Review of Thermal Energy Storage Options for Solar Energy Powered Absorption Cooling Systems

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Abstract- **As the world faces the global energy and environmental crisis, there is an urgent need to develop and promote environmentally benign sustainable cooling technologies. Solar absorption refrigeration is one such promising technology, and the cheapest and also widely available renewable energy that matches the cooling load requirements. Thermal applications are drawing increasing attention in the solar energy research field, due to their high performance in energy storage density and energy conversion efficiency. It is a fact that solar energy is intermittent in nature. The continuous use of solar air conditioning systems faces a challenge during operation at night due to unavailability of solar energy. This situation asks for thermal storage options. In these applications, solar collectors and thermal energy storage systems are the two core components. This paper provides a review of thermal energy storage systems and focuses on research articles in the field of storage materials, storage methods using sensible heat storage, latent heat storage, chemical storage and cascaded thermal storage systems. Various types of thermal energy storage systems are studied in terms of design criteria and material selection.**

Keywords: Solar Absorption cooling, Heat energy storage, Phase change material, Cascaded thermal storage

Abbreviations: HES, heat energy storage; SHS, sensible heat storage; PCM, phase change material; COP, coefficient of performance; HTF, heat transfer fluid; LHS, latent heat storage; CS, Cold Storage; CHES, cascaded heat energy storage.

I. INTRODUCTION

Refrigeration and air conditioning applications account for significant portion of total energy consumption in India. In recent years, these sectors have witnessed manifold growth, and have become essential not only for human comfort but also for a variety of applications, such as food preservation. Nearly 30% of all fresh produce, in developing countries like India, are lost owing to lack of cold storage facilities and unreliable grid supply [1]. Providing thermal cooling would minimize post harvest losses. Conventional cooling technologies are energy intensive and harmful to environment. Sustainable cooling technologies are essential to meet the increasing cooling demand in an environmentally friendly manner. Solar cooling has emerged as a viable alternative in this regard. In comparison with conventional electrically driven compression systems, substantial primary energy savings can be expected from solar cooling, thus aiding in conserving energy and preserving the environment. In solar vapour absorption cooling systems, the energy received from the solar collector is given as a heat input to the generator hence the energy has to be stored for a uniform heat supply to the generator. Another advantage of using solar energy is that the cooling demand is highest when the solar intensity is at its highest; however, the problem with solar energy is its intermittent nature and non-uniform intensity. Thermal storage therefore plays a vital role in solar based systems. Thermal storage is, therefore, critical. After the thermal energy is collected by solar collectors, it needs to be efficiently stored when later needed for a release. Thus, it becomes of great importance to design an efficient energy storage system. The following text focuses on the solar thermal energy storage, discussing its design criteria and desirable materials.

The concept of heat storage by an eco-friendly technology could help meet end-use demand economically. It enhances a fraction of the renewable energy utilization and energy efficiency of conventional systems. Energy storage has recently attracted increasing attention in many industrial and commercial applications. This paper illustrates the different types of storage methods, storage materials. The suitability of the PCM based cascaded storage system for solar cooling is also studied and presented in this paper.

The demand of solar energy based cooling systems has increased owing to certain advantages in recent times. The solar collection and storage system consists of a solar collector connected through pipes to the heat storage. Solar collectors transform solar radiation into heat and transfer that heat to the heat transfer fluid (HTF) in the collector. The hot fluid is then stored in a thermal storage unit to be subsequently utilized for various applications such as absorption cooling systems. The performance of solar collection can be enhanced by better stratification in the storage tank. The stratification in the storage tank enhances the solar collector efficiency.

II. SOLAR ENERGY STORAGE METHODS

The heat energy storage (HES) system is one of the most appropriate methods of bridging the gap that exists between the demand and supply of energy. Heat can be stored in sensible/latent form, and by thermo chemical techniques. Thermal energy storage can be achieved in the form of the

a) sensible heat of a solid or liquid medium,
b) the latent heat of a phase change substance, or
c) by a chemical reaction.

Various types of thermal energy storage systems like sensible heat storage, latent heat storage, chemical storage and cascaded storage are studied in terms of design criteria and material selection. The choice of the storage medium depends on the amount of energy to be stored in unit volume, or the weight of the medium, and the temperature range at which it is required for a given application. The sensible heat storage (SHS) units that use water, oil or pebble beds have very low heat capacity per unit volume. On the other hand, the latent heat storage (LHS) unit is particularly attractive, due to its high-energy storage capacity, and its isothermal behaviour during the charging and discharging process. Fig 1 shows the schematic digram of solar energy power cooling system with thermal storage [1].

