



## LOW-TEMPERATURE APPLICATIONS OF PHASE CHANGE MATERIALS FOR ENERGY STORAGE: A REVIEW

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### ABSTRACT

*Thermal storage is highly pertinent for systems that utilise solar energy for thermal applications, as well as for energy conservation in buildings. Phase change materials (PCMs) provide as a compelling alternative for thermal energy storage. This study offers a thorough overview of recent studies on the integration of phase change materials (PCMs) in low-temperature applications, including building envelopes, passive systems in buildings, solar collectors, solar photovoltaic systems, and solar desalination systems. Furthermore, methods for enhancing heat transmission in phase change material systems are delineated. All application studies demonstrate that performance enhances when a PCM is implemented. Combined photovoltaic-thermal systems (PVT) are among the most enhanced technologies. The latent heat storage in a Phase Change Material (PCM) is highly appealing due to its elevated storage density and less temperature fluctuation. The selection of the phase change material (PCM) is crucial for the construction of a latent heat storage system, alongside the heat transmission mechanism within the PCM. The literature contains extensive information on latent heat storage materials and systems. This paper aims to compile knowledge from prior research on phase change materials and latent heat storage systems.*

### 1. INTRODUCTION

Thermal energy storage (TES) refers to the temporary retention of thermal energy at elevated or reduced temperatures. Energy storage mitigates the temporal or quantitative discrepancies between energy supply and demand, significantly contributing to energy conservation. This technique stores thermal energy by heating or cooling a medium, allowing the stored energy to be utilised later for heating, cooling, and power production applications.

Thermal energy storage systems may be classified as either centralised or dispersed systems. Centralised applications may be utilised in district heating or cooling systems, extensive industrial facilities, combined heat and power plants, or renewable energy plants. Distributed systems are mostly utilised in residential or commercial structures to harness solar energy for water and space heating or cooling. In both instances, TES systems may diminish energy use at peak periods. The economic performance of a TES system is significantly influenced by its particular application and

operational requirements, including the quantity and frequency of storage cycles. Generally, PCM and TCS systems are costlier than sensible heat systems and are economically feasible solely for applications requiring a high frequency of cycles. In wealthy nations, a significant limitation for TES implementation is the low rate of new building construction, but in emerging economies, TES systems provide greater deployment potential. TES systems are utilised specifically in edifices and industrial operations. In these applications, over fifty percent of the energy utilised is in the form of thermal energy, the demand for which may fluctuate during the day and from one day to another. Consequently, TES devices can assist in equilibrating energy demand and supply on a daily, weekly, and even seasonal scale. They can diminish peak demand, energy consumption, CO<sub>2</sub> emissions, and expenses, while enhancing the overall efficiency of energy systems. Moreover, the conversion and storage of variable renewable energy as thermal energy can enhance the proportion of renewable energy in the energy portfolio. Thermal Energy Storage (TES) is increasingly vital for electricity storage in conjunction with concentrating solar power plants, allowing solar heat to be retained for electricity generation during periods of insufficient sunlight.

Energy storage mitigates the disparity between supply and demand, enhances the performance and stability of energy systems, and is crucial for energy conservation (Garg et al., 1985; Project Report; n.d). It results in the conservation of premium fuels and enhances cost-effectiveness by minimising energy waste and capital expenditure. For instance, storage would enhance the operation of a power producing facility through load levelling, while increased efficiency would result in energy conservation and reduced generation costs. A promising method for thermal energy storage is the utilisation of phase change materials (PCMs). Regrettably, before the extensive practical use of this technology, it is essential to address certain issues during the research and development phase. The following are types of energy storage methods.

If mass-specific heat capacity is not minimal, denser materials possess smaller volumes and hence offer a greater energy capacity per unit volume. The available space is constrained in both transportation and habitat purposes. The volume used by current storage systems is substantial and may significantly restrict the size of available storage. The quantity of energy storage available is determined by the expense. The expense of floor area or volumetric capacity should be a key factor in optimising storage dimensions.

The technology of thermal energy storage has advanced to a level where it can substantially impact contemporary living. The primary nontechnical application of thermal storage was to provide a consistent temperature in residences, ensuring warmth during frigid winter evenings. Substantial stones, cast iron blocks, and ceramics were employed to retain heat from an evening fire into the night. The industrial revolution heralded the introduction of thermal energy storage as a by-product of energy generation. A range of novel thermal energy storage systems has emerged in the past. A primary application for thermal storage now resides in residential homes. Heat storage at power plants is generally in the form of steam or hot water and is normally for a brief duration.

Recently, additional materials, such as oils with elevated boiling points, have been proposed as heat storage mediums for electric utilities. Alternative materials with elevated heat of fusion at high temperatures have also been proposed for this application. Another application of thermal energy storage in electric utilities is the provision of hot water. The most promising application of thermal energy storage is in solar-heated structures, and virtually any material can be utilised for this purpose.

There are three types of Thermal Energy Storage (TES) systems: 1) sensible heat storage, which involves the retention of thermal energy through the heating or cooling of a liquid or solid medium (e.g., water, sand, molten salts, rocks); 2) thermochemical storage (TCS), which employs chemical reactions to store and release thermal energy. 3) Latent heat storage utilising phase change materials (PCMs), such as the transition from solid to liquid form.

**Table 1.** A standard comparison of thermal energy storage systems ((Hauer. 2011)

TES System	Capacity (kWh/t)	Power (MW)	Efficiency (%)	Storage period (h, d, m)	Cost (€/kWh)
Sensible (hot water)	10--50	0.001-10	50-90	d/m	0.1-10
PCM	50-150	0.001-1	75-90	h/m	10--50
Chemical reactions	120-250	0.01-1	75-100	h/d	8-100

## 2. Sensible Heat Storage

Heating a liquid or solid without altering its phase is referred to as sensible heat storage. Sensible heat storage is comparatively economical in relation to PCM and TCS systems and is suitable for residential systems, district heating, and industrial applications. Nevertheless, sensible heat storage typically necessitates substantial volumes due to its poor energy density, which is three to five times inferior than that of phase change materials (PCM) and thermochemical storage (TCS) systems, respectively. Moreover, sensible heat storage devices necessitate meticulous design to release thermal energy at uniform temperatures. A number of developers in Germany, Slovenia, Japan, Russia, and the Netherlands are engaged in the advancement of new materials and methodologies for all Thermal Energy Storage (TES) systems, encompassing their incorporation into building walls (for instance, by embedding phase change materials within plaster or air vents) and the conveyance of thermal energy across various locations. The commercialisation of these novel applications is already underway, necessitating verification of their cost, performance, and dependability.

The selection of the material is primarily contingent upon the application's temperature, with water utilised for temperatures below 100°C and refractory bricks employed for temperatures approximately 1000°C. Sensible heat storage systems have a simpler design compared to latent heat or bond storage systems. However, they are disadvantaged by their larger bulk. Consequently, a crucial consideration in the selection of a material for sensible heat storage is its density and specific heat capacity. A secondary drawback of sensible heat systems is their inability to store or supply energy at a uniform temperature.

### 2.1 Liquids as a Medium for Thermal Storage

A diverse array of chemicals has been utilised in these systems. This encompasses liquids such as water, heat transfer oils, and specific inorganic molten salts, as well as solids like rocks, pebbles, and refractory materials.

Due to its superior specific heat capacity, water is the predominant medium utilised in sensible heat storage systems. Most solar water heating and space heating systems utilise hot water storage tanks situated either indoors, outside, or underground. The tank sizes range from few hundred litres to several thousand cubic meters. A general guideline for determining size is to allocate around 75 to 100 litres of storage for each square metre of collector surface.

Water storage tanks are constructed from various materials, including steel, concrete, and fibreglass. The tanks are adequately insulated with glass wool, mineral wool, or polyurethane. The insulating thickness is substantial, ranging from 10 to 20 cm. Consequently, the expense of insulation constitutes a substantial portion of the overall cost, necessitating the exploration of methods to mitigate this expenditure. Shelton has demonstrated that the insulating properties of the earth encasing an underground tank may be sufficient, perhaps supplying the majority of the necessary insulation thickness. It may require up to one year for the soil surrounding a big storage tank to attain a stable state by heating and drying, necessitating a significant amount of energy for this process. At atmospheric pressure, the temperature of water is restricted to 100°C. Water can be

stored at temperatures slightly over 100°C with pressurised tanks. This has occurred in several occasions.

