]. Encapsulated PCMs are generally used for microencapsulation and nanoencapsulation with diameters smaller than 1 cm and 1 mm, respectively [102]. The methods to form encapsulated PCMs vary depending on the material wrapped. Emulsion, *in-situ* polymerization, interfacial polymerization, electroplating, sol–gel processing, and mechanical packaging methods can be used for both inorganic and organic PCMs [103]. In addition, organic PCMs are suitable for the encapsulation of suspension polymerization, dispersion, coacervation, supercritical CO, spray drying, electrostatic encapsulation, and the one-step method [104]. Encapsulation storage can also enhance the thermal performance of PCMs. It can produce a larger heat transfer surface and solve the volume–stress problem of PCMs; however, it is expensive [102].

3.2 Container design considerations

3.2.1 Materials

Similar to the ideal properties of PCM, PCM storage containers have been suggested to have the following desirable properties [105]: 1) compatibility with the PCM in bulk, 2) high stability, 3) high strength, 4) high-temperature resistance, 5) sufficient flexibility to resist thermal stress caused by volume expansion, and 6) low cost.

In practice, it is difficult to find materials that can fully satisfy all the requirements. Moreover, container materials are typically selected after the PCM is selected. Only a small number of containers are usually compatible with a specific PCM. The selection of final container material should be considered in both system requirements and costs. The typical selection process relies on the experience of experts and opinions about past applications, making the process very subjective.

For bulk storage, metal is the most common container material. Research groups led by Cabeza [106], Farrell [107], and Moreno [108] investigated the compatibility of PCMs with steel, stainless steel, aluminum, brass, and copper in the short to long term. Current studies indicate that stainless steel is suitable and recommended for all studied PCMs [109]. Regular steel shows good compatibility only for specific salt mixtures such as $NaCl$-$NaNO_3$ [109]. Steel shows varying degrees of corrosion when exposed to other salt mixtures such as $ZN(NO_3)_2 \cdot 6(H_2O)$, $LiCl$-$LiNO_3$-$NaNO_3$, and KCl-$LiCl$ [110]. Therefore, regular steel is generally not recommended as a PCM container material [82]. Covering hydrated salts with aluminum can cause severe corrosion. Although aluminum soaked in fatty acids shows signs of corrosion, it does not destroy the sealing structure [111]. Therefore, aluminum can be a suitable container for PCMs. Copper and brass are suitable container materials for paraffin wax, but the encapsulation of fatty acids and hydrates requires anticorrosive treatment [107, 111]. In addition, nonmetallic materials have been developed; they are not corrosive but flexible. These materials are mainly plastics [112] such as acrylic and high-density polyethylene [113, 114].

The most commonly used capsule materials for microencapsulation and nanoencapsulation are organic polymers such as melamine–formaldehyde resins [115, 116], urea formaldehyde resin [117], phenolic resin [118], polystyrene [119], and arabic gum [120]. The mechanical strength of organic shell increases the structural stability of microcapsule system. However, its low thermal conductivity, toxicity, and flammability lead to a hysteresis for the thermal response and heat transfer. This limits the use of microcapsules with organic shells [121]. Inorganic materials for capsule walls include $CaCO_3$ [122, 123], SiO_2 [1124, 125], TiO_2 [126, 127], and ZnO [128]. Silicon is often used for the inorganic shell of microcapsules. However, because of the diffusion and decomposition of PCMs at high temperatures, the poor mechanical strength of silicon shell often leads to the cracking of microcapsule [125]. Therefore, inorganic materials with a high mechanical strength, a high thermal conductivity, and low cost are typically used for capsules. Examples include $CaCO_3$ and SiO_2-TiO_2 [129]. Because of the complementary advantages of inorganic materials and organic macromolecules, a suitable combination of organic and inorganic materials could be the future trend for encapsulation.

3.2.2 Geometric parameters

(1) Bulk storage

Both size and shape, i.e., geometric parameters, of latent thermal storage containers (LTSCs) considerably affect the heat transfer mechanism and melting behavior of PCMs [130, 131]. Current commonly used PCM container shapes are rectangular enclosures [132, 133], circular cylinders [134], and annular cavities [135, 136]. Zivkovic and Fujii [137] proposed a computational model for analyzing the isothermal phase transformation of PCMs encapsulated in a single container. The model neglects the conduction inside the PCM in the direction of heat transfer fluid (HTF) flow, thermal resistance of container wall, and effect of convection. They also compared the heat transfer properties of rectangular and cylindrical LTSCs through the model. The results show that the melting time of a PCM in a rectangular vessel is almost half of that in a cylindrical vessel, given both have the same initial volume and heat transfer area, i.e., a rectangular container is more beneficial for achieving a high thermal storage efficiency of LTESS. However, this conclusion only applies to the case where the system uses a flat thin-walled container. However, because a rectangular container has a melting dead angle in the late stage of PCM melting, it has been proposed to transform the rectangular shape into a wedge shape. Through enthalpy–porosity model simulation, the wedge scheme can effectively improve the vertical temperature distribution and enhance the convective heat transfer in the container in the late melting stage of PCM, reflected in the increase of instantaneous Nusselt number [138]. The heat storage time is shortened by more than 20% compared to the rectangular unit with the same heat source area. Hou et al. [139] experimentally analyzed the thermal storage performance of cylindrical and annular containers. When filled with the same mass of sodium acetate trihydrate, the thermal storage time of the annular type is 61.8% shorter than that of the cylindrical type. This is because the annular container has a larger surface area and faster heat transfer rate than the cylindrical container. To make the convective heat transfer dominant in the late stage of melting, an inverted cone scheme is used for the modification of cylindrical units. In the melting stage, the inverted cone unit can accumulate a large amount of PCM liquid at the top, thus forming a stronger natural convection than the cylindrical unit. This accelerates the melting rate and thus also accelerates the energy storage of the system. The experimental study by Seddegh et al. [140] found that the inverted cone unit can store 10% more energy during charging than the cylinder unit.

PCM melting in a finite closed container involves contact with the heat source at the initial melting stage and is generally dominated by heat conduction. In the later stage, with the melting proceeding, the amount of liquid phase gradually increases, and the difference in solid–liquid density enhances the liquid buoyancy lift, thus increasing the effect of natural convection. Therefore, many dimensionless numbers such as Nusselt number (Nu), Grashof number (Gr), Rayleigh number (Ra), and Prandtl Number (Pr) related to natural convection have been introduced to study the PCM melting characteristics in containers of different structures and geometries. For rectangular containers with a single-sided fixed heat source area, a lower aspect ratio (ratio of fixed width to variable height) has a positive effect on the heat storage efficiency of system. This is because on one hand, the amount of PCM present in the device decreases as the aspect ratio decreases, and the heat storage time is naturally shortened. On the other hand, the average Nusselt number in the container increases with the decrease in aspect ratio, and the natural convection is strengthened, accelerating the melting rate of solid phase [138]. However, the contribution of reducing the aspect ratio to the heat storage efficiency of system is limited. Hu et al. [141] calculated the limit of aspect ratio of a rectangular container filled with *n*-octadecane to be 1/8 from the enthalpy model. When the value is lower than the limit, the heat storage time remains fixed. For the wedge unit, the geometric factor that mainly affects the heat storage efficiency is the ratio of upper and lower sides. Because of the sharp angle of wedge shape, an excess large ratio of the upper and lower sides will form a more severe melting dead zone. Therefore, an optimum ratio exists for the upper and lower sides of wedge unit. Hu et al. [142] simulated the melting of octadecane in a wedge container through enthalpy–porosity method. The results confirmed that the optimum ratio of side length is between 5 and 6; therefore, 5.5 is recommended as the design reference for the aspect ratio of wedge unit. The melting of PCM in a cylindrical container is similar to that in a rectangular container. Similarly, the geometric factor affecting the heat storage efficiency of a cylindrical phase change unit is the ratio of the bottom diameter to the cylinder height. For the same reason, reducing the aspect ratio of a cylinder is beneficial for increasing the melting rate and decreasing the charging time [131, 143, 144]. In the annular unit, eccentricity is an important geometric factor. Because of eccentric setting, the upper space of unit increases, allowing more PCM to be located in the area where natural convection can work, and the natural convection is stronger. Therefore, this has a positive effect on improving the melting rate and reducing the related charging time. Because of natural convection, the melting rate of PCMs in an eccentric annular vessel is faster than that in a concentric annular vessel [136,145-147]. Hu et al. [148] studied the heat transfer of lauric acid in an eccentric annular unit with a characteristic size of 20 mm. The range of studied eccentricity varied from 3 mm to 8.5 mm. The group found that 7–8 mm is the optimal eccentricity.

(2) Encapsulation storage for a small volume

Apart from the well-known spherical shape, capsules can be cylindrical, tubes, or plates [149]. A sphere can form strong natural convection and heat storage and release efficiency owing to its simple structure and large ratio of volume to surface area [150]. Therefore, a spherical shape is the common shape for encapsulation [151]. However, parameters such as particle size, core–shell ratio, and shell thickness directly affect the durability and thermal performance of capsules [101, 152, 153]. Hence, they are important design factors for capsules. A general valid guideline is that the smaller the particle size of microcapsules, the better the structural stability and thermal performance of a heat storage system. This is because the melt fraction in a small capsule is high, resulting in a smaller thickness of melt layer near the capsule wall. This leads to a smaller thermal resistance in the capsule. On the other hand, it also provides a larger surface area of contact between the PCM and capsule wall. Because of a short heat transfer path, when the capsule radius is small, the energy is charged at a higher rate [154]. Wei et al. [151] studied the thermal properties of stainless steel–paraffin microcapsules with four different diameters (2.0, 3.0, 4.0, and 5.0 mm). The results show that the exothermic time decreases with decreasing particle size. Alvarado et al. [155] recommended that the diameter of microcapsule PCM (mPCM) should be 2–10 μm to ensure durability and high mechanical strength. However, the diameter of mPCM should not be too small, as this can cause supercooling [156, 157]. In addition, with the buildup of smaller-diameter capsules in the tank, the flow resistance increases substantially. Consequently, the turbulence and momentum transfer are suppressed, resulting in reduced heat transfer efficiency. Based on these results, it becomes clear that smaller-diameter sizes are preferred. However, it is necessary to add nucleating agents or to optimize both the shell composition and structure of mPCMs to avoid supercooling. Refs [104, 158] provide more detailed reviews of design parameter studies on encapsulated PCMs.