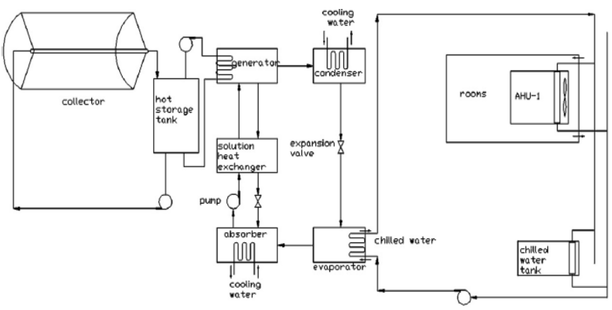

Fig. 1 Schematic diagram of solar energy powered absorption chiler integrated with a parabolic concentrator and storage tank.[1]

The materials used for solar thermal energy storage are classified into three main categories according to different storage mechanisms: sensible heat storage, latent heat storage and chemical heat storage (with their storage capacity in ascending order). Sensible heat storage is the most developed technology and there are a large number of low-cost materials available [2-4], but it has the lowest storage capacity which significantly increases the system size. Latent heat storage has much higher storage capacity, but poor heat transfer usually accompanies if not employing heat transfer enhancement. Chemical storage has the highest storage capacity, but the following problems restrict its application: complicated reactors needed for specific chemical reactions, weak long-term durability (reversibility) and chemical stability.

A. *Criteria for design*

There are three main aspects that need to be considered in the design of a solar thermal energy storage system: technical properties, cost effectiveness and environmental impact [5].
Excellent technical properties are the key factors to ensure the technical feasibility of a solar thermal energy storage system. Firstly, a high thermal storage capacity (sensible heat, latent heat or chemical energy) is essential to reduce the system volume and increase the system efficiency. Secondly, a good heat transfer rate must be maintained between the heat storage material and heat transfer fluid, to ensure that thermal energy can be released/absorbed at the required speed. Thirdly, the storage material needs to have good stability to avoid chemical and mechanical degradation after a certain number of thermal cycles. The other technical properties, such as compatibility and heat loss, are listed in Table 1.

Table 1: Design criteria of a solar thermal energy storage system [5]

Criteria	Influencing factors
Technical criteria	1. High thermal energy storage capacity;
	2. Efficient heat transfer rate between HTF and storage material;
	3. Good Mechanical and Chemical stability of storage material;
	4. Compatibility between HTF, heat exchanger and/ or storage material;
	5. Complete reversibility of a large number of charging and discharging cycles;
	6. Low thermal losses and ease of control.
Cost-effectiveness criteria	1. The cost of thermal energy storage materials;
	2. The cost of the heat exchanger;
	3. The cost of the space and/ or enclosure for the thermal energy storage.
Environmental criteria	1. Operation strategy;
	2. Maximum load;
	3. Nominal temperature and specific enthalpy drop in load;
	4. Integration to the power plant.

Cost effectiveness determines the payoff period of the investment, and therefore is very important. The cost of a solar thermal energy storage system mainly consists of three parts [6]: storage material, heat exchanger and land cost. Cost effectiveness is usually connected with the aforementioned technical properties, because high thermal storage capacity and excellent heat transfer performance can significantly reduce the system volume.
Apart from technical properties and cost effectiveness, there are other criteria to be considered, such as operation strategy and integration to a specific application, which are listed in Table 1.

B. *Stratification in TES*

Thermal storage is a very important link in any solar thermal supply network. Thermal stratification denotes the formation of horizontal layers of a fluid of varying temperatures with the warmer layers of fluid placed above the cooler ones. In a highly stratified storage, the return temperature to the solar collector is lowered leading to an increased efficiency of the solar collector. Collectors capitalize on low temperature heating with reduced heat loss leading to maximum heat gain from solar energy. Several studies have been carried out by researchers on the sensible heat storage systems to improve the overall efficiency of the storage system and collection. Thermal stratification holds the key for the effective charging and discharging of the energy stored. Most of the models proposed in the literature are for simple one dimensional cases. Zurigat et al. [7] have carried out a survey of the stratified thermal storage one-dimensional models available in the literature. They have validated six models with the experimental data, obtained at their laboratory and from the literature, conducted under both constant and varying inlet fluid temperature conditions. The models include the fully stratified storage tank model, a modified version of this model, the viscous entrainment model and the effective diffusivity model. They have further indicated that the increase in the exergy capacity is the greatest for storages at temperatures close to the environment temperature. The exergy analysis by Jack and Wrobel [8] has shown that stratification delays the mixing of the incoming fluid with that in the storage tank, leading to an increase in the overall second-law efficiency and a reduction in the optimum charging time compared to the fully mixed case. The effects of different parameters and dimensionless numbers that influence and characterize stratification have been analyzed by various investigators. [9,10]. The dimensionless group analysis shows that the Richardson number is generally used as the evaluate index. Aspect ratio is one of the critical parameters to obtain stratification. Ievers and Lin [11] analyzed stratification in a storage tank using Fluent software, and concluded that increasing the tank's height/diameter aspect ratio, decreasing the inlet/outlet flow rates and moving the inlet/outlet to the outer extremities of the tank, results in increasing levels of thermal stratification. Andersen et al. [12] presented the thermal behaviour of three different modern stratifiers with fabric and rigid pipes. The effectiveness of stratifiers especially at low flow rates has been shown by Stratification improvements by PCMs have also been reported by different investigators. Cabeza et al. [13] showed that the energy density of the hot water storage tank with stratification, increased with increasing amounts of the PCM module at the top of the tank. By means of simulation and experimental works on PCM integrated hot water stores, Mehling et al. [14] showed an improvement in the energy density, reheating and delay in heat loss of hot water stores.