**Table 2.** Characteristics of Liquid Media for Sensible Heat Storage.

Medium	Fluid Type	Temp. Range (°C)	Density Kg/m <sup>3</sup>	Heat Capacity (J/kg.K)	Thermal Conductivity (W/m.K)
Water	-	0 to 100	1000	4190	0.63 at 38°C
Water-Ethylene Glycol 50/50	-	-	1050	3470	-
Caloria HT43	Oil	-10 to 315	-	2300	-
Dowtherms	Oil	12 to 260	867	2200	0.112 at 260°C
Therminol 55	Oil	-18 to 315	-	2400	-
Therminol 66	Oil	-9 to 343	750	2100	0.106 at 343
Ethylene Glycol	-	-	1116	2382	0.249 at 20°C
Hitec	Molten salt	141 to 540	1680	1560	0.61
Engine oil	Oil	Up to 160	888	1880	0.145
Draw salt	Molten salt	220 to 540	1733	1550	0.57
Lithium	Liquid salt	180 to 1300	510	4190	38.1
Sodium	Liquid salt	100 to 760	960	1300	67.5
Ethanol	Organic liquid	Up to 78	790	2400	-
Propanol	- do -	Up to 97	800	2500	-
Butanol	- do -	Up to 118	809	2400	-
Isobuthanol	- do -	Up to 100	808	3000	-
Isopentanol	- do -	Up to 148	831	2200	-
Octane	- do -	Up to 126	704	2400	-

Heat transfer oils are utilised in sensible heat storage systems at intermediate temperatures between 100 and 300 °C. Dowtherm and Therminol are among the heat transfer oils utilised for this application. The issue related to heat transfer oils is their propensity to deteriorate over time. The deterioration is most severe when utilised over their prescribed temperature threshold. The utilisation of oils poses safety hazards due to the potential for fire exceeding their flash point. Consequently, it is advisable to utilise them in systems with an inert gas overlay. An additional constraint regarding the utilisation of heat transfer oils is their expense. Consequently, they may be deemed suitable exclusively for compact storage systems. Several molten inorganic salts have been evaluated for elevated temperatures (300°C and higher). One is a eutectic composition of 40 percent NaNO<sub>2</sub>, 7 percent NaNO<sub>3</sub>, and 53 percent KNO<sub>2</sub> (by weight), marketed under the trade name 'Hitec'. Hitec possesses a melting point of 145°C and is applicable at temperatures up to 425°C.

Above this temperature, breakdown and oxidation commence. Another molten salt under consideration for high-temperature storage is sodium hydroxide, possessing a melting point of 320°C and applicable for temperatures reaching 800°C. Nonetheless, it is quite caustic and poses challenges in containment at elevated temperatures. Water, due to its low cost and abundant availability, can be efficiently utilised for the storage of sensible heat.

The benefits and drawbacks of this storage can be encapsulated as follows:

*Benefits:*

- a. Water is economical, manageable, non-toxic, non-flammable, and readily accessible.
- b. Water possesses a relatively elevated specific heat and high density.
- c. Heat exchangers can be circumvented when water serves as the heat transfer medium in the collector.
- d. Natural convection currents can be employed when energy for pumping is limited.
- e. The storage tank can be charged and discharged simultaneously.
- f. The regulation and management of a water system are adaptable and versatile.

*Drawbacks:*

- a. Water may undergo freezing or boiling.
- b. Water has significant corrosive properties.
- c. Operational temperatures are restricted to below 100°C and frequently must be significantly lower than this boiling point.
- d. Water is challenging to stratify.

Chemical additives can address issues related to freezing and corrosion. Water can occasionally maintain economic competitiveness at elevated temperatures, particularly when kept in aquifers, despite the necessity for pressure containment. Organic oils, molten salts, and liquid metals mitigate the issues associated with vapour pressure; however, they present additional constraints regarding handling, containment, cost, storage capacity, and operational temperature range. Despite its utilisation in commercial operations, the longevity and cost constraints of these fluids restrict their employment in areas such as space heating. Oils and molten salts have been employed in solar thermal power systems.

## **2.2 Prudent energy storage in anhydrous molten salts/nitrates**

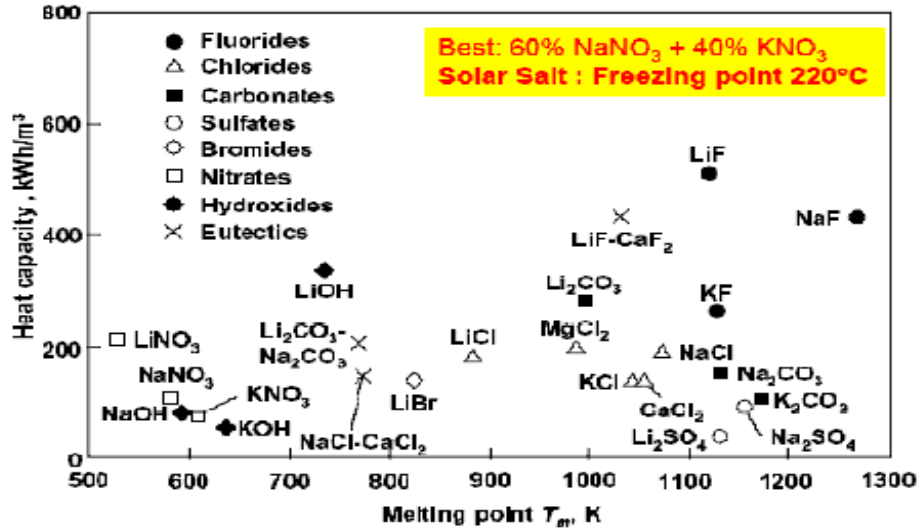
Molten salts are the most appropriate medium for sensible heat storage at extreme temperatures ( $T > 100\text{ }^{\circ}\text{C}$ ). The benefits of molten salts include their elevated thermal stability, comparatively low material expenses, substantial heat capacity, high density, non-flammability, and minimal vapour pressure. Pressurised vessels are unnecessary due to the low vapour pressure.

Molten salts have a higher melting point than organic heat transfer fluids. Consequently, a significant problem associated with molten salts is to prevent solidification during operation. Consequently, auxiliary heating systems or the creation of low-melting-point salts are generally necessary. A novel technique for identifying the composition of salt mixtures with a reduced melting point is introduced at the conclusion of this section. Moreover, the constraints of molten salt storage may stem from the expenses associated with storage media, the potential for corrosion, and the challenges in treating hygroscopic salts.

A non-eutectic molten salt mixture including 60 wt % sodium nitrate ( $\text{NaNO}_3$ ) and 40 wt % potassium nitrate ( $\text{KNO}_3$ ) is employed for sensible heat storage in solar power plants. This combination is commonly referred to as "Solar Salt." The elevated quantity of  $\text{NaNO}_3$  relative to the eutectic mixture allows for a reduction in material expenditures. The non-eutectic mixture exhibits a liquidus temperature of approximately 240 °C, whereas its thermal stability limit is around 550 °C. For high-temperature applications, salts containing alternative anions, such as carbonates,

chlorides, and fluorides, may be viable choices. Currently, experience with oxyanion salts and halogen salts is confined to theoretical investigations (Forsberg et al, 2006; Singer et al, 2010). A typical illustration of various types of salts utilised as sensible liquid heat storage materials is presented in the Figure. 1

Figure 1. Molten Salts (Sensible Liquid Heat Storage Materials) (7)



**2.3 Additional ways of sensible energy storage are currently under consideration as follows:**

*2.3.1 Underground Thermal Energy Storage (UTES)*

UTES is a prevalent storage technique that use subsurface resources for the storage of both thermal energy and refrigeration. UTES technologies encompass borehole storage, aquifer storage, cavern storage, and pit storage. The selection of these methods is heavily contingent upon local geological circumstances.

*2.3.2 Borehole Storage*

It relies on vertical heat exchangers situated underground, facilitating the flow of thermal energy to and from subsurface strata (e.g., clay, sand, rock). Numerous initiatives seek to achieve seasonal storage of solar thermal energy during summer for the purpose of heating residential or commercial spaces in winter. Ground heat exchangers are commonly utilised alongside heat pumps, wherein they extract low-temperature heat from the earth.

*2.3.3 Aquifer Reservoir*

It utilises a natural subterranean aquifer as a storage medium. Thermal energy transfer is accomplished through mass transfer, namely by withdrawing or reinjecting water into the subterranean layer. Most applications include the preservation of winter cold for the purpose of cooling large office buildings and industrial activities throughout the summer. A primary requirement for this technology is the presence of appropriate geological formations.

*2.3.4 Cavern and Pit Storage*

It relies on extensive subterranean water reservoirs established in the subsoil to function as thermal energy storage systems. These storage alternatives are technically viable; nevertheless, their applicability are constrained due to substantial investment costs. For high-temperature sensible heat storage (i.e., exceeding 100 °C), the preferred approach utilises liquids such as oil or molten salts, the latter suitable for temperatures up to 550 °C. For extremely high temperatures, solid materials like ceramics and concrete are also considered. Nevertheless, the majority of high-

temperature-sensible thermal energy storage alternatives remain in the stages of development or demonstration.

### **3. LATENT HEAT STORAGE**

Latent heat storage (LHS) relies on the absorption or release of heat during the phase transition of a storage medium between solid and liquid or liquid and gas states. Latent heat storage operates on the idea that when heat is applied to a material, it undergoes a phase transition from solid to liquid, storing energy as latent heat of fusion, or from liquid to vapour, storing energy as latent heat of vapourisation. Upon extraction of the stored heat by the load, the material will revert to its solid phase from liquid or to its liquid phase from vapour. The latent heat of phase transition between solid states is minimal. Solid-vapor and liquid-vapor transitions involve significant heat of transformation; yet, substantial volume changes complicate the system and render it impracticable. The solid-liquid transitions entail comparatively little alterations in volume. These materials exhibit a variety of transition temperatures. Sensible heat storage is cost-effective; nonetheless, it is characterised by poor energy density and fluctuating discharge temperatures (energy conversation, n.d).

These challenges can be addressed by phase change materials (PCM)-based thermal energy storage (TES), which facilitates enhanced storage capacities and specific discharge temperatures. The phase transition may occur as either a solid/liquid or a solid/solid event. Melting procedures require energy densities of 100 kWh/m<sup>3</sup> (e.g., ice), in contrast to the normal 25 kWh/m<sup>3</sup> for sensible heat storage alternatives. Figure 3 juxtaposes the attainable storage capacity at a specific temperature differential for a storage medium with phase transition vs one without.