In summary, a rectangular container is still the preferred container for bulk storage because of its high efficiency and simple manufacturing process. Some of the improved schemes involving rectangular and cylindrical containers such as wedge and conical units have improved the heat storage efficiency by more than 10%. However, economic analysis of these schemes is lacking, and it is difficult to determine the size of an appropriate system for these schemes. Furthermore, the datasets of container materials should be collected and organized similar to the PCM database because of the large number of container materials and related design parameters. The recommended container materials should be provided directly on the PCM selection page. PCMs and their container materials can be thoroughly evaluated using a specialized software, benefitting the design optimization for LTESSs of SACSs. According to the literatures mentioned above, it is clear that environmental friendliness is rarely considered in studies of container material selection, which is a different process than PCM selection. Eco-friendly PCMs from natural sources such as coconut oil are rarely used and developed for SACSs. PCMs or containers derived from bio-originated materials still have a high potential for improvement and new discoveries.

In addition, it is concluded from the abovementioned studies that the optimization of geometric factors and container shapes involves improving the heat transfer mechanism of PCMs (heat conduction in the early stage of melting and convective heat transfer in the later melting stage). Therefore, enhancing natural convection or contact area is a key breakthrough point in developing new configurations and designing the geometric parameters of containers. Furthermore, the heat transfer mechanism within the container can be described by flow-related dimensionless numbers such as Nu and Ra; the geometry of container can be optimized for enhancing the heat transfer mechanism. Therefore, in the future studies on PCM container optimization, the dimensionless number related to the heat transfer mechanism can be used to establish the relationship between the structure and geometrical factors of container to achieve the design and selection of PCM containers, instead of a large number of simulation work.

3.2.3 Effect of container design considerations on the performance of PCM integrated solar air conditioning system

From the above descriptions in Sections 3.2.1 and 3.2.2, it can be seen that most studies have contributed to the promotion of heat storage efficiency by design optimization of PCM containers. And these studies mainly focus on experimental and simulation studies of the thermal characteristics of single thermal storage unit. Relatively speaking, there are few studies on the system performance evaluation of LTESSs of SACSs by geometrical optimization of PCM containers. In the field of simulation research, Noro et al. [159] used TRNSYS software to simulate the annual energy performance of solar single-effect absorption refrigeration systems with latent cold and heat storage (heating season: November 1st - April 15th; cooling season: June 1st - September 15th). The system was located in a three-story building of 230 m^2 in Rome. The study evaluated energy efficiency of the whole SACS for different container capacities (500-1000, 1000-2000, 2000-3000 L). And fossil primary energy consumption (FPEC), primary energy saving (PES) and solar ratio (SR) were used as the evaluation index of the system. Obviously, the whole system is expected to consume the lowest fossil energy and be able to store more solar energy to satisfy the demands of heat storage and cold storage. Therefore, in order to obtain the PCM container capacity with the optimal system energy efficiency, the lowest FPEC, the highest PES, and the highest SR are expected. In the simulation results, the PCM container capacity of the 2000-3000 L was the best; it shows that increasing container capacity has a positive effect. The study found that the design of the PCM container plays an important role in system performance, but only simply compared the difference of energy benefits brought by storage capacity. Pintaldi et al. [160] simulated the annual system performance of a solar three-effect absorption refrigeration system with consideration of geometric parameters in the container and collector design. The collector area (1-4 m^2/ kW) and heat storage time (30 minutes, 1, 3, and 5 h) were considered as the representational parameters. Heat storage time was used to calculate the diameter and height of the PCM container, and the number, diameter and length of inner tube. Basically, the smaller the storage time represents the smaller the container size. The pros and cons of the system are mainly evaluated based on SR, heat loss and energy storage efficiency. The results show that short storage time (0.5 h) can lead to a high storage efficiency (more than 98%) because of the low heat loss. But at this time, the storage efficiency hardly changed with the increase of the collector area. At a high storage time (5 h), the storage efficiency was increased by nearly 1% with the increase of the collector area. All combinations of collector area and storage time can enable the system to achieve a SR of more than 0.5. And with the increase of collector area and storage time, the SR also increased, the highest value was nearly 0.94 when the collector area and heat storage time were 4 m^2/ kW and 5 h.

In addition, a few scholars tested the performance of thermal storage equipment by setting up an experimental platform of SACSs. In a series of studies by Zhai et al., [26, 161] a mathematical model of the charge/discharge process of the cold-storage capsule unit was established, and the system performance with the appropriate cold storage unit parameters was evaluated by the experimental platform of a solar adsorption air-conditioning system. At first, the authors established the equation for the phase change heat transfer process of the cold-storage capsule unit by the enthalpy method. The influence of the capsule wall material, thickness, and diameter of a cold storage unit on the cold storage capacity and the cold storage rate was theoretically analyzed by the equation. The results show that the cold storage capacity and cold storage time increase with the increase of the capsule diameter. A capsule wall material with a thermal conductivity higher than or closer to the PCM was suitable for engineering applications. In addition, under the same thermal conductivity of capsule wall, the cold storage time increased linearly with the increase of the wall thickness. Based on theoretical calculations results, the cold storage capsule with polyethylene shell, a wall thickness of 2.5 mm, and an outer diameter of 35 mm and 70 mm were combined and arranged in a cylindrical bulk container. The day test was conducted during the summer in Shanghai. It is worth noting that the main concerns of the experiment were the charge/discharge capacity and the thermal comfort of the user side during the discharge process. The experimental results show that the charge capacity was 1016.1 kJ, the discharge capacity was 942.8 kJ, and the cold loss was 7.11%. In addition, the average indoor temperature during the system discharge process was 26.2 °C.

In summary, it can be seen that only the optimal container parameters in the theoretical analysis can be verified in the experimental study, because of the long test cycle and high cost. Compared to experimental studies, simulation studies are worthy of advocacy. Because it can reliably compare the whole system operation and energy performance through geometric parameters and internal layout in the early stage of container design. However, most of the simulation studies in the field of SACS have mainly used PCM capacity instead of complex container parameters to analyze its impact on system energy efficiency. It cannot show the relative importance of the wide range of container design parameters to system performance. In addition, the comprehensive evaluation through SR and energy storage efficiency can select the appropriate single factor domain in the PCM container design, but it is difficult to obtain the optimal value under multiple design factors. From this perspective, we propose to introduce genetic algorithm, particle swarm optimization and other multi-objective optimization methods in the PCM container design of SACSs. These algorithms have not been fully developed yet in the field of LTESSs of SACSs, but they have been successfully applied in the PCM container design of solar household hot water systems [22, 162, 163] and industrial water waste heat recovery systems [164].

3.3 Selection of enhancement methods for containers

Each container has a unique structure and requires a different optimization method. Table 7 shows the corresponding strengthening techniques and specific selection criteria for different containers in reported studies.

Place Table 7 here

3.3.1 Adding fins on the container side

To enhance the heat transfer for bulk storage, fins can be added to increase the heat transfer area. The use of fins in thermal storage device design is very common [184, 185]. This is probably because the technology needed to configure fins is simple and easy to implement. Common types of fins are longitudinal/rectangular [186], circular/annular [187], and plate fins [188]. Among these fins, rectangular fins are used the most owing to easy fabrication and efficient heat transfer. Agyenim et al. [189] compared the thermal performance of horizontal concentric tube storage devices with three different structures (finless, circular fins, and longitudinal fins). The results show that storage efficiency of total amount charged of longitudinal fins was 70.9%, 9-20% higher than the other two structures. Thus, longitudinal fins perform the best. Zhai et al. [190] developed a refrigeration unit for high-temperature solar cooling systems. The effects of structural parameters such as spacing and the number and height of rectangular and circular fins on the cold storage performance were studied experimentally and numerically. The results show that compared with the finless unit, the phase transition time for a rectangular fin unit is reduced by 58.2%, 2 times higher than that for an annular fin unit. With respect to fin design, three structural parameters are important: width, spacing, and thickness [191]. Increasing fin thickness and width or decreasing fin spacing significantly shortens the phase transition time [192]. In addition, fins should be made of highly conductive metals to ensure good heat transfer.

3.3.2. Improving the internal structure

LTSCs could gain more thermal performance benefits than fins by improving the internal structure [193]; for example, the internal structure of LTSCs can be enhanced via the flow direction and arrangement of PCMs and inner tubes. In multitube LTSCs, increasing the number of inner tubes can effectively increase the efficiency of heat storage. Mehdi et al. [194] studied the influence of number of inner tubes on the melting and solidification rate of RT35. A higher number of internal tubes shortens the phase transition time. The melting time of LTESS with four internal tubes was 41% shorter than that for one internal tube. In addition, the right arrangement of inner tubes can also facilitate heat transfer, even with a few inner tubes. Pourakabar and Darzi [195] studied the influence of inner tube arrangement on the phase change rate of LTESSs. The results show that the melting and solidification rates for vertical two-tube arrangement in the ellipse container are similar to those for four-tube diamond arrangement. In LTSC, the flow direction of working fluid is divided into parallel flow, crossflow, and counterflow. Generally, the use of counterflow devices can produce a better heat transfer. Belusko et al. [193] compared the thermal performance of parallel flow and counterflow in LTSCs. They found that the heat transfer was better for a countercurrent device. The volume of redundant PCMs in LTSCs with a parallel flow device is almost four times that with a countercurrent device. This significantly affects the cost of thermal storage system.

The layout of PCMs in containers is also a common method to improve heat transfer. Lafri et al. [196] experimentally optimized the position of PCMs in a tank. They designed two different structures for their study. Structure A integrated paraffin wax directly into the side of the tank, whereas structure B had paraffin wax in the center of the tank. It was found that the melting time of PCM with structure A was almost twice as long as that for structure B. Similarly, when the capsule was placed in a cylindrical container tank, the number of layers and the number of capsules per layer severely affect the heat transfer [29]. Heat transfer can also be enhanced using a combination of different PCMs with different melting points. Yang et al. [183] designed a LTESS containing a spherical capsule packed bed with three types of PCMs. They conducted a numerical study on the thermal storage performance and compared the results with traditional single-type LTESSs. The results indicate that the designed system has a 65% exergy efficiency, which can be higher than that of single-type in theory.