C. Sensible heat storage (SHS)

In external heat storage systems, the HTF from the solar collectors will be circulated to the hot thermal storage tank to store energy for later use. An SHS system consists of a storage medium, a container and input/output ports. Containers must retain the storage material and prevent loss of thermal energy. The performance of SHS systems is influenced by factors, such as the thermal capacity of the fluid used, the operating temperature range, the design and geometry of the inlet and outlet ports, the mixing introduced during the charge and discharge cycles, thermal losses from the storage device and the degree of thermal stratification in the storage device. In sensible heat storage (SHS), thermal energy is stored by raising the temperature of a solid or liquid. Water is a most commonly used substance for thermal storage owing to its relatively high heat capacity. For cold storage where the difference between charging and discharging usually is lower than 10°C the energy density of the storage is in the order of 10 kWh/m^3. For heat storage this temperature difference can be greater, and the energy density larger, in the order of 40 kWh/m^3 [15]. For high temperatures the pressure in a tank containing water will have to be increased, this could be impractical and therefore other substances are often used. SHS systems utilize the heat capacity and change in temperature of the material during the process of charging and discharging. SHS characterized by temperature variation is a simpler technique, but occupies a larger volume. The amount of stored energy depends on the specific heat of the medium, temperature change and the amount of storage material. Dincer et al. [16] presented a detailed investigation of the availability of SHS techniques for solar thermal applications, selection criteria for SHS systems, and the economics and environmental impact of SHS systems.

D. Sensible heat storage materials

In sensible heat storage, thermal energy is stored during the rising or dropping of temperatures of thermal storage media, which can be either solid state or liquid state. The most commonly-used solid-state thermal storage materials, including sand-rock minerals, concrete, fire bricks and ferroalloy materials.

These materials have working temperatures from 200°C to 1200°C, and have excellent thermal conductivities: 1.0 W/(m K) –7.0 W/(m K) for sand-rock minerals, concrete and fire bricks, 37.0 W/(m K) –40.0 W/(m K) for ferroalloy materials. The materials shown in Table 3 are all low-cost ranging from Rs. 30/kg –Rs. 300/kg. The only disadvantage is their heat capacities being rather low, ranging from 0.56 kJ/kg to 1.3 kJ/kg, which can make the storage unit unrealistically large. Another method of SHS is the use of a packed bed of solids for storing thermal energy. The packed bed provides an effective means of energy storage for many systems and has been satisfactorily employed for various applications. Beasly and Clark [17] summarized the status of the SHS modeling of packed beds, including numerical investigations. Saez and Mcoy [18], Torab and Beasley [19] and Sozen [20] studied the performance of packed bed SHS systems using one-dimensional separate phase's models. Table 2 shows the main characteristics of the most commonly-used solid-state thermal storage materials [6].

Table 2 Solid-state sensible heat storage materials. [6]

Storage Materials	Working Temperature °C	Density [kg/m^3]	Thermal Conductivity W/mK	Specific heat kJ/kg °C	Specific heat kWht/m^{3o}C
Sand-rock minerals	200-300	1700	1.0	1.30	0.61
Reinforced Concrete	200-400	2200	1.5	0.85	0.52
Cast Iron	200-400	7200	37.0	0.56	1.12
NaCl	200-500	2160	7.0	0.85	0.51
Cast Steel	200-700	7800	40.0	0.6	1.30
Silica Fire brick	200-700	1820	1.5	1. 0	0.51
Magnesia brick	200-1200	3000	5.0	1.15	0.96