Phase change materials are applicable for both short-term (daily) and long-term (seasonal) energy storage, employing various processes and materials. The integration of micro-encapsulated phase change materials (e.g., paraffin wax) into gypsum walls or plaster can significantly enhance the thermal mass and capacity of lightweight construction walls. The micro-encapsulated phase change materials (PCMs) harden at night and melt during the day, thereby cooling the walls and minimising or eliminating the necessity for electric chillers. Additional uses for active cooling systems include the utilisation of macro-encapsulated salts that liquefy at a designated temperature. The PCM can be kept in the building's air vent ducts, and cold air can be distributed by extensive ceiling and floor ventilation systems. PCM slurries are a potential technique. Ice slurries or water-paraffin dispersions may be utilised for construction or industrial cooling applications. Slurries, being pumpable, can serve for the storage or distribution of heat energy.

Phase change heat storage offers the benefit of compactness, as the latent heat of fusion for most materials significantly exceeds their enthalpy change for 1 K or even 0 K. The ratio of latent heat to specific heat of water is 80, indicating that the energy necessary to melt one kilogramme of ice is 80 times greater than that needed to increase the temperature of one kilogramme of water by one degree Celsius.

Moreover, the phase change materials (PCMs) solidify and, as a result, are typically unsuitable as heat transfer mediums in solar collectors or for the load. Numerous phase change materials have inadequate thermal conductivity, necessitating extensive heat exchange surfaces. Some are corrosive and necessitate specialised containers. Latent heat storage materials are costlier than the commonly utilised sensible heat storage media, such as water and rocks. These augment the system expenses.

Owing to its substantial expense, latent heat storage is more apt to be utilised when:

- a. High energy density or high volumetric energy capacity is essential, particularly in environments where space is limited or in transportation when both volume and weight must be minimised.

- b. The load necessitates energy at a constant temperature or within a narrow temperature range, or
- c. The storage capacity is limited. Reduced storage possesses a greater surface area to volume ratio, resulting in elevated packing costs. Compactness is crucial for minimising containment expenses. Likewise, heat losses are approximately proportional to the surface area. Compactness is a crucial aspect in minimising heat losses in small-capacity storage systems.

### 3.1 Classification of Phase Change Materials (PCMs)

Phase Changing Materials can be categorised into three groups based on their composition: 1. Organic PCMs 2. Inorganic PCMs 3. Eutectic PCMs The categorisation of PCM according to their composition (Perez et al, 2010; Microtek Laboratories, 2010) is presented in Table 2.

**Table 2.** Classification of Phase Change Materials

Pcm Type	Composition
Organic	Paraffin Compounds Compounds Without Paraffin
Inorganic	Hydrated Salts, Metallic
Eutectics	Organic-Organic                      Organic-Inorganic Inorganic-Inorganic

#### 3.1.1 Organic Phase Change Materials

Organic materials undergo melting and freezing without deterioration or segregation and exhibit self-nucleation properties. Organic phase change materials are categorised into paraffins and non-paraffins.

##### 3.1.1.1 Alkanes

Paraffins consist of mixes of n-alkanes. The heat is emitted during the crystallisation of these alkane chains. As the chain length rises, both the latent heat of fusion and the melting point rise. Paraffins are reliable and economical. Systems utilising them exhibit prolonged freeze and melt cycles. Nonetheless, they exhibit several undesirable characteristics, including limited heat conductivity and flammability. Such unwanted characteristics can be eradicated by adjusting the wax content. Paraffin waxes are the predominant phase change materials (PCMs) utilised in electronic thermal management due to their elevated heat of fusion per unit weight, extensive melting point range, reliable cycling performance, non-corrosive nature, and chemical inertness. In the design of paraffin phase transition materials, void control is crucial due to the volumetric alteration from solid to liquid state. Paraffin phase change materials have low heat conductivity, hence establishing adequate conduction pathways is a crucial design consideration.

##### 3.1.1.2 Non-Paraffins

In contrast to paraffins, each material classified as a non-paraffin has distinct features. They surpass paraffins in quantity. They are abundantly available. The characteristics of these non-paraffins encompass elevated heat of fusion, diminished thermal conductivity, toxicity, and instability at elevated temperatures. Microencapsulation and macroencapsulation of phase change materials are the two methods that categorise them into micro and macro PCMs.

#### 3.1.2 Inorganic Phase Change Materials

Inorganic phase change materials do not experience supercooling to the necessary degrees, and there is no deterioration of latent heat of fusion. Inorganic phase change materials (PCMs) are further categorised into salt hydrates and metallics.

##### 3.1.2.1 Salt Hydrates

The standard formula for salt hydrates is  $AB_nH_2O$ . The most notable characteristics of salt hydrates are their high latent heat of fusion, elevated thermal conductivity, and minimal volume fluctuations. They are inert and non-toxic. The primary issue with utilising salt hydrates is congruent melting. The issue of congruent melting can be addressed through mechanical agitation, encapsulation, the

incorporation of thickening agents and water, as well as alterations to the chemical composition of the system. Hydrated salts constitute an additional group. These PCMs possess a substantial heat of fusion per unit weight and volume, exhibit relatively good thermal conductivity for non-metals, and demonstrate minimal volume variations between solid and liquid phases. These materials are infrequently utilised for electronic heat sinks due to their corrosive nature and the unknown long-term dependability over thousands of cycles. The predominant application is for extensive thermal storage systems (e.g., solar heating), where the much reduced cost is highly appealing.

**3.1.2.2. Metallic substances**

Low melting point metals constitute a subclass of metallic elements. Nonetheless, the application of metals is restricted, even in low-volume scenarios.

**3.1.3 Eutectics**

A eutectic is a compound of two or more components that has the lowest melting point, wherein each component melts and freezes congruently, resulting in a mixing of the component crystals during crystallisation. Eutectic compositions practically melt and solidify without segregation, as they crystallise into a homogeneous mixture, minimising the potential for component separation. Upon melting, both components liquefy together with improbable separation.

**Table 3.** PCM Types Include Paraffin Waxes, Non-Paraffin Organics, Hydrated Salts, and Metallics

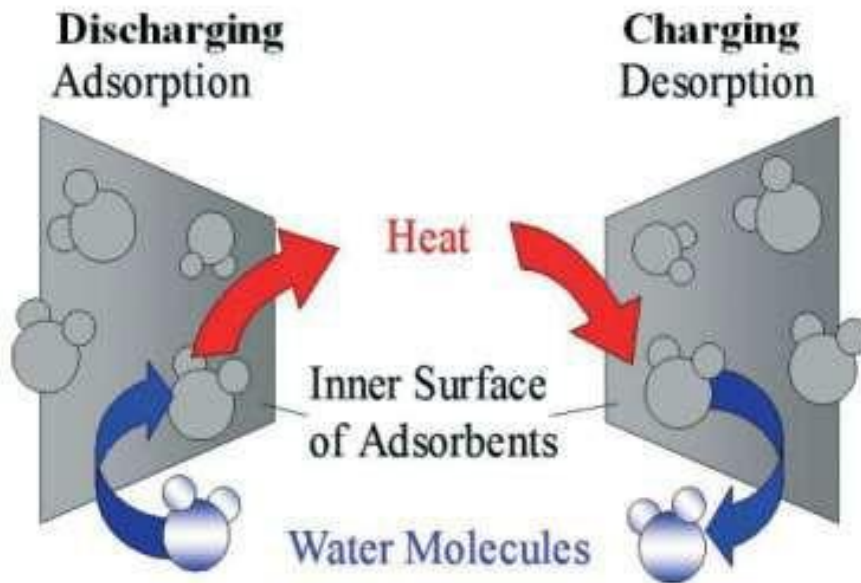
Property or Characteristic	Paraffin Wax	Non-Paraffin Organics	Hydrated Salts	Metallics
Heat of Fusion	High	High	High	Med.
Thermal Conductivity	Very Low	Low	High	Very High
Melt Temperature (°C)	-20 to 100+	5 to 120+	0 to 100+	150 to 800+
Latent Heat (kJ/kg)	200 to 280	90 to 250	60 to 300	25 to 100
Corrosive	Non-Corrosive	Mildly Corrosive	Corrosive	Varies
Economics	Medium	High to very high	Low cost	Medium to High
Thermal Cycling	Stable	Elevated Temperature Can Cause Decomposition	Unstable over Repeated Cycles	Stable
Weight	Medium	Medium	Light	Heavy

**4. THERMAL ENERGY STORAGE THROUGH CHEMICAL REACTIONS**

A chemical energy storage system typically consists of one or more chemical molecules. The TES category encompasses sorption and thermochemical processes. In a thermochemical energy system, energy is stored during a dissociation reaction and subsequently retrieved by a chemically reversal reaction (Abedin et al, 2011). In this entirely reversible chemical reaction, the temperature of certain compounds may be increased or decreased. Therefore, this chemical heat energy can be stored using many effective methods for long-term use. The heat retained is contingent upon the quantity of storage material, the endothermic heat of reaction, and the degree of conversion (Atul et al, 2009).