3.3.3 Modification of capsule material

The capsule material can also be modified to improve the heat transfer. All capsule materials suffer from a low thermal conductivity, especially organic capsule materials. To solve this problem, some researchers added metal coatings [197], expanded graphite [198, 199], graphene oxide [200, 201], and nanotubes [182] to the capsules. Compared to ordinary mPCM with the same concentration, the heat transfer coefficient of mPCM slurry with a metal coating increased by more than 10 % [170]. Moreover, the thermal conductivity increased with increasing metal coating coverage until the capsule was fully covered [179]. Wang et al. [180] added 10% and 20% expanded graphite to the shell of a melamine–formaldehyde resin; the thermal conductivity of microcapsules increased 10 times and 22 times, respectively. Wang et al. [181] also increased the thermal conductivity of microcapsules by adding graphene oxide to the silica shell. The experimental results express that the thermal conductivity of microcapsules with 1wt% graphene increased by 193%, compared with the ordinary silica shell.

4 Thermal storage technologies for solar air-conditioning

4.1. Thermal storage use

4.1.1 Thermal power applications

In solar absorption and jet air-conditioning systems, LTESSs provide the heat source to heat a medium water driving regenerator and steam ejector. Poshtiri and Jafari [202] reported a PCM unit in a solar adsorption system that stores energy in the daytime to drive the adsorption cooler at night. The PCM unit stores 409 kg of fatty acid to drive the charging of 10:00-16:00 in the day and the discharging of 22:00-8:00 in the night. The study simulated 24-h solar adsorption cooling in a room of 8.0 × 8.0 × 3.125 m^3. The results show that the application of PCM reduces the nighttime auxiliary energy consumption by ~31% compared to systems without PCM. However, even with the application of PCM, the entire solar adsorption system consumes 3.28 times more energy than a conventional split-type air-conditioning system.

In solar desiccant air-conditioning systems, LTESSs represent a heat source of regenerated air at a low solar intensity. A schematic diagram of such a system is shown in Figure 4. A PCM heat storage tank is mostly an independent unit connected with a collector system. Generally, the PCM unit serves two purposes: (1) preheating of the regenerated air before it enters the solar collector. (2) The PCM is heated by hot air that is discharged from a desiccant wheel or a solar air collector. Kabeel et al. [203] compared the energy saving performance of desiccant air-conditioning driven by pure electric heating (A type), electric heating + solar heating (B type), and electric heating + PCM + solar heating (C type). In particular, C type had the design of two serpentine loops (see Figure 4 (b)) in a paraffin-filled heat storage tank to transport the regenerated air. The PCM unit was designed to store energy from 10:00 to 17:00 the day before the workday and release energy from 10:00 to 22:00 the second day. The results show that compared to purely electrically driven type, the energy saving rate of C type is up to 75.82%, almost four times that of B type. In addition, an economic analysis of the three systems was also carried out. According to the price of Egyptian energy market, the C type has the highest total fixed cost, twice that of A type, but the total annual operating cost of C type is 626 LE, which is about a quarter of A type. This shows that the application of an PCM unit in the system can provide great energy saving potential for long-term operation. To minimize the use of municipal electricity, Ren et al. [204] integrated a solar air collector and photovoltaic collector to drive a desiccant cooling system and an auxiliary heating equipment. They also designed a PCM TES unit to satisfy the thermal demand of regenerated air, consisting of several parallel PCM boards. The group designed a bypass in the PCM unit to avoid the overheating of regenerated air (see Figure 4 (c)). The new design applied for a 66 m^2 solar-powered room was simulated with the experimental data provided by Lopez et al [205]. At regenerative temperatures of 60 °C, 65 °C, and 70 °C, the system achieved a humidity satisfaction rate of over 80%. When the regeneration temperature was 60 °C, the regeneration coefficient reached 100%. This proves the feasibility of this new system without municipal power supply. Table 8 shows the possible options for power solar air-conditioning. Table 8 also shows the operation effect of the system mentioned in the literature.

Place Figure 4 here
Place Table 8 here

Among the PCM heat storage applications, we found that most PCM tanks are connected behind solar collectors as separate units. In fact, the design principle of SACSs is to facilitate the use of simple and compact equipment to produce an economic system [209]. Therefore, PCM TES units, which can be integrated with collectors as well as adsorption units or regenerators, are valuable for both research and commercialization. Although this integrated design has attracted the attention of some researchers, it has failed to enter large-scale production. Mohammadreza et al. [206] designed an integrated component consisting of an adsorption element, a collector, a PCM regenerator, and a combined condenser/evaporator under a vacuum-containing glass case. The adsorption element is a thermochemical storage device, which achieves desorption and adsorption through a LiCl-H_2O solution. The PCM regenerator is mainly used to provide instantaneous cold and heat sources for the adsorption module. The results of both experiment and simulation indicate that this new solar adsorption air-conditioning system is feasible, and the average coefficient of performance (COP) of the system can reach 0.36 (cooling) and 0.42 (heating).

4.1.2 Heat recovery applications

An air-conditioning system produces condensed heat far greater than its cooling capacity [210]. This heat is emitted directly into the environment, thus wasting energy and producing local thermal pollution [211]. Hence, separating the heat of condenser from the refrigeration cycle of conventional air-conditioning system can extend the heat rejection of condenser to compressor downtime, thus increasing the heat transfer for the condenser and providing a lower condensation temperature [212-215]. PCMs are integrated with evaporators in solar absorption systems. This enables the use of dry cooling systems in place of a wet cooling tower. Additionally, it reduces the water consumption, decreases cleaning needs and the risk of bacterial growth, and minimizes the requirements for a cooling system. Helm et al. [39] designed a solar absorption system with a PCM unit combined with a dry cooler instead of a wet cooler. During the refrigeration operation, a portion of the waste heat of the cooler was buffered, so that the cooler works under the peak load and the coolant temperature is lowered. At lower ambient temperatures such as nighttime or nonpeak loads, the stored waste heat is discharged. At this time, the auxiliary energy source is applied during the nonpeak operation, and thus electricity is consumed. However, because of the policy of ladder-type electricity prices, the overall cost of municipal electricity is balanced, and the load distribution is more uniform. At runtime, the PCM unit stores ~50% of the daily waste heat under hot ambient condition (32 °C) and releases heat from PCM units below 20 °C. In addition, the PCM unit has 10 times volume storage density, thus reducing the cost and size of the entire system compared to the water system.

In addition, the waste heat obtained from the high-concentration photovoltaic (HCPV) module was significant, and the heat flux increased. Therefore, effective cooling is needed to ensure that the module has the right temperature needed for a normal operation of the photovoltaic power generation system. In the absence of a PCM unit heat recovery system, the waste heat generated by the photovoltaic system can only be discharged into the environment. PCMs can be combined with a photovoltaic heat recovery system to increase the energy efficiency of system and save municipal electricity. Zhang et al. [216] designed a PCM unit to absorb the wasted heat generated by the photovoltaic module to drive an adsorption air-conditioning unit or a hot water system. Circulating water stores the waste tropical to PCM heat recovery units during the day. When the photovoltaic module stops working at night, the circulating water heated from the PCM unit is transported to the adsorption air-conditioning module or the hot water system. When the waste heat generated by the photovoltaic module is insufficient for heat storage, the heated circulating water is sent to the PCM unit for heat storage. The author developed a theoretical COP calculation method for the system. In theory, the COP is significantly improved compared to a photovoltaic air conditioning system without PCM units. Unfortunately, the authors did not make a quantitative comparison between the two. Table 9 shows the possibilities for heat recovery.

Place Table 9 here

In summary, the application of heat recovery is relatively less compared to thermal power applications in LTESSs of SACSs. This is probably because the residual heat in SACS is relatively small, and the use of water as a heat storage medium is more cost-effective than PCM. At the same time, it is difficult for the solid–liquid PCM unit to extract waste heat directly, generally through water or other heat transfer medium. Therefore, the layer-by-layer heat transfer between waste heat, water, and PCM results in heat loss. In addition, solid–liquid PCM units are limited in cost and heat storage time; they are more suitable for day-based and unstable waste heat commonly found in small independent SACSs. For large-scale SACSs that require long-term heat recovery, the application of latent heat storage systems is limited. Therefore, the economic analysis of latent heat recovery systems and the quantification of system COP enhancement should be strengthened to identify suitable application objects.

4.2 Cold storage applications

Latent cold storage enables high energy density, facilitating continuous cooling and reducing the volume of cold storage equipment. These advantages stimulated research in this field. Diaconu et al. [220] proposed a mathematical model for a solar ejector cooling system with a PCM cold storage unit. The energy consumption of an office building was simulated. The results show that the COP of the system with PCM refrigeration unit is 80% higher than that without PCM unit. Chen et al. [221] conducted an experimental study on the thermal performance of a solar ejector cooling system that uses a cylindrical PCM tank. Any remaining energy was stored in the PCM unit and used to maintain the normal operation of the system when the ejector was not running. The results indicate that a PCM cold storage can help maintain a constant COP. They also suggested that the use of PCM cold storage in a solar ejector cooling system is promising. Allouche et al. [25] used TRNSYS to develop a dynamic simulation model for an ejector cooling system that was integrated with a PCM unit. The group strongly recommends the use of latent cold storage for ejector solar cooling. The maximum COP in the simulation is 0.193, and the monthly average COP is more stable and almost double than the system without a PCM unit. However, only relatively small PCM thermal storage tanks should be used for sun-rich areas. A large thermal storage capacity can add thermal inertia and initial system cost. Zheng et al. [222] studied the effect of microcapsule PCM on the daytime operation of a solar compression air-conditioning system in a laboratory scale. The PCM unit was connected to the refrigeration unit for storing cold. In the hourly energy consumption record from 8 a.m. to 17 p.m., the system with a PCM unit saved more than 20% energy compared with the electrically driven air-conditioning system. The maximum energy saving of a system with a PCM unit could save 30.5% at 13:00. Table 10 shows the possibilities for cold storage.

Place Table 10 here

5. Discussion

From the abovementioned literatures, it can be concluded that the development of LTESSs in SACSs (not including the system control and management) involves four stages: First, a feasibility study of PCM is carried out in a solar air-conditioning system. Second, a large number of studies were carried out to find a suitable PCM and its heat transfer mechanism. Scholars have sought to find suitable PCMs with the goal of improving thermal conductivity and proposed improvement methods. The research field has gradually expanded to material and geometry configuration optimization of PCM containers. Third, the energy saving and cost of PCM unit are considered for a solar air-conditioning system compared with a sensible unit. Some new system structures have been proposed to save cost and power. However, up to now, the current stage has not systematically studied the cost and operation problems caused by introducing enhanced measures to LTESSs. Fourth, studies are conducted on the integration of latent thermal storage units with some components in solar air-conditioning systems such as collectors, photovoltaics, or condensers. These stages do not stagnate with each other but develop together. However, many key issues still need further discussion.