In a rock-bed-storage rocks, kept in a container, are used as substance. Air is blown through the container to charge and discharge it. This can be practical if the heat source as well as the heat demand is in form of hot air. It seems like it could be used as a cool storage as well. Energy losses from a sensible heat storage are in form of heat flow the storage to the cooler or warmer ambient environment outside the storage. This increases as the temperature difference increases. If additional heat exchangers are needed (to reduce the amount of antifreeze for example) there are also temperature losses. For large-scale storage applications filled rooms below surface of the ground or bore holes into the bedrock can be used. (Note that a single bore hole will not do well as a storage because of extensive heat leakage. For a bore hole storage to work a group consisting of several bore holes is needed). The temperature requirement for the generator will be different depending on the type of vapor absorption system (half/single/double/triple effect). However, for all these systems, heat has to be supplied within a narrow operating temperature range of 5–10°C for better performance. Hence, storing a large quantity of heat within a narrow temperature range in a sensible heat form requires a large volume storage tank. This type of sensible heat storage tank may be useful only for the purpose of providing uniform heat flux to the generator, irrespective of fluctuations in solar radiation intensity. Sensible heat storage is not capable of providing a large quantity of heat required for the generator during non-sunshine hours. Liquid-state thermal energy storage materials are shown in Table 3 [6], including oils, liquid sodium and inorganic molten salts. Liquid-state thermal energy storage materials include oils, liquid sodium and inorganic molten salts.

Table 3 Molten salts and high temperature oils [6].

Storage Material	Working Temperature °C	Density [kg/m³]	Thermal Conductivity W/mK	Specific heat kJ/kg	Specific heat kWht/m³
Mineral oil	200-300	770	0.12	2.6	0.56
Synthetic oil	250-350	900	0.11	2.3	0.58
Silicone oil	300-400	900	0.10	2.1	0.53
Nitrite salts	250-450	1850	0.57	1.5	0.76
Liquid sodium	200-300	850	71	1.3	0.31
Nitrate salts	200-300	1870	0.52	1.6	0.83
Carbonate salts	200-300	2100	0.2	1.8	1.05

Oils have rather high vapour pressure [3] which causes serious safety issues due to requiring an airtight system. Liquid sodium has a thermal conductivity as high as 71.0 W/(m K); however, it is highly unstable in chemical reactivity, therefore incurring much more cost by adopting extra safety measures. Molten salts are regarded as the ideal materials [2-4,6] for use in solar power plant because of their excellent thermal stability under high temperatures, low vapour pressure, low viscosity, high thermal conductivities, non-flammability and non-toxicity.

Zhao and Wu [3] reported a serial of novel ternary salt mixtures with ultra-low melting temperatures of 76°C, 78°C and 80°C, which are all below 100°C so that the system unfreezing becomes much easier. Their salt mixtures consisting of KNO_3, $LiNO_3$ and $Ca(NO_3)_2$ showed much lower viscosities (more than 80%) than synthetic oils and commercial molten salts. Their salt mixtures were also found to have good chemical stability under high temperatures (500°C). Such eutectic salts with melting temperatures below 100°C were also reported by Wang et al. [21] recently. They found a novel quaternary eutectic salt with its melting temperature as low as 99°C. The common advantage of sensible heat storage is its low cost, ranging from Rs. 30/kg – Rs. 300/kg compared to the high cost of latent heat storage which usually ranges from Rs. 260/kg –Rs. 20450/kg [2].

E. Latent heat storage (LHS)

Latent heat storage (LHS) systems are capable of storing a large quantity of heat in smaller volumes and have isothermal behaviour during the heat retrieval process. Hence, the problem encountered in sensible heat storage is avoided in a latent heat storage system that can supply heat to the generator at an approximately constant temperature for a longer duration even during non-sunshine hours. The latent heat storage (LHS) is based on heat absorption or release when a phase change material (PCM) undergoes a phase change. The latent heat storage by PCM in comparison with SHS, possesses a greater density of stored energy and operates in a narrower operational temperature range. Zalba et al. [22] have reviewed various aspects of latent heat storage systems, such as PCMs heat transfer and applications. PCMs are advantageous for the dynamic and static storage of heat energy as they absorb and release large amounts of energy at specific temperatures. However, the low thermal conductivity of PCMs and the losses associated with thermal storage, are its disadvantages. A detailed description on various aspects of thermal storage systems are presented by Dincer et al. [23]. A good understanding of the heat transfer processes involved in an LHTS unit is essential for accurately predicting the thermal performance of the system, and for avoiding a costly system design. Solidification and melting are important phenomena in thermal storage applications.

F. Latent heat storage materials

Phase change materials (PCMs) can store/release a large amount of heat when reforming their phase structures during melting/solidification or gasification/liquefaction processes. Since the phase-transition enthalpy of PCMs are usually much higher (100-200 times as shown in Table 4) than sensible heat, latent heat storage has much higher storage density than sensible heat storage.

Table 4 Commercial PCMs materials, inorganic salts and eutectics [6, 2].