High energy density (i.e., 300 kWh/m<sup>3</sup>) thermal energy storage systems can be realised by chemical reactions (e.g., thermo-chemical storage, TCS) (energy conversation, n.d). Thermo-chemical reactions, including adsorption (the adherence of a material to the surface of another solid or liquid),

can be utilised for the storage of heat and cold, as well as for humidity regulation. Common applications include the adsorption of water vapour onto silica gel or zeolites, which are micro-porous crystalline aluminosilicates. Open sorption systems utilising lithium chloride for water cooling and zeolites for humidity management are particularly significant for application in hot, humid areas or confined places with elevated humidity levels. Figure 2 illustrates an instance of thermal energy storage via an adsorption process (e.g., water vapour on zeolite): during the charging phase, water molecules are desorbed from the internal surface of the adsorbent. The TES persists in this condition until water molecules are absorbed by the adsorbent, at which point the TES is recharged.



**Figure 2** - TES De/Adsorption Mechanism

Thermochemical materials (TCMs) represent a promising alternative for long-term thermal energy storage. The process in question relies on a reversible chemical reaction that is energy-intensive in one direction and energy-releasing in the other way. Typically, TCMs exhibit superior storage density with repeating storage characteristics suitable for sorption storage systems, and certain materials may approach the storage density of biomass features (Hastings et al, 2007). Due to their elevated energy density, thermochemical thermal energy storage systems can offer more compact energy storage compared to latent and sensible thermal energy storage systems (Bales et al, 2006; Hadorn, 2005). Extensive research and trials on diverse storage technologies indicate that thermochemical energy storage systems may emerge as the most efficient and cost-effective means of storing and utilising waste heat (Darkwa et al, 200; Perry et al, 1984).

**Table 4.** Shows some of the sorption materials that are currently under investigation

Material	Density( $\rho$ ), kg/m <sup>3</sup>	Energy density, MJ/m <sup>3</sup>
Aluminium oxide, Al <sub>2</sub> O <sub>3</sub>	3970	4320
Barium oxide, BaO	5720	4906
Borax, Na <sub>2</sub> B <sub>4</sub> O <sub>2</sub> .10H <sub>2</sub> O	1730	1218
Calcium oxide, CaO	3300	6158
Magnesium oxide, MgO	3580	6874

#### **4.1 Combined Heat and Power Storage Systems**

CHPs exemplify systems for the conversion and storage of chemical thermal energy (Kato et al, 2007). A CHP utilises the conversion of thermal energy into potential energy (Wang et al, 2008). CHPs employ reversible chemical reactions and sorption to modify the temperature of thermal energy stored in chemical compounds (Kawasaki, et al, 1999; Wongsuwan et al, 2001). These chemical substances are crucial in the absorption and release of heat (Kato et al, 1996). Depending on the nature of the chemical reaction, numerous chemical substances may be involved in CHPs. A CHP system can be classified as either a mono-variant system or a di-variant system (Wang et al, 2008; Wongsuwan et al, 2001).

### **5. ECONOMIC ASSESSMENT OF THERMAL ENERGY SYSTEMS**

Cost assessments of TES systems encompass storage materials, technical apparatus for charging and discharging, and operational expenses. Thermal energy storage systems for sensible heat are quite economical, as they primarily comprise a basic tank for the storage medium and the apparatus for charging and discharging. Storage medium, such as water, soil, rocks, concrete, or molten salts, are typically cost-effective. The storage material's container need efficient thermal insulation, which could significantly impact the TES cost. Several seasonal thermal energy storage systems have been implemented in Germany (Solites et al, 2007). Most systems have a water reservoir of 5,000-10,000 m<sup>3</sup>, possessing an energy content of 70-90 kWh/m<sup>3</sup> and investment expenditures ranging from €50-200/m<sup>3</sup> of water equivalent, resulting in a particular investment cost of €0.5-3.0 per kWh. In UTES systems, boreholes and heat exchangers are the primary cost components for activating subterranean storage. Particular costs vary from €0.1 to €10 per kWh and are significantly influenced by local variables.

Phase change material (PCM) storage and thermo-chemical storage (TCS) systems exhibit considerably more complexity and cost compared to sensible heat storage systems. In numerous instances (e.g., thermo-chemical reactors), advanced heat and mass transport technologies are employed to attain the necessary performance regarding storage capacity and power, resulting in equipment costs significantly exceeding those of the store material. The price of a PCM system typically varies from €10 to €50 per kWh (Solites et al, 2007). The expense of systems employing costly micro-encapsulated phase change materials, which eliminate the necessity for heat exchange surfaces, might be significantly greater. The total cost of complete plasterboard (€17/kg), incorporating micro-encapsulated paraffin for use as a passive cooling mechanism in building constructions (e.g., gypsum boards), comprises the price of paraffin (about €5/kg) and the micro-encapsulated substance (€13/kg).

The disparity between pure PCM and the comprehensive TES system is even greater for active PCM installations. The expenses associated with a calcium-chloride storage system for the heat expelled from a thermally-driven absorption chiller encompass the cost of calcium chloride, which is quite low (€0.3/kg), as well as the expenses for a container, heat exchanger, and additional components, totaling approximately €65/kWh. Materials for thermo-chemical storage (TCS) are costly due to the necessity of preparation, such as pelletisation or layering on supporting structures. The containers and supplementary TCS equipment for heat and mass transfer during energy charging and discharging are also costly. TCS systems can function as either open systems (essentially packed beds of pellets at ambient pressure) or closed systems. Open systems are typically the most economical choice, whereas closed systems require advanced heat exchangers. The TCS cost varies from €8 to €100 per kWh.

### **6. TES — CONCERNS AND CHALLENGES**

ES technologies encounter several obstacles to market introduction, with cost being a significant concern. Additional obstacles are to material characteristics and stability, particularly concerning TCS. Every storage application necessitates a tailored TES design to accommodate certain boundary constraints and requirements. Research and development endeavours concentrate on all thermal

energy storage systems. Most of these R&D initiatives focus on materials (i.e., storage media for various temperature ranges), containers, and the development of thermal insulation. More intricate systems (e.g., PCM, TCS) necessitate research and development endeavours to enhance reactive materials, alongside a deeper comprehension of system integration and process parameters. Market development and penetration fluctuate significantly based on application domains and geographical regions. In Europe, the adoption of TES systems in the building sector is very sluggish, with new construction occurring at approximately 1.3% annually and renovation rates at about 1.5%; hence, the incorporation of TES systems is more feasible during the construction phase. The assessment of European potential relies on a 5% adoption rate of TES systems in edifices. Penetration may be significantly greater in emerging economies due to their elevated rates of new development. The potential of thermal energy storage for co-generation and district heating in Europe is linked to the existing building stock. The co-generation implementation rate is 10.2% (Darkwa et al, 2006), but the implementation of thermal energy storage in these systems is estimated at 15%. In the realm of thermal energy storage (TES) for power applications, a significant area is concentrating solar power, where nearly all new power plants currently operational or under construction are outfitted with TES systems, predominantly utilising molten salt. This may be the most significant advancement submitted for big, centralised thermal energy storage installations. In the industrial sector, around 5% of final energy consumption is estimated to be utilised by thermal energy storage systems. The utilisation of industrial waste heat is anticipated to increase due to the rising costs of fossil fuels, with energy efficiency becoming crucial for competitiveness. The University of Lleida study indicates that the proliferation of TES technologies is anticipated to be substantial in Europe and Asia, especially in Japan, while it is projected to be moderately lower (50%) in the United States. The worldwide potential is approximated to be thrice that of the European potential.

Researchers across are seeking novel and renewable energy sources. One possibility is to develop energy storage devices, which are equally crucial as creating new energy sources. Thermal energy storage is crucial for numerous operations. Latent heat storage is particularly appealing due to its capacity to store substantial energy inside a compact volume while maintaining minimal temperature variation in the medium. Latent heat storage is a novel field of research initiated by Dr Telkes in the 1940s (Lane,1983). It garnered limited attention until the energy crisis of the late 1970s and early 1980s, during which it was actively studied for application in solar heating systems (Lane,1983;Abhat, 1983). As the energy crisis diminished, far less focus was placed on latent heat storage. While investigations into latent heat storage for solar heating systems persist (Kaygusuz, 1999 ; Sari et al, 2000), it is progressively regarded for waste heat recovery and load levelling in power generation (El-Dessouky et al, 1997). Latent heat storage can be achieved via solid-liquid, liquid-gas, solid-gas, and solid-solid phase transitions; however, the only two of practical significance are solid-liquid and solid-solid. The solid-gas and liquid-gas systems possess restricted utility due to the substantial volumes necessitated by these systems. Among the two practical systems, the solid-liquid system is the most extensively researched and widely available in commercial applications. Solid-solid systems exhibit considerable potential, however they have only lately been subjected to investigation (Singer et al, 2010). A multitude of phase change materials (PCMs) have been examined for practical applications. This study compiles extensive practical information on various phase change materials and systems produced utilising latent heat storage technology.

## **7. THERMAL ENERGY STORAGE**

Thermal energy storage can be retained as a variation in the internal energy of a material by sensible heat, latent heat, thermochemical processes, or a combination thereof. In Sensible Heat Storage (SHS), thermal energy is accumulated by increasing the temperature of a solid or liquid. The SHS system employs the heat capacity and the temperature variation of the material during the charging and discharging processes. The quantity of stored thermal energy is contingent upon the specific heat capacity of the medium, the variation in temperature, and the volume of the storage material.

$$Q = \int mC_p dT = mC_{ap}(T_f - T_i) \quad [1]$$

Latent Heat Storage (LHS) relies on the absorption or release of heat during the phase transition of a storage substance between solid and liquid or liquid and gas states. The storage capacity of the LHS system utilising a PCM medium is specified by

$$\begin{aligned} Q &= ma_m \Delta h_m + \int_i^m mC_p dT + \int_m^f mC_p dT \\ &= m[a_m \Delta h_m + C_{sp}(T_m - T_i) + C_{lp}(T_f - T_m)] \end{aligned} \quad (2)$$

LHS systems possess specific advantages over SHS systems. The paramount factor is the increased energy density per unit mass and per unit volume.