5.1 Hybrid strengthening of PCM and its container

In Chapters 2 and 3, the enhancement strategies for PCM and its containers are introduced. Some of the findings are summarized here. First, many PCMs are available in the temperature range of heat recovery, thermal power, and cold storage of SACSs. Studies concluded that the PCMs used in SACSs are mainly concentrated in paraffin, $CaCl_2.6H_2O$, and other commercial materials. Many enhancements are also based on such materials. More suitable PCMs and strengthening methods are still waiting to be explored. In addition, the strengthening strategies mainly focused on improving the heat transfer mechanism of PCM in the container, such as to strengthen the heat conductivity of the PCM itself and to enhance the convective heat transfer in the container in the late melting stage. From the literature review, it can be concluded that the most effective way to improve the heat conductivity of PCM is by adding micro-nano additives (carbon nanotubes [73], and carbon fibers [89]) and graphite additives (expanded graphite [72]). Regarding the shape of containers, conical and wedge-shaped containers have been developed to enhance the convective heat transfer in the late stage of melting. In the geometric optimization of containers, the following methods such as increasing the specific surface area of a spherical capsule to enhance heat conduction, adjusting the ratio of upper and lower sides of wedge unit, and the eccentricity of ring are used to enhance the heat transfer effect by allowing more liquid phase of PCM to be located in the area where natural convection can occur. The shell-and-tube design is mostly used in the structure of containers. The structures that can enhance the heat transfer area such as the serpentine tube was also used in recent systematic studies [203]. Among all the studies on strengthening strategies, the study on increasing fins is the most because of its high cost performance (easy to manufacture and low cost).

In addition, the enhancement of PCM has reached the stage of hybrid enhancement compared to single enhancement in the past. The strengthening of organic materials mainly focused on solving the comprehensive problem of poor thermal stability, flammability, and thermal conductivity. By combining metal foam and nanoparticles, a combination of graphite and nanoparticles doubled the thermal conductivity. The strengthening of inorganic materials mainly focused on solving the problems of supercooling and heat conduction, which are strengthened by a combination of nucleating agents/thickeners, nanoparticles, and metal foams. Notably, some methods have solved the problems of supercooling, phase separation, etc., but they have caused changes in thermal characteristics. For example, the addition of bentonite in $CH_3COONa \cdot 3H_2O$ has led to a decrease in latent heat [77]. At the same time, the combination of various strengthening methods has resulted in more complex changes in the thermal characteristics of PCM. For example, a low-porosity metal foam is more beneficial for increasing the heat storage time [92]. However, when nanoparticles and metal foams are used in combination to strengthen a PCM, the addition of nanoparticles reduces the effect of natural convection during PCM melting. A high-porosity metal foam is selected to ensure that the PCM volume is minimized to promote the positive contribution of natural convection [92]. Therefore, when selecting a strengthening method for PCM, the thermal conductivity and heat storage time should be balanced according to the application conditions to correctly select the amount of additive.

In addition to hybrid strengthening for PCM defects, hybrid strengthening measures for PCM and PCM containers have also been studied to increase the thermal storage efficiency of PCM unit. In the field of LTESSs of SACSs, this type of hybrid strengthening studies mainly uses the method of adding nanoparticles to PCM and changing the geometric parameters of fins in the container. A series of studies [173, 185, 225] have been conducted to investigate the effect of adding different concentrations of Al_2O_3 nanoparticles and changing the size and quantity of fins. According to the analysis of melting process of PCM R82 in a triplex-tube heat exchanger, the melting time of fin group, nanoparticle group, and fin + nanoparticle group saved 59%, 17%, and 44% at the most compared to the nonenhanced group. During the solidification, the solidification time of fin group, nanoparticle group, and fin + nanoparticle group saved 55%, 8%, and 30% at the most. Notably, although the number of improvement methods has increased, the best thermal storage effect has not been achieved. Second, structural strengthening will provide better thermal storage performance improvement than PCM additives. From the perspective of heat transfer mechanism, both fin and nanoparticles can provide advantages in heat conduction in the early stage of melting, but fins can also enhance the convection in liquid PCM. In the late stage of melting, the existence of fins will suppress the buoyancy effect and thus weaken the convective heat transfer. The convection of liquid PCM is also limited by the viscosity of nanoparticles. Eventually, the hybrid strengthening effect of nanoparticles and fins is weaker than that of individual fins. Therefore, it would be biased to consider only the advantages of increasing conduction or convection in the future studies of hybrid strengthening. Instead, the strengthening methods should be selected reasonably, and the ratios and parameters used in the methods should be adjusted to balance the benefits of heat conduction and heat convection during phase change. This will help researchers to achieve an effective hybrid improvement scheme. At the same time, hybrid strengthening methods that can be applied to the field of LTESSs in SACSs have not been fully studied. For example, it is not clear whether a single high-performance additive (such as carbon nanotubes and carbon nanofibers) or a special structure (such as the PCM slabs and cascaded PCMs) can achieve better heat storage performance than a combination of traditional and cheaper strengthening methods.

5.2 Design and economic evaluation of LTESSs in SACSs

From the discussion in Sections 2.3 and 5.1, we can extend a problem worthy of discussion. A simple optimization of PCM materials and containers can solve the problem of local heat conductivity, but it often causes larger problems in the system, such as cost control. For example, increasing the number of fins will reduce the PCM volume. Therefore, to satisfy the energy storage capacity of the system, it is necessary to increase the size of the system; thus, the initial investment cost and space naturally increases accordingly. However, the use of fins can significantly increase the heat storage efficiency of the system, saving electricity during the operation period. At this time, it is more important to measure the economic impact of adding a technology on the system than to measure the heat conductivity of PCM on the successful application of technology. In the LTESSs, the following costs should be considered: PCM costs, container costs, enhanced technology costs, auxiliary electricity costs during operation, and other ancillary costs. The importance of these cost assessments lies in measuring the cost and benefit of design factors such as adding improvement strategies, changing operation methods, and updating system structure. On the other hand, it is expected that cost control will bring limitations and optimization to design. According to the literature review, most studies related to strengthening technology and container optimization only discussed the effect of improving system efficiency, and fewer studies theoretically calculated the economic impact of the optimal scheme on the overall system. Economic research on the application of LTESSs in SACSs is also rare. We can learn the economic evaluation methods from studies of LTESS in the field of solar energy application to generate positive thinking on the cost analysis of LTESS in SACS. Table 11 shows the economic evaluation methods for LTESS of solar thermal utilization. As shown in Table 11, for solar power systems, levelized cost of energy (LOCE) is the main economic analysis method. For small solar thermal utilization systems, such as HVAC systems and solar still systems, the main economic analysis methods are payback period and cost calculation. The separate use of these methods enables comparison of system cost under different design parameters of the LTESS. Thus, the design parameters with the best economy can be obtained. But the optimal system is expected to be both energy efficient and economical. Therefore, exergy economic analysis, payback period and cost calculation can be combined in the economic analysis of the LTESSs in SACSs. Limited exergy efficiency and cost can help to determine the upper and lower limits of the design parameters, and payback period can help to determine the optimal value of the design parameters. This is more beneficial for determining the specific range of feasible design parameters. At the same time, the ratio of operating energy saving benefits to the initial investment costs of strengthening technology applied to LTESS in SACS can be considered as a simple evaluation index, which will be beneficial for the economic selection of strengthening technology.

Place Table 11 here

6. Conclusions and suggestions for future research

Latent thermal storage technology can effectively enhance the stability of solar air-conditioning systems and compensate possible power interruptions. In this paper, PCM selection methods, thermal storage container design, and the use of LTESSs in SACSs are reviewed. First, this paper summarizes the available PCMs with a suitable phase transition temperature in the field of SACSs and introduces the database and evaluation methods commonly used in the selection of PCMs. Aiming at the disadvantages of PCMs, the improved methods are summarized. Second, the effect of material and geometry of PCM container is introduced. The heat transfer enhancement methods on the container side are summarized, such as fins, capsule modifications, flow direction of working fluid, PCM layouts, and other structural optimizations. Third, this paper introduced and evaluated the application of LTESSs in SACSs. Then, the hybrid enhancement methods and the cost estimation method of LTESSs in SACSs are discussed. The following conclusions are drawn:

(1) Although many PCMs are available at present, only some commercial materials (paraffin R series, erythritol, etc.) are used in the research work. More new materials and their enhancement methods are worth exploring.

(2) The enhanced heat transfer strategy and configuration optimization of PCM and its container mainly involve improving the heat transfer mechanism of PCM in the container. The more effective heat transfer enhancement method on a PCM is to add micro-nano additives such as carbon nanotubes and carbon nanofibers. For a container, the fins are both economical and effective. The development of new container configurations can improve the convection in the late melting stage of PCM to strengthen the heat transfer. Therefore, in the future research of PCM container optimization, the dimensionless number related to the heat transfer mechanism can be used to establish the relationship between the structure and geometrical factors of the container to achieve the design and selection of a PCM container instead of a large number of simulation studies.

(3) The strengthening of PCM and its containers has developed from the improvement of a single factor to hybrid enhancement. However, the heat storage effect of hybrid strengthening method is not always better than that of single-factor strengthening method. When selecting a hybrid strengthening strategy, the effect of strengthening strategy on the heat transfer mechanism of PCM should be considered to adjust the proportion of the method applied.

(4) The application of LTESSs in SACSs is often limited because of their low-cost

performance ratio, especially in the field of heat recovery. Moreover, there is a lack of quantitative economic analysis for solar latent thermal storage air-conditioning systems. Therefore, for the cost assessment of LTESSs in SACSs, we suggest that the exergy analysis, payback period and cost calculation can be combined to analyze the economy of system. This will be more beneficial for determining the specific range of feasible design parameters. At the same time, the cost evaluation of enhanced technology is relatively lacking. We suggest that the ratio of energy saving benefits to the initial investment cost can be used as a simple evaluation index to economically select the strengthening technology, which has a high potential for research.