Storage material	Phase change temperatu re °C	Density (kg/ m3)	Thermal Conducti vity (W/m K)	Laten t heat (kJ/k g)	Latent heat (MJ/ m3)
E117(inorg anic)	117	1450	0.70	169	245
$NaNO_3$	307	2260	0.5	172	389
KNO_3	333	2110	0.5	226	477
KOH	380	2044	0.5	150	306
AlSi12	576	2700	1.6	560	1512
$MgCl_2$	714	2140	4	452	967
NaCl	800	2160	5	492	1063
Na_2CO_3	854	2533	2	276	698
KCO_3	897	2290	2	236	540

These materials have phase change temperatures ranging from 100 to 897°C, and latent heat ranging from 124 to 560 kJ/kg. Unlike sensible heat storage in which materials have a large temperature rise/drop when storing/releasing thermal energy, latent heat storage can work in a nearly isothermal way, due to the phase change mechanism. This makes latent heat storage favourable for those applications which require strict working temperatures. However, the main disadvantage of latent heat storage is its low thermal conductivities, which mostly fall into the range of 0.2 W/(m K) to 0.7 W/(m K), and therefore relative heat transfer enhancement technologies must be adopted [24].

G. Chemical storage

Chemical storage uses the same principles as sorption heat pumps. In the closed liquid absorption cycle, storage can be obtained by storing strong or even crystallized solution in (or in connection with) the generator and absorber and refrigerant in the condenser (or in a separate tank). In the solid sorption cycle, storage is obtained by simply holding the process after water has been desorbed from the sorbent. In the open absorption and the desiccant systems, storage can be accomplished in the same way with the exception that no refrigerant needs to be stored. Since the system is still essentially a heat pump the storage cannot be discharged without either input or rejection of heat. When heat is discharged, low-grade heat (low temperature heat) must be provided to an evaporator to create steam that can be absorbed or adsorbed. When cooling capacity is discharged, heat from the absorber/adsorber must be rejected. Rejecting heat should not be a problem when the storage (for example) is used for compensating for lack of solar radiation in a solar air conditioning (because of clouds or during the night). However, if used to cover peak demand due to high solar insolation, high outdoor temperature and high outdoor humidity, heat rejection could be a serious problem. When the storage is being charged, heat needs to be rejected from the condenser; this could also be problematic in a solar air conditioning system since at the time that the energy supply from the solar collectors to charge is most abundant, during peak noon, heat rejection is, as mentioned above, not uncomplicated. A suggested solution for these problems, to use a pond as heat sink, actually is the same as having it connected to a sensible cold storage. Thereby a kind of hybrid storage has been created. The need for heat rejection at storage is not present in an open system.

Collier [25] suggested that open absorption systems are more suitable for chemical storage than a closed, because in an open absorption system the generator is at atmospheric pressure while in a close system it is at subatmospheric pressure. Thus the strong solution in an open system can be stored in a simple tank while strong solution in a closed system would have to be stored in large pressure vessels. However, introducing an additional pump to pump the strong solution from the sub-pressure in the system to a storage tank at atmospheric pressure could easily solve this disadvantage for the closed system. The total lift of this additional pump and the systems normal solution pump together would then be the same as the pressure lift required by the single solution pump in an open system. Adsorption of water in silica gel or on zeolites is a demonstrated technology leading to energy densities based on the volume of adsorbent in the order of 150 kWh/m^3. Reactions involving water and solid salts have been tested but have not yet reached commercial level [7]. Losses in a chemical storage are connected to charging and discharging the storage. Unlike the sensible and latent storage there are no continues heat losses when not charged and discharged. The system could therefore be charged and then left charged for extended times without any energy being lost. A disadvantage with chemical storage is that the sorptive substances seem to be rather expensive, and the storage is also rather complex compared to a sensible or latent storage. This could make it economically unattractive.

Table 5 Materials used as chemical energy storage media.

Materials	Temperature range (°C)	Enthalpy change during chemical reaction
Iron carbonate [26]	180	2.6 GJ/m^3
Metal hydrides [27]	200–300	4 GJ/m3
Ammonia [28]	400–500	67 kJ/mol
Hydroxides, e.g. [27]	500	3 GJ/m3
Calcium carbonate [27, 29]	800–900	4.4 GJ/m3

III. COLD STORAGE (CS)

Storage of cold produced during sunshine hours in a cool thermal storage tank, either in a sensible heat form or in a latent heat form is yet another option of storing energy. Cold storage (CS) has recently attracted increasing interest in industrial refrigeration applications, such as process cooling, food preservation and building air conditioning systems. CS appears to be one of the most appropriate methods for correcting the mismatch that occurs between the supply and demand of energy. Cold energy storage requires a better insulation tank as the energy available in the cool state is expensive, compared to the heat available in a hot storage tank.