Thermochemical systems depend on the energy received and released during the cleavage and reformation of molecular bonds in a fully reversible chemical reaction. The heat stored is contingent upon the quantity of storage material, the endothermic heat of reaction, and the degree of conversion.

$$Q = a_r m \Delta h_r \quad [3] \text{ (Abhat, 1983)}$$

Among the aforementioned thermal heat storage techniques, latent heat thermal energy storage is especially appealing due to its capacity for high energy storage density and its ability to retain heat at a constant temperature corresponding to the phase transition temperature of the phase change material (PCM). Phase transitions may occur in the following forms: solid to solid, solid to liquid, solid to gas, and liquid to gas.

In solid-solid transitions, thermal energy is absorbed during the transformation of one crystalline structure to another. This transition often exhibits reduced latent heat and volume alterations compared to solid-liquid transitions. Solid–solid phase change materials have the benefits of reduced container specifications and enhanced design versatility (Pillai et al, 1976). The most promising materials are organic solid solutions of pentaerythritol, pentaglycerine,  $\text{Li}_2\text{SO}_4$ , and  $\text{KHF}_2$  (Garg et al, 1985). A Trombe Wall constructed with these materials may exhibit superior performance compared to a conventional concrete Trombe Wall.

Solid-gas and liquid-gas transitions exhibit elevated latent heat of phase transition; yet, their significant volume changes during phase transitions present containment challenges, hence limiting their potential application in thermal storage systems. Significant fluctuations in volume render the system convoluted and unfeasible.

Solid-liquid conversions possess relatively lower latent heat than liquid-gas transitions. Nonetheless, these conversions entail a minimal alteration (about 10 percent or less) in volume. Solid-liquid transitions have demonstrated economic viability for application in thermal energy storage systems. Phase Change Materials (PCMs) cannot serve as a heat transmission medium. A heat transfer medium must be utilised with a heat exchanger to transmit energy from the source to the phase change material (PCM) and from the PCM to the load. The heat exchanger must be specifically engineered due to the generally poor thermal diffusivity of phase change materials (PCMs). The volume alterations of the PCMs during melting will require specialised volumetric design of the containers to accommodate the PCM. It must accommodate these volumetric variations and be compatible with the employed PCM. Any latent thermal energy storage system must include at least the following three properties: an appropriate phase change material (PCM)

with a melting point within the needed temperature range, an adequate heat exchange surface, and a compatible container for the PCM.

## **9. MATERIALS FOR LATENT HEAT STORAGE**

Phase Change Materials (PCM) are substances that store latent heat. As the source temperature increases, the chemical bonds inside the PCM disintegrate as the material transitions from solid to liquid, specifically in the context of solid-liquid PCMs, which are of particular importance here. The phase change is an endothermic process, resulting in the absorption of heat by the PCM. When the storage material accumulates heat, it commences melting upon reaching the phase change temperature. The temperature remains constant until the completion of the melting process. The thermal energy retained during the phase transition (melting) of a substance is referred to as latent heat. The impact of latent heat storage presents two primary benefits: 1. It is feasible to accumulate substantial quantities of heat with little temperature variations, hence achieving a high storage density. 2. The phase change at a constant temperature requires time to complete, allowing for the mitigation of temperature fluctuations. They retain 5 to 14 times more thermal energy per unit volume than sensible heat storage materials like water, masonry, or rock (Hale et al, 1971). A significant quantity of phase change materials (PCMs) is recognised to melt with a certain heat of fusion across any desired range. The phase change material (PCM) utilised in the design of thermal storage systems must possess favourable thermophysical, kinetic, and chemical properties (Abhat et al, 1978; Buddhi et al, 1994).

### **9.1 Thermophysical characteristics**

They include:

- a. Melting temperature within the specified operational temperature range.
- b. Elevated latent heat of fusion per unit volume, resulting in a reduced container volume necessary to hold a specified amount of energy.
- c. Elevated specific heat to facilitate substantial sensible heat storage.
- d. Elevated thermal conductivity in both solid and liquid phases to facilitate the energy charging and discharging processes of storage systems.
- e. Minor volume alterations during phase transformation and minimal vapour pressure at operational temperatures to mitigate containment issues.
- f. Consistent melting of the phase change material for a certain storage capacity during each freezing/melting cycle.

### **9.2 Kinetic characteristics**

They include:

- a. High nucleation rate to prevent supercooling of the liquid phase.
- b. Elevated crystal growth rate to ensure the system satisfies the heat recovery requirements from the storage system.

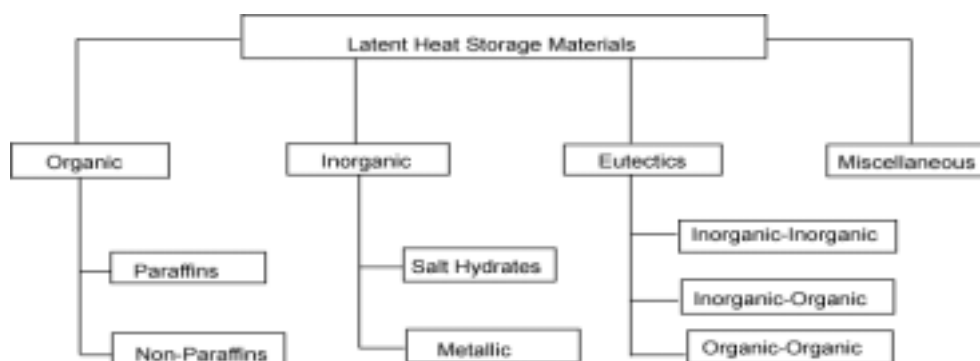
### **9.3 Chemical characteristics**

They include:

- a. Chemical stability.
- b. Complete reversible freeze/melt cycle.
- c. No deterioration following numerous freeze/thaw cycles.
- d. Resistance to corrosion of construction materials.
- e. Materials that are non-toxic, non-flammable, and non-explosive for safety purposes.
- f. Furthermore, the affordability and widespread accessibility of phase transition materials are also crucial.

### **9.4 Categorisation of Phase Change Materials**

A multitude of phase change materials (organic, inorganic, and eutectic) is accessible over any specified temperature range. A taxonomy of phase change materials (PCMs) is presented in the Figure 1.



**Figure 1.** Categorisation of latent heat storage materials

A multitude of organic and inorganic substances can be classified as phase change materials (PCMs) based on their melting temperature and latent heat of fusion. Tables 1 and 2 present the organic and inorganic categories of phase change materials (PCMs), respectively. Since no singular material possesses all the requisite features for optimal thermal storage media, it is necessary to utilise accessible materials and compensate for inadequate physical characteristics through effective system design. Metallic fins can enhance the thermal conductivity of phase change materials (PCMs), supercooling can be mitigated by incorporating a nucleating agent into the storage medium, and incongruent melting can be prevented by employing an appropriate thickness. The distinct thermal and chemical characteristics of each subgroup, which influence the design of latent heat thermal energy storage systems utilising PCMs from that subgroup, are elaborated upon below.

**Table 1.** List of organic PCMs (94 - 98)

Material	Melting point (°C)	Latent heat of fusion (kJ/kg)	Material	Melting point (°C)	Latent heat of fusion (kJ/kg)
N-Tetradeca	5.5	226	N-Penta Cosane	53.7	164
Formic Acid	7.8	247	Myristic Acid	54.0	199
N-Pentadeca	10.0	205	Oxolate	54.3	178
Acetic Acid	16.7	273	Tristearin	54.5	191
N-Hexadeca	16.7	237	O-Xylene	55.0	121
Caprilone	40.0	260	□-Chloroacetic	56.0	147
Docasyle	40.0	201	N-Hexacosane	56.3	255
N-Henicosan	40.5	161	Nitro	56.7	103
Phenol	41.0	120	□-Chloroacetic	61.2	130
N-Lauric	43.0	183	N-Octacosane	61.4	134
P-Joluidine	43.3	167	Palmitic Acid	61.8	164
Cynamide	44.0	209	Bees Wax	61.8	177
N-Docosane	44.5	157	Glyolic Acid	63.0	109
N-Tricosane	47.6	130	P-Bromophenol	63.5	86
Hydrocinna	48.0	118	Azobenzene	67.1	121
Cetyl	49.3	141	Acrylic Acid	68.0	115
O-Nitroanili	50.0	93	Dintro Toluene	70.0	111
Camphene	50.0	239	Phenylacetic	76.7	102
Diphenyl	52.9	107	Thiosinamine	77.0	140

## **9.5 Paraffins**

The normal paraffins, represented by the formula  $C_nH_{2n+2}$ , constitute a group of saturated hydrocarbons with highly analogous characteristics. Paraffins ranging from C5 to C15 exist as liquids, while those outside this range are waxy solids. Paraffin wax is the predominantly utilised commercial organic phase change material for thermal energy storage (Lane, 1983; Hale et al, 1971). It primarily comprises straight-chain hydrocarbons with melting points ranging from 23 to 67 °C (Abhat, 1983). Commercial-grade paraffin wax is derived from petroleum distillation and is not a pure product; rather, it is a mixture of several hydrocarbons. Generally, an increase in the average length of the hydrocarbon chain correlates with elevated melting temperatures and heat of fusion (Hiran et al, 1994). Table 3 presents the properties of some paraffins. Paraffins are readily obtainable from numerous producers and are often more costly than salt hydrates (Lane, 1983; Hale et al, 1971).