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Tables

Table 1

The characteristics of different types of PCMs

Properties	Organic	Inorganic	Eutectic
Phase change enthalpy per unit	Low	Higher than organic PCMs	The higher the proportion of high melting entropy components, the higher the Phase change enthalpy of eutectic PCMs.
Supercooling	Low or no	Yes	Yes
Toxic	No	Low or no	Low or no
Corrosives	No	Yes	Yes
Cost	Low	The cost of salt hydrates is low; the costs of molten salts and metallic alloys are higher than organic PCMs.	The cost of eutectic PCM is related to its composition.
Application in LTESSs of SACSs	Widely used	Extensively used	Frequently used in cold storage applications

Table 2

Ideal properties of PCMs applied in solar air conditioning system

Classifications	Properties	Measure Indexes
Thermal Properties	Phase change temperature matched with heat and cold storage conditions	Melting temperature/ Solidification temperature [°C]
	High latent heat	Enthalpy of fusion/ solidification [kJ/kg]
	Excellent thermal conductivity	Thermal conductivity [W/(m·K)]
Physical Properties	High density	Density [kg/m³]
	High specific heat capacity	Specific heat capacity [kJ/(kg·K)]
	Small change of volume in phase transition	Volume expansion rate [%]
	Minimum super-cooling	Degree of super-cooling [°C]
Chemical Properties	Non-toxic	
	Non-corrosiveness	
	Long-term stability of chemical properties	
Economics	Low-cost	
	Abundant resource	

Table 3

The appropriate melting temperature range in the application field of different solar energy storage

Application	The melting temperature range of PCMs °C	References
Heat storage in SACSs	Above 25	[29]
Solar energy absorption (single effect) system	60-120	[36]
Solar energy absorption (dual effect) system	140-200	[37]
Driving solar ejector cooling system	120-150	[38]
Heat recovery of solar absorption cooling system	25-30	[39]
Heat recovery of condenser applied in the compression system	40-50	[40]
Cold storage in SACSs	Up to 20	[41]
Solar energy absorption (single effect) system applied in the field of freezing	-10-15	[31]
Compression cooling system	5-10	[29]

Table 4

The PCMs considered for use in the LTESS field in SACSs

Materials	Types of materials	Melting temperature	Heat of fusion	Thermal conductivity	Specific heat capacity	Applicable scenarios in Reference	Reference
□	□	°C	kJ/kg	W/(m·K)	kJ/(kg·K)	□	□
Parafol 14 (tetradecane 97 %)	Organic	4-8.0	220	□	□	Cold storage for an ejector cooling system	[38]
Parafol 14/16 (13 vol.-% of Parafol 14)	Eutectic	6-13.0	170	□	□	Cold storage for an ejector cooling system	[38]
RT 10	Organic	8.7-11.7	176	□	□	Cold storage for an ejector cooling system	[38]
$Na_2SO_4{\cdot}10H_2O$	Eutectic	12.8	□	□	□	Cold storage for an absorption cooling system	[42]
Capric-Lauric acid eutectic and 10% Oleic acid	Eutectic	13	90.9	0.207	2.196	Cold storage for a solar cooling system	[43]
RT15	Organic	13.2-15.8	40.81	□	6-20.0	Cold storage for an ejector cooling system	[25, 44]
Capric-Lauric acid eutectic and 6% Oleic acid	Eutectic	14.5	109.7	0.208	2.214	Cold storage for a solar cooling system	[43]
Parafol 16/18 (67 vol.-% of Parafol 16)	Eutectic	15-19.5	170	□	□	Cold storage for an ejector cooling system	[38]
S15	Inorganic	15	142	0.43	0.67	Cold storage for an ejector cooling system	[45]
capric and lauric acid	Eutectic	16.91	115.1	0.572	1.825	Cold storage for an adsorption cooling system	[26]
Capric-Lauric acid eutectic and 2% Oleic acid	Eutectic	17	127.2	0.213	2.232	Cold storage for a solar cooling system	[43]
RT 20	Organic	17.2-24.2	142	□	□	Cold storage for an ejector cooling system	[38]

Parafol 16 (hexadecane 97 %)	Organic	17.4-20.7	249	□	□	Cold storage for an ejector cooling system	[38]
Heptadecane	Organic	19.9-22.7	168	□	□	Cold storage for an ejector cooling system	[38]
$CaCl_2 \cdot 6H_2O$	Inorganic	27-29	150-240	□	□	Heat storage in heat recovery system of an absorption cooling system	[39, 46, 47]
RT44	Organic	39.1-42.5	256.9	0.2	2	Store the waste heat of the photovoltaic module to drive an adsorption air conditioning	[48]
RT55	Organic	51-57	170	0.2	2	Heat storage for driving a desiccant cooling system	[49]
Paraffin (85.1%)	Organic	55	179	0.2	□	Heat storage for driving a desiccant cooling system	[50]
RT60	Organic	55-61	160	0.2	2	Heat storage for driving a desiccant cooling system	[49]
RT65	Organic	57-68	150	0.2	2	Heat storage for driving a desiccant cooling system	[49]
Stearic acid	Organic	69	202.5	0.172	2.2	Heat storage for driving an adsorption cooling system	[51]
RT70HC	Organic	69-71	260	0.2	2	Heat storage for driving a desiccant cooling system	[49]
RT42	Organic	38-43	174	0.2	2	Heat storage for driving a desiccant cooling system	[52]
RT82	Organic	81-85	176	0.2	2	Heat storage for driving a liquid desiccant cooling system	[53]
S83	Inorganic	83	141	0.62	2.31	Heat storage for driving an adsorption cooling system	[54]
S89	Inorganic	89	151	0.67	2.48	Heat storage for driving an adsorption cooling system	[54]
RT100	Organic	99	168	0.2	2.4	Heat storage for driving an $LiBr/H_2O$ adsorption cooling system	[55]
$MgCl_2 \cdot 6H_2O$.	Inorganic	116.7	168.6	0.7	2.6	Heat storage for driving an $LiBr/H_2O$ adsorption cooling system	[55]

Erythritol	Organic	117.7	339.8	0.326	2.76	Heat storage for driving a single effect LiBr/H_2O absorption cooling system	[56]
Polyethylene PE-HD [GHR 8110]	Organic	122-133	150-200			Heat storage for driving an ejector cooling system	[38]
Polyethylene PE-UHM [GUR4120]	Organic	124-134	150-200			Heat storage for driving an ejector cooling system	[38]
Polyethylene Licocene PE 4201	Organic	125-130	246			Heat storage for driving an ejector cooling system	[38]
KNO3-NaNO2-NaNO3 (53-40-7)	Eutectic	142	80			Heat storage for driving an ejector cooling system	[38]
Palatinitol (Isomalt)	Organic	145	170			Heat storage for driving an ejector cooling system	[38]
Mannitol	Organic	167	325			Heat storage for driving an ejector cooling system	[38]
Hydroquinone	Organic	172.5	225			Heat storage for driving an adsorption cooling system	[57]

Table 5

The defects of PCMs and corresponding solutions

Defect of material	Approaches to strengthen the heat transfer	Details	References
Low thermal conductivity	Adding a material with large thermal conductivity	Adding aluminum powder, expanded graphite, carbon fiber and carbon nanotubes	[70-74]
	Adding Nano-Particles		[75]
Leakage of PCM	Encapsulation of the PCM	Encapsulating in spherical capsules or microcapsules	[28]
	Forming CPCMs	Metal foams, porous carbon materials, such as expanded graphite, carbon nanotubes, graphite foams.	[71]
High flammability	Addition of flame retardants	Forming nano-composite PCMs	[76]
		Adding metals, such as iron, magnesium, aluminum, and zinc	[77]
Phase separation	Adding gelling or thickening agent	The addition of starch The addition of cellulose derivatives, such as methyl cellulose and hydroxyethyl methyl cellulose	[28]
		The addition of diatomite	[78]
		The addition of bentonite	[79]
Super-cooling	Encapsulating PCMs		[28]
	Adding nucleating agents	Carbon nanofibers, copper, titanium oxide, potassium sulfate, and borax	[28]
	Cold finger		[80]

	Preparing porous surfaces		[81]
Corrosive	Addition of additives to improve chemical stability	Adding NaCl	[28]
	Selection of a container with excellent corrosion resistance	Stainless steel is more resistant to salt hydrates than carbon steel, aluminum alloy and copper.	[82]
		Polypropylene and polyolefins could be used as container materials to resist most PCMs.	[83]

Table 6

The PCM enhancement methods applied to LTESSs in SACSs.

PCM	Additives	Control Variables	Key observation	Evaluation index	Recommended parameters	Improvement effect	Remarks	Reference
Paraffin wax	Aluminum	Aluminum mass fraction was 0, 0.1 wt%,0.3wt%, 0.4wt% and 0.5wt%, respectively.	Temperature distribution; the position of the phase change interface	Charging process: the average heat transfer coefficient Discharging process: The mean daily efficiency	The recommended mass fraction of aluminum is 0.5.	The average daily heat storage efficiency of composite PCM was increased by 82%-94%.		[70]
Erythritol	Spherical graphite/ expanded graphite/ nickel particle	The range of each filler content was 1-44 vol %.	Thermal conductivity	Theoretical effective thermal conductivity base on the Nielsen's model		The thermal conductivity increases with the increase of additive content. Compared with the pure PCM, the thermal conductivity of PCM with 15 vol% expanded graphite increased by 640%; the thermal conductivity of PCM with 17 vol% spherical graphite increased by 290%.	The enhancement effect of expanded graphite was greater than that of spherical graphite; the enhancement effect of nickel particles was the worst among the three.	[72]
Erythritol	Modified multi-walled carbon nanotubes with average diameter and length of 10 nm and 50 μm, respectively.	(1).The pretreatment methods of multi-walled carbon nanotubes are different: ball milling, mechanochemistry and acid oxidation；(2). the content of modified multi-walled carbon nanotube is 0.5, 1, 2, 3, 4 and 5 wt%, respectively.	Melting enthalpy; melting point; solidification enthalpy; solidification point		Acid oxidation treatment is recommended.	The addition of 1% modified multi-walled carbon nanotubes increased the thermal conductivity of PCM from 0.1956 W/ (m.K) to 0.9779 W/ (m.K).		[73]