Sensible heat chilled water storage systems utilizing stratification tanks were studied by Tran et al. [30] and Musser and Bahnfleth [31]. Nelson et al. [32] have pointed out that the percent cold recoverable in a discharge cycle increases with increasing initial temperature difference, aspect ratio and flow rate. Karim [33] has indicated that partial discharging in one discharge cycle involves a relatively longer residence time of cool water in storage that leads to a significant decrease in thermal efficiency, as the temperature of the chilled water in the tank increases because of heat conduction through the walls. Hence, for any practical requirements the storage system should be designed with several tanks, so that based on the cooling requirement, the required number of tanks can be charged and discharged. Storing energy in the latent form has its own advantage, compared to the energy storage in a sensible heat form. Fukusako and Yamada [34] have reviewed the transport phenomena observed during the melting of the PCM inside ducts and over external bodies. Ermis et al. [35] have proposed a feed-forward back-propagation artificial neural network algorithm, for the heat transfer analysis of the phase change process in a finned tube latent heat thermal energy storage system. They have compared the performance of the model with experimental data and the numerical results obtained through heat transfer analysis with ethyl alcohol as the HTF and pure water as the PCM. For a similar PCM‐HTF combination, Erek and Dincer et al. [36] have dwelt on the entropy and exergy efficiency analysis of a shell and tube latent heat storage system. Ezan et al. [37] investigated the energetic and exergetic performances of a shell and tube latent energy storage system using water as PCM and ethylene glycol as the HTF. They concluded that for the charging period, the exergetic efficiency increased with the increase in the inlet temperature and the flow rate. For the discharging period, irreversibility increased as the temperature difference between the melting temperature of the PCM and the inlet temperature of the HTF increased, and hence the exergy efficiency increased. Bedecarrats et al. [38] presented the experimental results of the charge and discharge modes of LHTS for air conditioning/refrigeration applications using PCM encapsulated spherical capsules. The improvement in the heat transfer rates in storage units employing multiple PCMs, inserting a metal matrix into the PCM, using PCM dispersed with high conductivity particles, and micro-encapsulation of the PCM, have been studied and reported by various researchers. Velraj et al. [39] carried out investigations in cold storage integrated with a large air conditioning system located at Chennai, India. They have concluded that the integration of CS integrated systems in applications such as food preservation, would prove beneficial. Cheralathan et al. [40] investigated the performance of an industrial refrigeration system integrated with CS. The authors have indicated significant savings in capital and operating cost, in thermal storage integrated systems. The size of the PCM based CS system was also considerably reduced when compared with that of a chilled water system. Wu et al. [41] investigated the effects of the flow rate, inlet temperature of the HTF, porosity of the packed bed consisting of n-tetradecane, and the size of the capsules on the dynamic performance of the cool thermal storage system during the charging and discharging process. Fang et al. [42] reported better performance and stable charging and discharging periods of an experimental cool storage air-conditioning system, with a spherical capsules packed bed. The numerical heat transfer analysis of an encapsulated ice thermal energy storage system with a variable heat transfer coefficient by Erek and Dincer [43], has revealed that the solidification process is chiefly governed by the magnitude of the Stefan number, capsule diameter and capsule row number.

A. Chemical heat storage materials

Special chemicals can absorb/release a large amount of thermal energy when they break/form certain chemical bonds during endothermal/exothermal reactions. Based on such characteristics, the storage method making use of chemical heat has been invented. Suitable materials for chemical heat storage can be organic or inorganic, as long as their reversible chemical reactions involve absorbing/ releasing a large amount of heat. When designing a chemical storage system, three basic criteria need to be considered: excellent chemical reversibility, large chemical enthalpy change and simple reaction conditions (reactions cannot be too complicated to be realised). Table 5 gives a list of potential materials for chemical heat storage, most of which have an enthalpy change of 3.6 GJ/m^3 –4.4 GJ/m^3. As seen from Table 4 and Table 5, latent heat storage has storage densities in the order of MJ/m^3, whilst chemical heat storage has much higher storage densities in the order of GJ/m^3. However, chemical storage has not yet been extensively researched, and its application is limited due to the following problems: complicated reactors needed for specific chemical reactions, weak long-term durability (reversibility) and chemical stability.

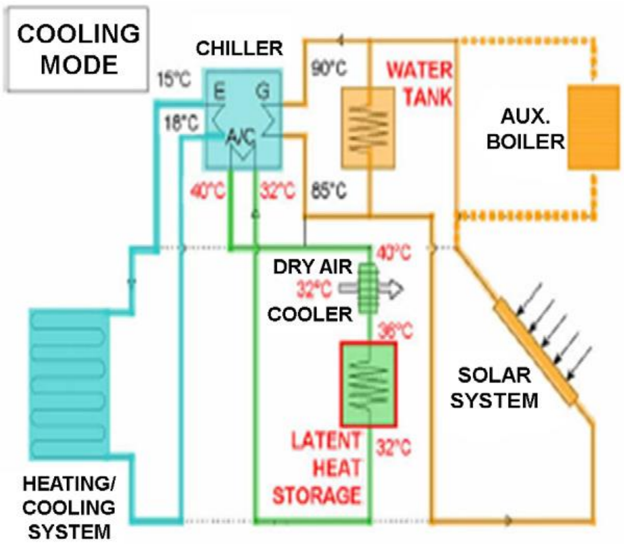

Fig. 2. Solar heating/cooling system with an absorption chiller and latent heat storage in the cooling mode [44].