### *9.5.1 Benefits*

Paraffin waxes exhibit little propensity for segregation. They exhibit chemical stability; nevertheless, Lane (1983) indicates that gradual oxidation occurs upon exposure to oxygen, necessitating the use of closed containers. Sharma et al. (1999) and Sharma et al (2002) indicated consistent characteristics over 1500 cycles in commercial-grade paraffin wax. Paraffin waxes exhibit elevated temps of fusion, as demonstrated in the Table. 3.

They also lack inclinations towards supercooling, rendering nucleating agents unnecessary (Lane, 1983; Hale et al., 1971). Paraffin waxes are nontoxic and inert. They are compatible with all metallic containers and may be seamlessly integrated into thermal storage systems (Lane, 1983). Precautions should be exercised while utilising plastic containers, since paraffins may permeate and compromise the integrity of certain plastics (Lane, 1983).

### *9.5.2 Disadvantages*

Paraffins exhibit limited thermal conductivity in their solid form, as demonstrated in Table 4. This is a challenge when elevated heat transfer rates are necessary during the freezing stage. Veraj et al. (1998) indicates that this issue can be mitigated by employing finned containers and metallic fillers or by utilising combined latent/sensible storage methods. Aluminium honeycombs have been shown to enhance system performance (Hale et al, 1971). Paraffins exhibit a significant volumetric variation between their solid and liquid phases. This engenders numerous issues in container design (Hasnain, 1998). Paraffins are combustible; this risk can be effectively mitigated through the use of an appropriate container (Hiran et al, 1994; Hasnain, 1998). Lane ((1983) additionally indicates that paraffins may compress sufficiently to detach from the walls of the storage container, significantly reducing heat storage capability. In contrast to salt hydrates, commercial paraffins typically lack distinct and precise melting points.

Abhat (1983) indicates melting ranges of 43 °C. This results from the combination of materials and a solid-solid phase transformation in commercial-grade paraffins just prior to melting, which retains a significant amount of the material's latent heat capacity (Abhat, 1983). This diminishes the efficiency of the heat storage system, as it is no longer isothermal.

## **9.6 Non-paraffins**

This constitutes the predominant group of candidates' materials for phase change storage. Lane et al. (1983); Lane (1978); Lane (1989); Buddhi et al. (1994, Abhat (1983) and Buddhi (12) have performed a comprehensive examination of organic materials, identifying several esters, fatty acids, alcohols, and glycols appropriate for energy storage. These materials are combustible and must not be subjected to elevated temperatures, fires, or oxidising agents. Non-paraffins are included in Table 4.

## **9.7 Lipids**

Fatty acids, defined by the chemical formula  $\text{CH}_3(\text{CH}_2)_n\text{COOH}$ , exhibit similar properties to paraffins. Their benefits of more acute phase transitions are counterbalanced by the drawback of approximately threefold the expense of paraffins (Hasnain, 1998). They are also mildly corrosive. Table 5 enumerates several fatty acids pertinent to latent heat thermal energy storage applications at low temperatures. Sharma et al., (1999; 2002) indicates consistent characteristics following 1500 cycles for stearic acid.

## **9.8 Hydrated Salts**

Salt hydrates are among the earliest and most extensively researched phase change materials for thermal energy storage. They comprise a salt and water that amalgamate into a crystalline matrix during solidification. They can be utilised individually or in eutectic combinations (Abhat, 1983). Table 6 presents the properties of some salt hydrates. Numerous materials possess melting temperatures between 15 and 117 °C (Lane,1983). Salt hydrates constitute the most significant category of phase change materials (PCMs), which have been thoroughly investigated for their application in latent heat thermal energy storage systems. Three categories of melted salt behaviour can be distinguished: congruent, incongruent, and semi-congruent melting.

### *9.8.1 Benefits*

The low cost and easy accessibility of salt hydrates render them commercially appealing for thermal energy storage applications. Calcium chloride hexahydrate ( $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ ) and sodium sulphate decahydrate ( $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$ ) are among the most economical and readily accessible salt hydrates. Numerous salt hydrates are cost-effective for storage applications (Lane, 1978). Salt hydrates has a distinct melting point, hence optimising the efficacy of a thermal energy storage device. They have superior thermal conductivity relative to other heat storage phase change materials (PCMs). This can enhance thermal transport into and out of the storage unit. They possess a substantial heat of fusion to minimise the required dimensions of the storage system. Salt hydrates exhibit a reduced volumetric variation compared to alternative phase change materials (PCMs).

### *9.8.2 Disadvantages*

Segregation refers to the production of alternative hydrates or dehydrated salts that tend to precipitate, hence diminishing the active volume available for thermal storage. Abhat (Abhat, 1983) indicates a reduction above 73% in the heat of fusion of  $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$  over 1000 melt/freeze cycles. This issue can be mitigated to some degree by employing gelled or thicker mixes (Lane,1983), although this method adversely affects the thermal storage properties of the combination, and the mixture continues to deteriorate over time (Abhat, 1983). Salt hydrates exhibit supercooling due to their inability to initiate crystallisation at the phase change material's freezing point. This may involve refraining from the use of appropriate nucleating agents to initiate crystal formation in the storage medium. Lane (1983) provided an exhaustive catalogue of nucleating agents for the majority of prevalent salt hydrates. Abhat ( 1983) indicated material degradation in  $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$  after merely two cycles when the test sample was not hermetically sealed. Consequently, it is essential to design containers that retain the content while preventing water leakage. Another issue with salt hydrates is their propensity to induce corrosion in metal containers frequently utilised in thermal storage systems (Abhat, 1983). The compatibility of PCM and the container must always be verified prior to use.

## **9.9 Eutectics**

A eutectic is the mixture with the lowest melting point among two or more components, all of which melt and solidify congruently. Eutectic compositions often melt and solidify without segregation, as they crystallise into a homogeneous mixture, minimising the potential for component separation. Upon melting, the components liquefy concurrently. Table 7 presents a compilation of eutectic substances.

**Table 2.** Inventory of Inorganic Phase Change Materials (1, 2, 12, 94 - 98)

Name	Melting point (°C)	Latent heat of fusion (kJ/kg)	Name	Melting point (°C)	Latent heat of fusion (kJ/kg)
H <sub>2</sub> O	0.0	333	Bi <sub>3</sub>	31.8	10
POCl <sub>3</sub>	1.0	85	SO <sub>3</sub> (β)	32.3	151
D <sub>2</sub> O	3.7	318	TiBr <sub>4</sub>	38.2	23
SbCl <sub>5</sub>	4.0	33	H <sub>4</sub> P <sub>2</sub> O <sub>6</sub>	55.0	213
H <sub>2</sub> SO <sub>4</sub>	10.4	100	SO <sub>3</sub> (γ)	62.1	331
IC 1 (β)	13.9	56	SbCl <sub>3</sub>	73.4	25
MOF6	17.0	50	NaNO <sub>3</sub>	307	172 – 199
SO <sub>3</sub> (α)	17.0	108	KNO <sub>3</sub>	333 - 380	116 – 266
IC 1 (□)	17.2	69	KOH	380	149
P <sub>4</sub> O <sub>6</sub>	23.7	64	MgCl <sub>2</sub>	714 - 800	452 – 492
H <sub>3</sub> PO <sub>4</sub>	26.0	147	NaCl	800 - 802	466 – 492
Cs	28.3	15	Na <sub>2</sub> CO <sub>3</sub>	854	275
Ga	30.0	80	KF	857	452
AsBr <sub>3</sub>	30.0	38	K <sub>2</sub> CO <sub>3</sub>	897	235

**Table 3.** Melting point and latent heat of fusion of paraffins (1, 2, 12, 94 - 99)

Name	No. of "C" Atoms	Melting point (°C)	Density (kg/m <sup>3</sup> )	Thermal Conductivity (W/mK)	Latent heat of fusion(kJ/kg)
n - Dodecane	12	-12	750		n.a.
n - Tridecane	13	-6	756	0.21 <sup>S</sup>	n.a.
n - Tetradecane	14	4.5 - 5.6	771		231
n - Pentadecane	15	10	768	0.17	207
n - Hexadecane	16	18.2	774	0.21 <sup>S</sup>	238
n - Heptadecane	17	22	778		215
n - Octadecane	18	28.2	814 <sup>S</sup> (14),	0.35 <sup>S</sup> (14), 0.149 <sup>L</sup> (14)	245
n - Nonadecane	19	31.9			222
n - Eicosane	20	37			247
n - Heneicosane	21	41			215
n - Docosane	22	44	912 <sup>S</sup> , 769 <sup>L</sup>	0.21 <sup>S</sup>	249
n - Tricosane	23	47			234
n - Tetracosane	24	51			255
n - Pentacosane	25	54			238
Paraffin Wax	n.a.	32	785 <sup>S</sup> (15),	0.514 <sup>S</sup> (15),	251(15)
n - Hexacosane	26	56	770		257
n - Heptacosane	27	59	773		236
n - Octacosane	28	61			255
n - Nonacosane	29	64	910 <sup>S</sup> , 765 <sup>L</sup>	0.21 <sup>S</sup>	240
n - Triacontane	30	65			252
n - Hentriacontane	31	n.a.			n.a.
n - Dotriacontane	32	70	930 <sup>S</sup> , 830 <sup>L</sup>		n.a.
n - Tritriacontane	33	71			189