Paraffin wax	Iron/ magnesium/ aluminum/ zinc (75-150 μm in diameter)	The quantity of each filler content was 0%, 1%, 3%, 5% parts per hundred paraffin, respectively.	Volatilization intensity of carbon dioxide and ammonia; the maximum heat release capacity; the heat release rate; phase transition temperature; latent Heat			Metal (iron, magnesium, aluminum, and zinc) can enhance flame retardancy and thermal stability of the paraffin.	The latent heat of PCM decreased by about 20 kJ/kg after adding metal.	[77]
$CH3COONa\cdot3H_2O$	20wt% simple wheat flour/ 30wt% methyl hydroxyethyl-cellulose/ 30wt% methyl-cellulose/ 50wt% bentonite	(1). Different kinds of thickeners: starch, cellulose and bentonite; (2). Different kinds of cellulose with the same content: 30 wt% methyl hydroxyethyl-cellulose and 30 wt% methyl-cellulose.	Melting temperature; measured enthalpy		30wt%methylhydroxyethyl-cellulose and methyl-cellulose are recommended.	All three materials possess the properties of thickening, but the PCM with bentonite had a supercooling temperature of 10 °C.	The addition of starch suspected to change the melting point and freezing point of PCM.	[79]
$CH3COONa\cdot3H_2O$	Ag anode	(1).The direct-current voltage range was 0.8-2.0 V;(2).The degrees of supercooling was 48 °C, 38 °C, 28 °C, and 18 °C, respectively;(3). Operational cycle numbers were 0, 1000, 2000, 5000, and 10,000; (4). The surface roughness of the Ag electrode was 0.05-2μm.	Induction time of the electrical nucleation; the retention time of the supercooled solution		(1). Voltage over 1.4-1.8 is required; (2). The optimal range of surface roughness of the Ag electrode is 0.6-1.0 μm	The electronucleation system mentioned in this paper can be supplied by 1.5V dry batteries and obtain 100% nucleation. The electronucleation method has reliability and repeatability.	(1). The experiment was carried out on a heat storage system with a 5 L PCM container at most; (2). The electro nucleation system with the optimal parameters mentioned in this paper can be used for more than 10 years when only one to two operations per day are performed.	[84]

$CH_3COONa \cdot 3H_2O$	Nucleating agent: $Na_4P_2O_7 \cdot 10H_2O$; thickening agent: polyacrylamide	(1). The content of polyacrylamide was 1.0 wt%, 1.5 wt% and 2.0 wt%, respectively; (2). The concentration range of sodium acetate was 96-98 wt%.	Supercooling degree; distinct phase stratification; melting temperature		(1).1.5% mass ratio of the polyacrylamide is required to avoid phase stratification; (2). $CH_3COONa \cdot 3H_2O$ with 1.5 wt% of $Na_4P_2O_7 \cdot 10H_2O$ can achieve the lowest supercooling degree.	The addition of 1.5 wt% $Na_4p_2o_710H_2O$ can reduce the supercooling of PCM to 4K.		[85]
$CH_3COONa \cdot 3H_2O$	Silicon carbide and bentonite	The mass fractions of bentonite：1-50 wt %；the mass fraction of silicon carbide：0.5-15 wt%	The melting temperatures and peak temperatures; supercooling degree; heat storage time; heat release time		(1). The mass fraction of bentonite over 26 wt.% is needed for infiltration avoidance; (2). When the content of silicon carbide is more than 10wt%, PCM have almost no supercooling.	The addition of silicon carbide and bentonite improves the leakage, thermal stability, supercooling and thermal conductivity of PCMs. The addition of 26 wt% bentonite and 10 wt% reduced the heat storage and release time of PCM by 25.44% and 78.5%, respectively.	The addition of bentonite and SC lead to a decrease in latent heat.	[86]
$CH_3COONa \cdot 3H_2O$	Disodium hydrogen phosphate dodecahydrate/ sodium carbonate decahydrate/ sodium silicate nonahydrate/	The amount of each additive is 2, 4, 6, 8 wt%, respectively; the porosity of copper foam is 98%, 88%.	Subcooling degree; latent heat; phase change temperature; phase change time	Theoretical effective thermal conductivity base on the Bhattacharya model	(1).2 wt% carboxymethyl cellulose and 2 wt% disodium hydrogen phosphate dodecahydrate is	The supercooling of PCM with 2 wt% carboxymethyl cellulose and 2 wt% disodium hydrogen phosphate dodecahydrate was reduced to 4.6K.		[87]

	borax decahydrate/ quart sand/ the carboxymethyl cellulose/ copper foams				recommended; (2). the 88% porosity of copper foam is recommended.			
Erythritol	Porous nickel	Pore sizes of 100, 300, and 500 μm		Theoretical effective thermal conductivity	The 15 vol% porous nickel with a pore size of 500 μm is recommended.	The thermal conductivity of erythritol increased to 11.6W/(m.K) by adding 15 vol% porous nickel with a pore diameter of 500 um, which was two orders of magnitude higher than that of pure erythritol.	The pore size has no effect on melting point and latent heat.	[88]
Erythritol	Short carbon fiber with diameter of about 9 μm	(1). The aspect ratio of SCF is 5 and 25; (2). the mass fraction of 1, 2, 4 , 7 and 10 wt%	Graphitization morphology; heat storage time; thermal conductivity		The aspect ratio of 25 is recommended.	The addition of 10 wt% short carbon fiber with an aspect ratio of 25 led to an increase in the thermal conductivity of PCM by 407.8%.	Thermal conductivity of PCM changes after cycling. After one cycle, the thermal conductivity of PCM with 10 wt% short carbon fiber (aspect ratio of 25) was reduced by 21.1%.	[89]
Erythritol	Expanded graphite	The amount of 1, 2, 3 and 4wt%	Melting time; thermal conductivity		From the point of view of thermal conductivity, the addition of 4 wt% expanded graphite is the best. Considering the melting time, 3 wt% expanded graphite is	The thermal conductivity of PCM with 4wt% expanded graphite increased about 2.5 times, and the composite phase change material had a 16.7% lower melting time than pure erythritol.		[90]

					recommended.			
Paraffin wax	TiO_2	The range of content was 0-7 wt%.	Thermal conductivity; phase transition temperature; latent heat capacity	Theoretical effective thermal conductivity	0.7wt% TiO_2 is recommended.	The addition of 0.7 wt% TiO_2 improved the thermal conductivity of paraffin wax by 20.1J/g. Composite PCM has lower latent heat capacity than paraffin when the content of TiO_2 was more than 2wt%.		[91]
RT82	Al2O3 nanoparticles and porous copper foam	(1). The content of Al2O3 nanoparticles is 0, 0.01, 0.03, and 0.05, respectively; (2). the porosity of copper foam is 95% and 98%.	Liquid fraction; isotherm at different melting times; melting time		Low volume fraction of Al2O3 nanoparticle and high porosity copper foam are recommended.	The addition of Al2O3 nanoparticles and porous copper foam resulted in a 7-90% savings in heat storage time.		[92]

Table 7

The heat transfer enhancement technologies for different thermal storage containers

The types of thermal storage container	Approaches to strengthen the heat transfer	Details	References
Shell and tube	Changing the direction of the heat exchanger	The horizontal type has a better heat transfer performance compared to the vertical type.	[165]
	Changing the geometric shape of the shell	The time of the solidification of PCM is shorter in the cylindrical shell compared to the rectangular shell.	[166]
	The use of fin: The change of fin materials	It was observed that copper, aluminium and aluminium 6063 had considerably better thermal performance with paraffin as compared to steel AISI 4340.	[167]
	The use of fin: The change of fin length	The melting time reduced by 57.32% as the length of the fin is increased from 12.7 mm to 38.10 mm.	[167]
		The stored energy increases with increasing fin radius.	[168]
	The use of fin: The change of fin thickness	The thermal storage capacity of the system is decreased by 5.7% as the fins' thickness is increased from 1 mm	[167]

			to 5 mm.	
		The change of fin space	The stored energy increases with decreasing fin space.	[168]
Sleeve tube	Adjusting the arrangement of heat transfer tube bundles		The melting time of PCM is shortest when the heat transfer tube was arranged in a concentric circle, compared with the staggered square pitch, in-line square pitch and in-line triangle pitch.	[169]
	The use of fin	The change of angles between neighbor fins	The angle between the neighbor full-scale fins set to 60-90°, and the thermal performance of the system is best.	[170]
		The change of fin thickness	The influence of fin thickness is very small compared with that of the angle between neighbor fins.	[170]
Multi-tube	Changing the quantity of the inner tube		The four-tube type reduced the melting time of the PCM by 29%.	[171]
	The use of fin	The position of added fins	The heat transfer capability of adding internal and external fins is stronger than that of adding internal fins and external fins respectively.	[172, 173]
		The change of the geometric shape of the fin	The use of direct and T shaped fins can be used to further enhance heat transfer.	[174]
		The change of the quantity of the fins	The more the fins, the shorter the melting time of PCMs.	[172, 173]

		The change of fin length	The melting time decreased as the fin length increases.	[172, 173]
		The change of fin thickness	The influence of the fin thickness could be ignored.	[172, 173]
Cylindrical type	The use of fin	The change of fin angles	When the temperature of HTF is low (50 °C), the fin with an angle can slightly shorten the melting time. But when the temperature of the HTF is high (60 °C), the influence of the angle fin could be ignored.	[175]
Flat plate	Changing the direction of plate		With the horizontal arrangement of PCM capsules arrangement, the heat transfer rates increase up to twofold.	[176]
	The change of plate thickness		The decrease of PCM thickness makes the heat transfer rate increase by five times.	[176]
			The function correlation developed can be used for simplified design procedures to calculate the maximum plate thickness that can be used to optimize thermal performance.	[177]
Plate-fin	The use of fin	The change of fin length	The impact of increasing the fin length can be ignored.	[178]
		The change of fin space	The smaller the fin space, the shorter the melting/ solidification time.	[178]
Capsule	Modification of Capsule Material	The addition of metal coating	The heat transfer coefficient of mPCM slurry with metal coating can be increased by over 10%, compared	[179]

		with the non-metal coating type.	
	The addition of expanded graphite	Adding 10% expanded graphite to the shell can increase thermal conductivity of the mPCM by 10 times.	[180]
	graphene oxide	1 wt% of graphene dosing already results in a notable increase of the thermal conductivity.	[181]
	nanotubes	The thermal conductivity sees a nearly double increase by adding 0.15g of nanotubes results in shell.	[182]
	Multiple PCMs	The average energy and exergy collection efficiency of the system are increased significantly.	[183]