Helm et al. [44] have described the operation of an absorption cooling system, that involves latent heat storage supporting the heat rejection of the absorption chiller, in conjunction with a dry cooling system as shown in Fig. 2. They have indicated low temperature latent heat storage together with a dry air cooler, as a promising alternative to the conventional

ISSN: 2278-0181
RACEE - 2015 Conference Proceedings

wet cooling tower, as it substantially reduces the over-sizing of the solar collector system. Berlitz et al. [45] have introduced one more concept of storing a cool refrigerant internally in the absorption chiller system, in order to ensure a continuous supply of cool energy with minimal dependence on an external heat source to normalize fluctuation in the availability of solar energy. Rizza [46] has observed that the storage volumetric efficiency for the LiBr/H2O system is greater than or comparable to, that of a thermal storage system based on water-ice, and that it far exceeds the value of a thermal storage system based on liquid water.

IV. CASCADED HEAT ENERGY STORAGE (CHES)

The main advantage of latent heat storage over sensible heat storage is the high storage density within a small temperature band. For the small temperature difference covering the phase change, there is a factor of three between the heat stored in the latent heat storage system and the sensible heat storage system. For a larger temperature difference, the advantage of the latent heat storage shrinks to 6:4 = 1.5, so that there is no reason to prefer a latent heat storage system to a sensible heat storage system. A cascaded storage system offers vast potential for the improvement of a solar cooling system performance. In a cascaded storage system, PCMs with different melting temperatures are arranged in a series to store heat in different temperatures. In comparison with a conventional single PCM based storage system, a cascaded multiple PCM based storage system would improve solar collecting efficiency as the lower temperature at the bottom of the tank is connected to the inlet of the solar collector. The numerical results from the parametric study investigated by Shaikh and Lafdi [47] indicated that the total energy charged rate can be significantly enhanced by using composite PCMs as compared to the single PCM. Gong and Mujumdar [48] proposed a solar receiver store consisting of multiple PCMs and found that the fluctuation of the outlet temperature of the HTF can be greatly dampened by using multiple PCMs compared with a single PCM.

Deng et al. [49] have outlined the need for R&D in the cascade utilization of thermal energy in combined cooling, heating and power systems. Gordon and Ng [50] have proposed a high efficiency solar cooling involving a thermodynamic cascade that comprises of solar-fired gas micro-turbine producing electricity that drives a mechanical chiller, with the turbine heat rejection running an absorption chiller. Depending on the stored temperature level and the temperature required in the generator of an absorption cycle, different solar absorption cooling equipments can be employed to facilitate the use of stored heat. Multiple effect absorption chillers have a higher COP but can operate only at high temperatures. Though half and single effect absorption cooling systems have lower COPs, they are advantageous in utilizing the stored heat at a low temperature. A combination of the multiple effect and half/single effect can thus be chosen, based on stored temperature availability. Technical considerations favour such a combination of thermally driven cooling technologies with a multiple PCM based storage system. However, the cost and space requirements might be a limiting factor. The thermo-economic optimization of such a system would lead to a prudent design, optimization and selection of equipments. However, its economic viability needs further study.

Mehling and Cabeza [51] suggested that the use of a cascaded arrangement of multiple PCMs with different melting temperatures should solve the above problem. Figure 3(b) shows a typical three-stage cascaded storage system: the PCM I with the lowest melting temperature is heated from T_1 to T_2, the PCM II with the medium melting temperature is heated from T_2 to T_3, and the PCM III with the highest melting temperature is heated from T_3 to the maximum temperature. Using such a cascaded storage system, the difference of the stored energy between cascaded latent heat storage and single sensible heat storage is 10:4 = 2.5.