*S: solid; L: liquid; n.a.: not available*

**Table 4.** Melting point and latent heat of fusion of non - paraffins (1, 2, 12, 94 - 99)

Name	Melting point ( <sup>o</sup> C)	Density (kg/m <sup>3</sup> )	Latent heat of fusion (k J/ kg)
Formic Acid	7.8	1226.7 <sup>15C</sup>	247
Acetic Acid	16.7	1050 <sup>20C</sup>	187
Glycerin	17.9	1260 <sup>20C</sup>	198.7
Lithium Chloride Ethanolate	21	n.a.	188
Polyethylene Glycol 600	20-25	1100 <sup>20C</sup>	146
D – Lactic Acid	26	1249 <sup>15C</sup>	184
1-3 Methyl Pentacosane	29	n.a.	197
Camphenilone	39	n.a.	205
Docasyl Bromide	40	n.a.	201
Caprylone	40	n.a.	259
Heptadecanone	41	n.a.	201
1-Cyclohexyloctadecane	41	n.a.	218
4-Heptadecanone	41	n.a.	197
Cyanamide	44	1080 <sup>20C</sup>	209
Methyl Eicosanate	45	851 <sup>79C</sup>	230
3-Heptadecanone	48	n.a.	218
2-Heptadecanone	48	n.a.	218
Camphene	50	842 <sup>54C</sup>	238
9-Heptadecanone	51	n.a.	213
Methyl Behenate	52	n.a.	234
Pentadecanoic Acid	52.5	n.a.	178
Hypophosphoric Acid	55	n.a.	213
Chloroacetic Acid	56	1580 <sup>20C</sup>	130
Trimyristin	33-57	862 <sup>20C</sup>	201-213
Heptaudecanoic Acid	60.6	n.a.	189
Bee Wax	61.8	950	177
Glycolic Acid	63	n.a.	109
Oxazoline-Wax-TS 970	74	n.a.	
Arachic Acid	76.5	n.a.	227
Bromcamphor	77	1449 <sup>81C</sup>	174
Durene	79.3	838 <sup>20C</sup>	156
Acetamide	81	1159	241
Methyl Brombrenzoate	81	n.a.	126
Alpha Naphthol	96	1095 <sup>98.7C</sup>	163
Glutaric Acid	97.5	1429	156
p-Xylene Dichloride	100	n.a.	138.7
Methyl Fumarate	102	1045	242
Catechol	104.3	1370 <sup>15C</sup>	207
Quinone	115	1318 <sup>20C</sup>	171
Acetanilide	115	1210 <sup>4C</sup>	142
Succinic Anhydride	119	1104	204
Benzoic Acid	121.7	1266 <sup>15C</sup>	142.8
Stibene	124	1164 <sup>15C</sup>	167
Benzamide	127.2	1341	169.4
Phenacetin	137	n.a.	136.7
Alpha Glucose	141	1544	174
Acetyl – p- Toluidene	146	n.a.	180
Phenylhdrazone Benzaldehy	155	n.a.	134.8

Salicylic Acid	159	1443 <sup>20C</sup>	199
Benzanilide	161	n.a.	162
O-Mannitol	166	1489 <sup>20C</sup>	294
Hydroquinone	172.4	1358 <sup>20C</sup>	258
p- Aminobenzoic Acid	187	n.a.	153

**Table 5.** Melting point and latent heat of fusion: Fatty acids (1, 2, 12, 94 - 99)

Name	Melting point (°C)	Density (kg/m <sup>3</sup> )	Thermal conductivity (W/mK)	Latent heat of fusion (kJ/kg)
Propyl Palmiate	10	n.a.	n.a.	186
Isopropyl Palmiate	11	n.a.	n.a.	100
Oleic Acid	13.5 - 16.3	863 <sup>60C</sup>	n.a.	n.a.
Isopropyl Stearate	14 - 19	n.a.	n.a.	140 – 142
Caprylic Acid	16	901 <sup>30C</sup>	0.149 <sup>39C</sup>	148
Butyl Stearate	19	n.a.	n.a.	140
Dimethyl Sabacate	21	n.a.	n.a.	120 – 135
Myristic Acid +	24	888 <sup>25C</sup> , 1018 <sup>1C</sup>	0.164 <sup>39C</sup> , 0.154 <sup>61C</sup>	147.7
Vinyl Stearate	27 - 29	n.a.	n.a.	122
Methyl Palmitate	29	n.a.	n.a.	205
Capric Acid	32	878 <sup>45C</sup>	0.153 <sup>38.5C</sup>	152.7
Erucic Acid	33	853 <sup>70C</sup>	n.a.	n.a.
Lauric Acid	42 - 44	862 <sup>60C</sup>	n.a.	178
Elaidic Acid	47	851 <sup>79C</sup>	n.a.	218
Pelargonic Acid	48	n.a.	n.a.	n.a.
Myristic Acid	49 - 51	861 <sup>55C</sup>	n.a.	205
Palmitic Acid	64	850 <sup>65C</sup>	0.162 <sup>68.4C</sup>	185.4
Stearic Acid	69	848 <sup>70C</sup>	0.172 <sup>70C</sup>	202.5
Valporic Acid	120	n.a.	n.a.	n.a.

**Table 6.** Melting point and latent heat of fusion of salt hydrates (1, 2, 12, 94 - 99)

Name	Melting Point (°C)	Density (kg/m <sup>3</sup> )	Thermal Conductivity (W/m K)	Latent Heat (kJ/kg)	Melting Behavior <sup>a</sup> (13)
LiClO <sub>3</sub> .3H <sub>2</sub> O	8	n.a.	n.a.	253	C
NH <sub>4</sub> Cl.Na <sub>2</sub> SO <sub>4</sub> .10H <sub>2</sub> O	11	n.a.	n.a.	163	n.a.
K <sub>2</sub> HO <sub>4</sub> .6H <sub>2</sub> O	14	n.a.	n.a.	108	c
NaCl.Na <sub>2</sub> SO <sub>4</sub> .10H <sub>2</sub> O	18	n.a.	n.a.	286	n.a.
KF.4H <sub>2</sub> O	18	n.a.	n.a.	330	c
K <sub>2</sub> HO <sub>4</sub> .4H <sub>2</sub> O	18.5	1447 <sup>20C</sup>	n.a.	231	n.a.
Mn(NO <sub>3</sub> ) <sub>2</sub> .6H <sub>2</sub> O	25	1738 <sup>20C</sup> (12),	n.a.	148	n.a.
LiBO <sub>2</sub> .8H <sub>2</sub> O	25.7	n.a.	n.a.	289	n.a.
FeBr <sub>3</sub> .6H <sub>2</sub> O	27	n.a.	n.a.	105	n.a.
CaCl <sub>2</sub> .6H <sub>2</sub> O	29 – 30	1562 <sup>32C</sup>	0.561 <sup>61.2C</sup>	170 - 192	Ic
LiNO <sub>3</sub> .3H <sub>2</sub> O	30	n.a.	n.a.	189 - 296	C
Na <sub>2</sub> SO <sub>4</sub> .10H <sub>2</sub> O	32	1485 <sup>24C</sup>	0.544	251 - 254	Ic
Na <sub>2</sub> CO <sub>3</sub> .10H <sub>2</sub> O	33 – 36	1442	n.a.	247	Ic
KFe(SO <sub>4</sub> ) <sub>2</sub> .12H <sub>2</sub> O	33	n.a.	n.a.	173	Ic