Table 8

The latent application for driving solar air conditioning

Types of solar collector	Types of system	Types of materials	Materials	Storage containers	Research method	Application evaluation	References
Flat plate	Adsorption	Organic	Stearic acid	Shell and tube	Theoretical simulation	Compared with the system without PCM, the use of PCM reduced the auxiliary energy consumption at night by about 31%. But even with the application of PCM, the whole system still consumed 3.28 times more energy than the ordinary split air conditioning system.	[202]
Air collector	Desiccant	Organic	Paraffin	Rectangular container with serpentine tube inside	Theoretical simulation	This study compared the energy-saving performance of desiccant air conditioning driven by pure electric heating (A type), electric heating + solar heating (B type), electric heating + PCM + solar heating (C type).The results show that compared to the purely electric drive type, the energy saving rate of C-type was up to 75.82% which was nearly four times that of the B type. In addition, the C-type had the highest total fixed cost, twice that of the A-type, but the total annual operating cost of C-type was 626 LE, which was about a quarter of the A-type.	[203]
	Desiccant	Organic	RT65	The PCM TES unit consists of multiple PCM layers arranged in parallel	Theoretical simulation	At regenerative temperatures of 60 °C, 65 °C and 70 °C, the system could achieve a humidity satisfaction rate of over 80%. At the temperature of 60 °C, the regeneration coefficient could reach 100%. This study proved the technical feasibility of using mixed PVT-SAH and LTESS to drive the desiccant wheel regeneration.	[204]
Evacuated tube collector	Ejector	Organic	Polyethylene	Buffer tanks	Theoretical simulation	The PCM unit of 800 kg polyethylene could produce 62.5 kg of steam. Under rated operating conditions, the solar ejector cooling system operated at full load for more than 15 minutes.	[38]
	$LiCl-H_2O$ sorption module	Organic	RT11(cold storage)/RT27(heat storage)	Tubular double jacket heat exchanger	Theoretical simulation and experimental study	The results of both experiment and simulation indicated that this new solar adsorption air-conditioning system is feasible, and the average COP can reach 0.36 (cooling) and 0.42 (heating).	[206]

	Single effect LiBr/H_2O absorption	Organic	Erythritol	Shell and tube	Theoretical simulation	The energy stored in a 20 kg PCM could be released by 70.9% within 200 minutes.	[207]
Parabolic trough collector	Adsorption	Inorganic	S89/S83	Cylindrical storage	Theoretical simulation	LTESS could only be applied when the collector area is higher than 0.9 m2. When LTESS was applied, the number of daily refrigeration cycles increased from 25 to 37, and the daily refrigerating capacity increased by 785 kJ/kg. The continuous cooling time was extended to 26.28 h.	[208]

Table 9

The latent application for heat recovery

Types of system	Installation position	Types of materials	Materials	Storage containers	Research method	Application evaluation	References
Absorption	The PCM unit is integrated in the dry cooler	Inorganic	$CaCl_2 \cdot 6H_2O$	Capillary tubes	Experimental study	At runtime, the PCM unit stored approximately 50% of the daily waste heat under hot ambient condition (32 °C) and released heat from PCM units below 20 °C. In addition, the PCM unit has 10 times volume storage density compared to the water system, which reduces the cost and size of the entire system.	[39]
	The PCM unit is integrated in the dry cooler	Inorganic	Hydrated salts	Well-mixed tank	Theoretical simulation and experimental study	During the experiment, the PCM unit could store 65.22 kWh in 12 hours. The integrated system of PCM unit and dry cooler was not suitable for areas with high ambient temperature, such as Serbia. The overall efficiency of the whole system was improved by 50% and the COP increased by 1 unit, compared to the system with wet cooler.	[217]
	The PCM with dry re-cooled sorption chiller in the heat rejection loops	Inorganic	$CaCl_2 \cdot 6H_2O$	Capillary tubes	Experimental study	The application of PCM unit raised efficiency of the whole system up to 64% compared to a system with only dry re- cooling.	[218]
Absorption cooling system driven by photovoltaic waste heat	Composite phase change material (CPCM) and PCM（auxiliary）regenerative system are integrated in the heat exhaust system to recover the residual heat of photovoltaic		CPCM: Acetamide with 20 wt% expanded graphite；PCM: RT44	Rectangular container	Theoretical simulation	The authors designed a PCM unit to absorb the wasted heat generated by the photovoltaic module to drive an adsorption air conditioning unit or a hot water system. They presented a theoretical COP calculation method of the system. PCM unit can improve COP of whole system significantly in theory, compared to the systems without PCM units. But unfortunately, the author did not make a quantitative comparison between the two.	[219]

Table 10

The latent application for cold storage

Types of system	Installation position	Types of materials	Materials	Storage containers	Research method	Application evaluation	References
Absorption	Connection with the refrigeration unit	Eutectic	$Na2SO4 \cdot 10H_2O$	Shell and tube	Theoretical study	It is feasible for the design system to store energy during the daytime and supply single effect absorption air conditioning at night.	[223]
Adsorption	Connection with the solar adsorption chiller	Eutectic	Capric and lauric acid	Spherical capsule packed bed	Experimental study	In the stable state, the charging and discharging period could be 230 and 220 minutes respectively.	[26]
Ejector	In chilled water networks	Organic	30 wt. %paraffin/water dispersion	Buffer tank (phase change slurry)	Theoretical simulation	The PCM unit can diminish the scale of the total system and fulfill the demand for refrigeration.	[38]
	Between Air handler and Evaporator	Organic	RT15	Horizontal tank with tube-bundle heat exchanger	Experimental study	The maximum COP of the ejector cooling system with PCM was 0.193, and the monthly average COP was almost no change and nearly twice that of the system without PCM unit.	[25, 224]
	The PCM cold storage charging unit integrates with the evaporator vessel	Inorganic	S15	Finned straight tube PCM tank	Experimental study	The COP of injection systems cooling system without PCM unit was reduced from 0.315 to 0.216. The cop of the system with PCM unit could keep constant value of 0.31.	[222]

Table 11

Economic evaluation for LTESS of solar thermal utilization.

System	System size	Economic evaluations	Optimized objects	Details	References
Solar absorption system with LTESS	Total system load of 45.4kW	Payback period		In this paper, solar absorption chiller without latent heat storage system is optimized by exergy economy analysis and genetic algorithms. The payback period of the optimal solar absorption chiller with the latent heat storage unit was calculated. The results show that using latent storage system was caused payback period increase from 0.61 years to 1.13 years in optimum point.	[226]
Solar single-stage absorption cooling system with LTESS	The system is installed in a three-storey building with cooling demand of 35kWh· m $^{-2}$ ·y $^{-1}$ and heating demand of 63 kWh· m $^{-2}$ ·y $^{-1}$.	Maximum net present value; minimum discount payback period		The economic analysis of sensible heat storage, latent cold storage and latent heat storage was carried out in this paper. The sensible heat storage has an economic competitive advantage. The cost of latent storage unit is acceptable only if the price of natural gas is high or the cost of pcm is low.	[227]
Integration of ejector cooling system and Photovoltaic/ Thermal system with LTESS	The thermal output of the Photovoltaic/ Thermal system is 28,816 kW.	Payback period		The payback period of photovoltaic thermal ejector cooling systems with PCM units is 3.405 years. The payback period is very sensitive to cooling costs. When the cooling cost is below $26 per ton, the payback period is less than 4 years.	[228]
Solar still with LTESS	Daily water production capacity of 2-4L/m2	Total cost (including operating cost, maintenance cost and fixed cost)	PCMs	This paper compared the economic competitiveness of composite materials (mixture of paraffin and black gravel) and phase change materials (paraffin) through cost analysis. The cost of a solar still system with composite material is 0.0014$ / Lm2, which is 27% lower than that with paraffin.	[229]

Concentrating solar power applications with LTESS	The demand thermal storage power of 3000MWth	Capital cost		The system cost for different pipe lengths, HTF capacity and PCMs calculated in this paper is between 17.745$/kWhth and 23.744$/kWhth. It is proved that the shell-and tube type LHTES is economically competitive compared to the two-tank molten salt indirect thermal storage system.	[230]
Solar power plants with LTESS	The annual capacity of 100MWe	Levelized Cost of Energy (LCOE); total cost; uncertainty analysis		This paper compared the economic competitiveness of sensible heat storage, latent heat storage and thermochemical energy storage in solar power system. The cost of the thermal storage system is determined primarily by LCOE. Based on the optimal capacity configuration, the total investment cost of solar power plants with different heat storage technologies is calculated. The uncertainty analysis is used to evaluate the cost controllable range of each system. The LCOE of the phase change thermal storage system is 19 cents/kWh; because of the wide pricing range of commercial PCM, the LCOE of commercial PCM is 6 to 43 cents/kWh; the overall system cost is 507 million. The cost of the latent heat storage system is lower than the cost of thermochemical energy storage, higher than that of the sensible heat storage system.	[231]
Concentrating solar power plants with LTESS	The annual capacity of 200 MWe	System Cost Limitation(< $87.95 million); LCOE (< 6 cents/kWh); exergy economy analysis (＞95%)	Tank radius, tank height, HTF channel width/length and longitudinal spacing between heat pipes of LTESS	In this paper, the geometric parameters of phase change heat storage unit were designed by means of economic analysis. The results show that the cost of the thermal storage unit is a monotonic increasing function of the capsule radius, the tank radius and the channel width/length. It is also a monotonic decreasing function of the longitudinal spacing of the heat pipes. Three evaluation methods can help determine the range of design parameters.	[232]

Figure captions

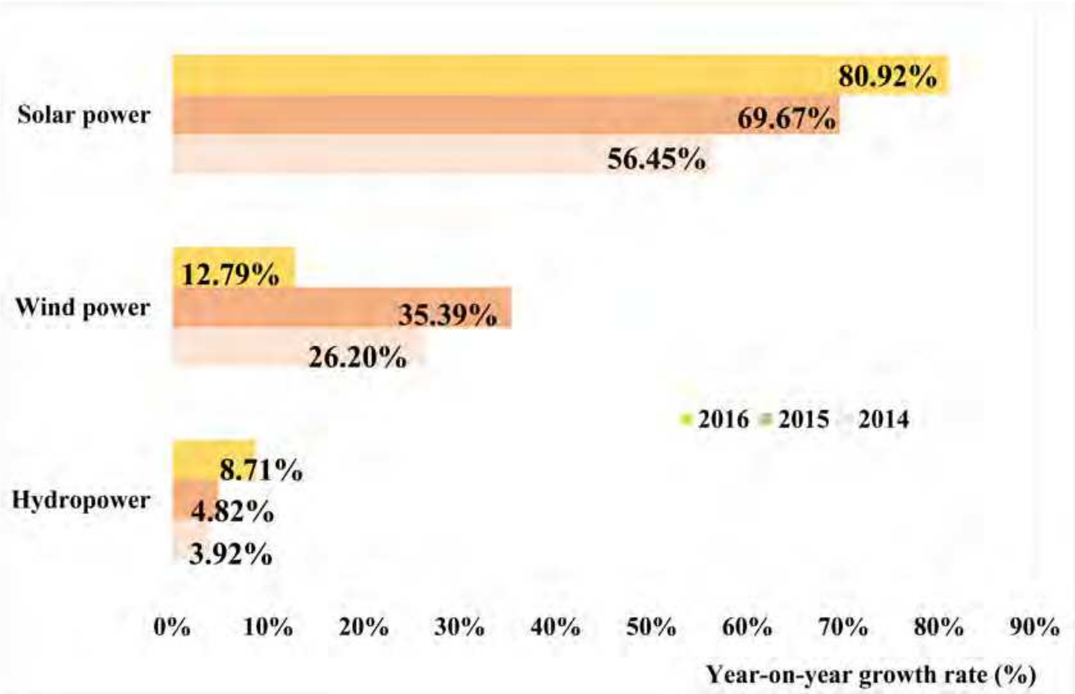
Figure 1. The installed capacity of renewable energy power generation in China