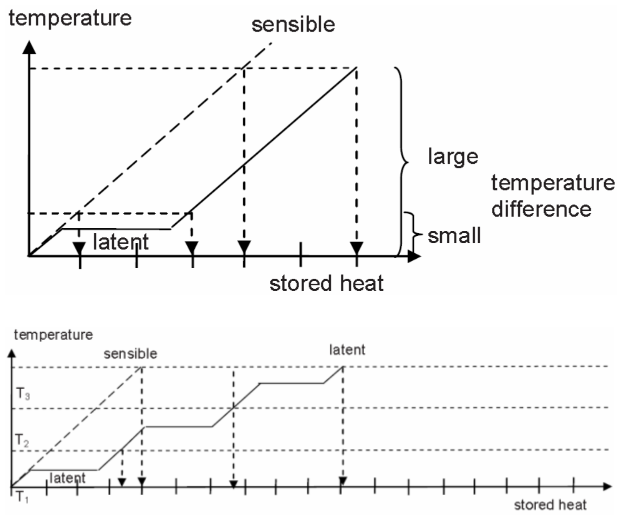

Fig. 3. Comparison of stored heat between sensible heat storage and latent heat storage [51]: (a) With a single PCM; (b) With cascaded latent heat storage.

Another reason for using cascaded thermal energy storage is illustrated as following. A very common practical situation is that the charging and discharging time is usually limited and the heat needs to be absorbed or released quickly. When charging a storage system with only a single-stage PCM, the heat transfer fluid rapidly transfers heat to the PCM. The temperature of the heat transfer fluid therefore reduces, which reduces the temperature difference between the PCM and heat transfer fluid [26] and leads to poor heat transfer at the end of the storage. As a result, the PCM is melted rapidly at the entrance part where the heat transfer fluid enters the storage, but the PCM is melted more slowly at the end of the storage where the heat transfer fluid outflows. For the discharging process, the problem is that the PCM at the end of the storage might not be used for latent heat storage as the temperature of heat transfer fluid rises. By using cascaded thermal energy storage, such problems can be all solved.

Figure 4 gives a comparison between a single-stage PCM system and a five-stage cascaded PCM system [2, 52]. For charging process, a PCM with a lower melting temperature can be placed at the end of the heat exchanger, so that the temperature difference can be large enough to ensure all PCMs to be melted. The cascaded storage system also works efficiently for discharging process. Michels and Pitz-Paal [53] investigated cascaded latent heat storage for parabolic trough solar power plants, and they found that a higher portion of the PCM can run through the phase change process and a more uniform heat transfer fluid outlet temperature was achieved during the discharging process than in the traditional single stage storage system. As the research by Michels and Pitz-Paal suggested, Cascaded Heat Energy Storage (CHES) was found to have higher energy utilisation efficiency than the traditional Single-stage Thermal Energy Storage (STES).

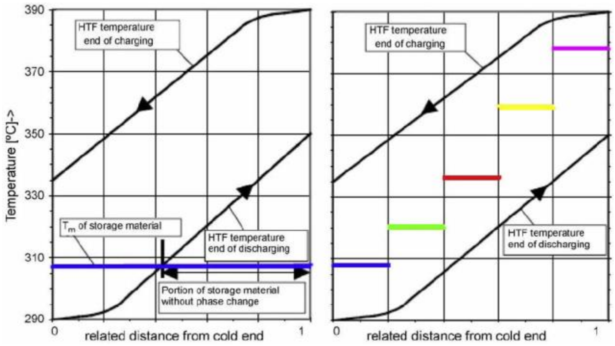

Fig 4. Comparison between a single-stage storage system and a five-stage cascaded storage system

Very recently, Tian and Zhao [54] examined and compared STES, CHES and their newly-proposed Metal Foam-enhanced Cascaded Thermal Energy Storage (MF-CHES). Their research showed that the CHES can not only achieve higher energy efficiency (up to 30%) than STES but can also achieve higher exergy efficiency (up to 23%) than STES. Other findings from their research are: Firstly, MF-CHES can further increase heat transfer rate of CHES by 2–7 times, depending on the properties of the metal-foam samples used (higher pore density and lower porosity can achieve a better performance). Secondly, MF-CHES cannot improve exergy efficiency of CHES, but can help CHES to finish melting more quickly by having higher heat transfer rates (melting time reduced by 67–87%). Thirdly, exergy transfer rate of CHES is further increased by 2–7 times if MF-CHES is used.

V. CONCLUSIONS

It can be concluded from this review that thermal energy storage is essential in the continuous working of the solar energy powered absorption cooling system, in order to correct the intermittent nature of the solar energy. Thermal storage integrated solar cooling systems increase the cooling availability, capacity and improve the overall performance. Absorption chillers have gained considerable attention among researchers. The materials used for high-temperature thermal energy storage systems have been compared, and a comparison between different categories of thermal storage systems has been presented. Molten salts with excellent properties are considered to be the ideal materials for high-temperature thermal storage applications. Heat transfer enhancement is also essential to overcome the poor heat transfer in these applications. For this purpose, graphite composites and metal foams are found to be the ideal materials. More research and development on enhanced solar cooling techniques coupled with a simpler, energy efficient and cost effective thermal storage system, possessing higher energy density would lead to economic competitiveness. It would also assist in the further development of affordable thermal storage systems and increase the market penetration of solar cooling.

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