Figure 2. Technical classification of solar air conditioning systems

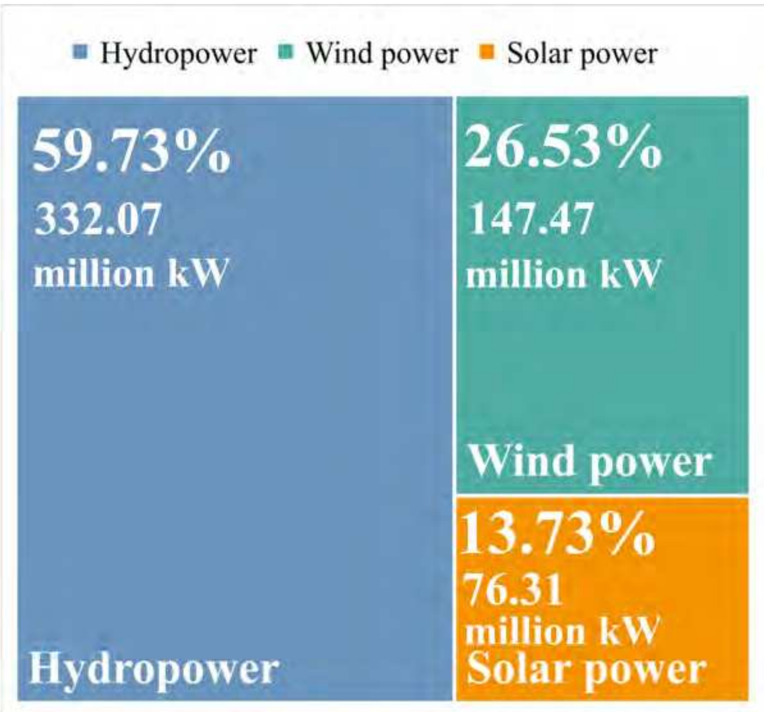
Figure 3. The thermal storage technology and the classification of PCMs

Figure 4. The schematic diagram of solar desiccant air conditioning system

Figure 1



(a) Year-on-year Growth Rate of Renewable Energy Installation Capacity in China from 2014 to 2016



(b) China's Renewable Energy Installation Capacity by the end of 2016

Figure 2

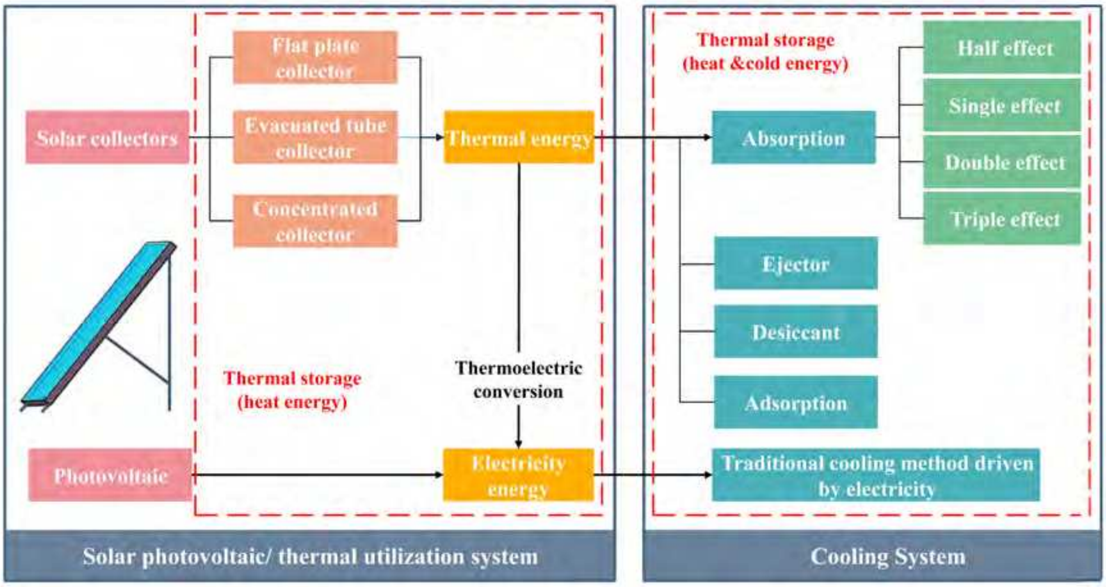


Figure 3

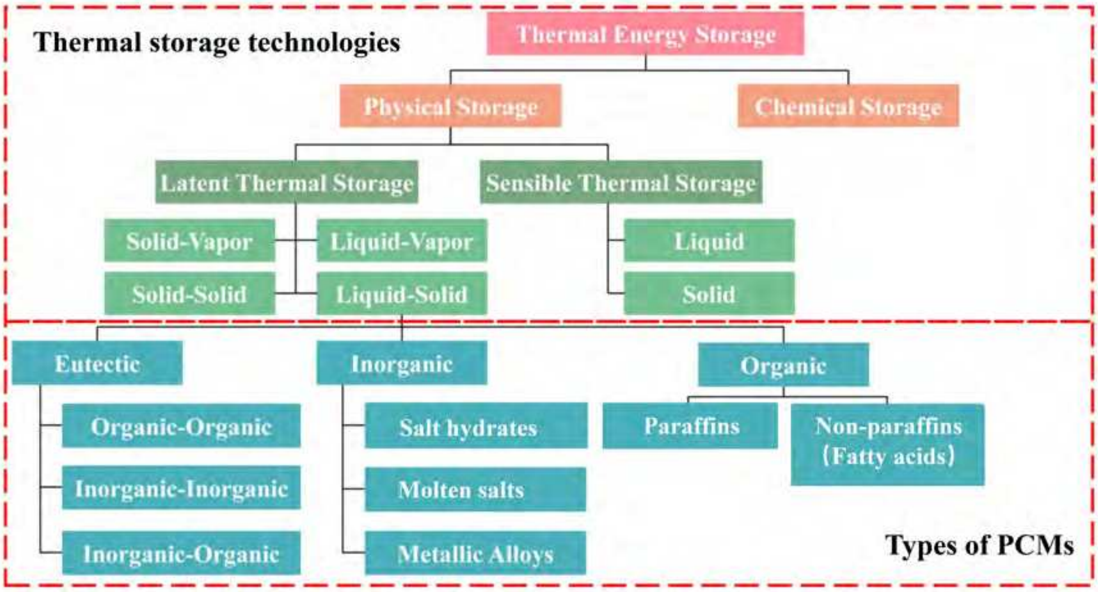
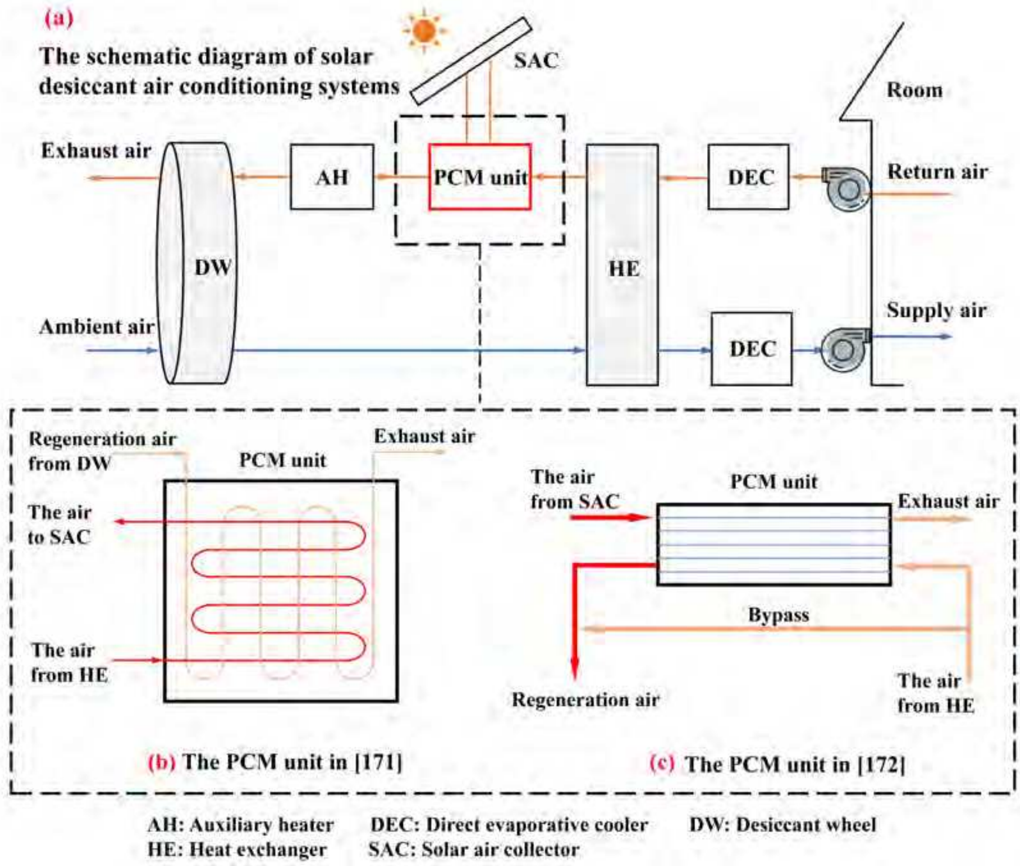


Figure 4



(a)
The schematic diagram of solar desiccant air conditioning systems
SAC
Room
Exhaust air
AH
PCM unit
DEC
Return air
DW
HE
Supply air
Ambient air
DEC
Regeneration air from DW
PCM unit
Exhaust air
The air to SAC
The air from HE
The air from SAC
PCM unit
Exhaust air
Bypass
Regeneration air
The air from HE
(b) The PCM unit in [171]
(c) The PCM unit in [172]
AH: Auxiliary heater
DEC: Direct evaporative cooler
DW: Desiccant wheel
HE: Heat exchanger
SAC: Solar air collector