CaBr <sub>2</sub> .6H <sub>2</sub> O	34	1956 <sup>35C</sup> ,	n.a.	115 - 138	n.a.
LiBr.2H <sub>2</sub> O	34	n.a.	n.a.	124	Ic
Na <sub>2</sub> HPO <sub>4</sub> .12H <sub>2</sub> O	35	1522	n.a.	256 - 281	Ic
Zn(NO <sub>3</sub> ) <sub>2</sub> .6H <sub>2</sub> O	36	1828 <sup>36C</sup> ,	0.464 <sup>39.9C</sup> ,	134 - 147	C
Mn(NO <sub>3</sub> ) <sub>2</sub> .4H <sub>2</sub> O	37	n.a.	n.a.	115	n.a.
FeCl <sub>3</sub> .6H <sub>2</sub> O	37	n.a.	n.a.	223	C
CaCl <sub>2</sub> .4H <sub>2</sub> O	39	n.a.	n.a.	158	Ic
CoSO <sub>4</sub> .7H <sub>2</sub> O	40.7	n.a.	n.a.	170	n.a.
CuSO <sub>4</sub> .7H <sub>2</sub> O	40.7	n.a.	n.a.	171	n.a.
KF.2H <sub>2</sub> O	42	n.a.	n.a.	162 - 266	C
MgI <sub>2</sub> .8H <sub>2</sub> O	42	n.a.	n.a.	133	n.a.
CaI <sub>2</sub> .6H <sub>2</sub> O	42	n.a.	n.a.	162	n.a.
Ca(NO <sub>3</sub> ) <sub>2</sub> .4H <sub>2</sub> O	43 - 47	n.a.	n.a.	106 - 140	C
Zn(NO <sub>3</sub> ) <sub>2</sub> .4H <sub>2</sub> O	45	n.a.	n.a.	110	n.a.
K <sub>3</sub> PO <sub>4</sub> .7H <sub>2</sub> O	45	n.a.	n.a.	145	n.a.
Fe(NO <sub>3</sub> ) <sub>3</sub> .9H <sub>2</sub> O	47	n.a.	n.a.	155 - 190	Ic
Mg(NO <sub>3</sub> ) <sub>3</sub> .4H <sub>2</sub> O	47	n.a.	n.a.	142	n.a.
Na <sub>2</sub> SiO <sub>3</sub> .5H <sub>2</sub> O	48	n.a.	n.a.	168	n.a.
Na <sub>2</sub> HPO <sub>4</sub> .7H <sub>2</sub> O	48	n.a.	n.a.	135 - 170	Ic
Na <sub>2</sub> S <sub>2</sub> O <sub>3</sub> .5H <sub>2</sub> O	48	1600	n.a.	209	n.a.
K <sub>2</sub> HPO <sub>4</sub> .3H <sub>2</sub> O	48	n.a.	n.a.	99	n.a.
MgSO <sub>4</sub> .7H <sub>2</sub> O	48.4	n.a.	n.a.	202	n.a.
Ca(NO <sub>3</sub> ) <sub>2</sub> .3H <sub>2</sub> O	51	n.a.	n.a.	104	n.a.
Na(NO <sub>3</sub> ) <sub>2</sub> .6H <sub>2</sub> O	53	n.a.	n.a.	158	n.a.
Zn(NO <sub>3</sub> ) <sub>2</sub> .2H <sub>2</sub> O	55	n.a.	n.a.	68	C
FeCl <sub>3</sub> .2H <sub>2</sub> O	56	n.a.	n.a.	90	n.a.
CO(NO <sub>3</sub> ) <sub>2</sub> .6H <sub>2</sub> O	57	n.a.	n.a.	115	n.a.
Ni(NO <sub>3</sub> ) <sub>2</sub> .6H <sub>2</sub> O	57	n.a.	n.a.	168	n.a.
MnCl <sub>2</sub> .4H <sub>2</sub> O	58	n.a.	n.a.	151	n.a.
CH <sub>3</sub> COONa.3H <sub>2</sub> O	58	n.a.	n.a.	270 - 290	Ic
LiC <sub>2</sub> H <sub>3</sub> O <sub>2</sub> .2H <sub>2</sub> O	58	n.a.	n.a.	251-377	n.a.
MgCl <sub>2</sub> .4H <sub>2</sub> O	58.0	n.a.	n.a.	178	n.a.
NaOH.H <sub>2</sub> O	58	n.a.	n.a.	272	n.a.
Na(CH <sub>3</sub> COO).3H	58	n.a.	n.a.	n.a.	n.a.
Cd(NO <sub>3</sub> ) <sub>2</sub> .4H <sub>2</sub> O	59	n.a.	n.a.	98	n.a.
Cd(NO <sub>3</sub> ) <sub>2</sub> .1H <sub>2</sub> O	59.5	n.a.	n.a.	107	n.a.
Fe(NO <sub>3</sub> ) <sub>2</sub> .6H <sub>2</sub> O	60	n.a.	n.a.	125	n.a.
NaAl(SO <sub>4</sub> ) <sub>2</sub> .12H	61	n.a.	n.a.	181	Ic
FeSO <sub>4</sub> .7H <sub>2</sub> O	64	n.a.	n.a.	200	n.a.
Na <sub>3</sub> PO <sub>4</sub> .12H <sub>2</sub> O	65	n.a.	n.a.	168	n.a.
Na <sub>2</sub> B <sub>4</sub> O <sub>7</sub> .10H <sub>2</sub> O	68	n.a.	n.a.	n.a.	n.a.
Na <sub>3</sub> PO <sub>4</sub> .12H <sub>2</sub> O	69	n.a.	n.a.	n.a.	n.a.
LiCH <sub>3</sub> COO.2H <sub>2</sub> O	70	n.a.	n.a.	150 - 251	C
Na <sub>2</sub> P <sub>2</sub> O <sub>7</sub> .10H <sub>2</sub> O	70	n.a.	n.a.	186 - 230	Ic
Al(NO <sub>3</sub> ) <sub>2</sub> .9H <sub>2</sub> O	72	n.a.	n.a.	155 - 176	Ic
Ba(OH) <sub>2</sub> .8H <sub>2</sub> O	78	1937 <sup>84C</sup> ,	0.653 <sup>85.7C</sup> ,	265 - 280	C
Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> .18H <sub>2</sub> O	88	n.a.	n.a.	218	Ic
Sr(OH) <sub>2</sub> .8H <sub>2</sub> O	89	n.a.	n.a.	370	Ic
Mg(NO <sub>3</sub> ) <sub>2</sub> .6H <sub>2</sub> O	89 - 90	1550 <sup>94C</sup>	0.490 <sup>95C</sup>	162 - 167	C

KAl	91	n.a.	n.a.	184	n.a.
(NH <sub>4</sub> )Al(SO <sub>4</sub> ).6H	95	n.a.	n.a.	269	n.a.
Na <sub>2</sub> S.51/2H <sub>2</sub> O	97.5	n.a.	n.a.	n.a.	n.a.
LiCl.H <sub>2</sub> O	99	n.a.	n.a.	212	Ic
CaBr <sub>2</sub> .4H <sub>2</sub> O	110	n.a.	n.a.	n.a.	n.a.
Al <sub>2</sub> (SO <sub>4</sub> ) <sub>2</sub> .16H <sub>2</sub> O	112	n.a.	n.a.	n.a.	n.a.
MgCl <sub>2</sub> . 6H <sub>2</sub> O	115	–	1450 <sup>120C</sup> ,	0.570 <sup>120C</sup> ,	165 - 169
NaC <sub>2</sub> H <sub>3</sub> O <sub>2</sub> .3H <sub>2</sub> O	137		1450	n.a.	172

### 9.10 Cross-linked Polyethylene

Cross-linked Polyethylene resembles the polyethylene utilised in plastic bottles, with the distinction that it is minimally cross-linked to inhibit liquefaction upon melting. Similar to a liquid-solid phase change material, it stores energy through the formation and disruption of crystalline structures. The characteristics of two cross-linked polyethylene samples are presented in Table 8. In contrast to a liquid-solid phase change material, it possesses a stable form and can be utilised without encapsulation.

#### 9.10.1 Benefits

Despite being more expensive than alternative phase change materials (PCMs), a lower cost is essential for the complete heat storage system, offering greater feasibility compared to other PCMs (Lane,1983). Cross-linked polyethylene is non-toxic and predominantly chemically inert.

#### 9.10.2 Disadvantages

The working temperatures of 110 to 140 °C are excessively high for several applications, including space and water heating. To the author's knowledge, no company has commercially produced cross-linked polyethylene for thermal energy storage applications at this time.

### 9.11 Polyols

Research has also been conducted at playschools (lane, 1983). Polyols retain energy by transitioning from a heterogeneous state at lower temperatures to a face-centered cubic structure at elevated temperatures (Wangm, 2000). Polyols offer numerous advantages over solid-liquid phase change materials, including little volume alteration, absence of leakage, and material stability. These benefits are accompanied by the drawbacks of low latent heat, elevated phase change temperatures, and increased cost. Wang (2000) describes a method for integrating polyalcohols to modify operational temperatures. Table 8 presents some of his findings for the Neopentyl Glycol (NPG)/Pentaerythritol (PE) and Neopentyl Glycol (NPG)/Trihydroxy Methyl-Aminomethane (TAM) systems.

## 10. LATENT HEAT STORAGE SYSTEMS

The fluctuating and variable characteristics of solar irradiation, along with the necessity to employ solar energy systems for consistent and stable loads, render storage systems indispensable for the majority of solar energy applications. Latent heat storage is of particular relevance among the many heat storage techniques when compared to sensible heat storage. Phase change materials (PCMs) are utilised in solar energy storage systems for water heating, greenhouses, building climate control, cooking, and waste heat recovery systems.

### 10.1 Solar Water Heating

Solar water heaters are gaining popularity due to their relative affordability and ease of fabrication and maintenance. Prakesh et al. (1985) examined a built-in storage water heater featuring a layer of phase change material (PCM) at the bottom (Figure 2).

During daylight hours, the water is heated, thus transferring thermal energy to the PCM beneath it. The PCM absorbs energy as latent heat and undergoes melting. During non-sunlight hours,

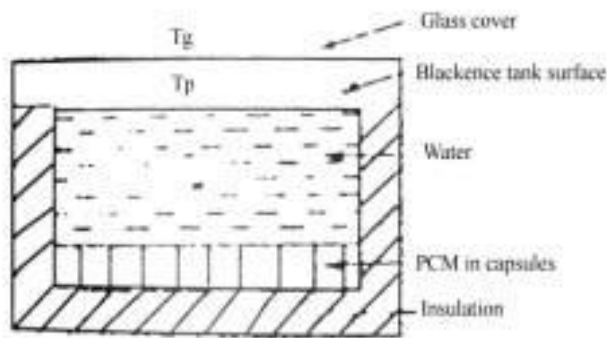
heated water is replaced with cold water, which absorbs energy from the PCM. The energy is released by the PCM during its phase transition from liquid to solid. This method may lack efficacy due to inadequate heat transmission between the phase change material and water.

**Table 7.** List of organic and inorganic eutectics (1, 2, 10, 12, 94 - 99)

Name	Composition (wt %)	Melting point	Latent Heat of fusion (kJ/
Na <sub>2</sub> SO <sub>4</sub> +NaCl+KCl+H <sub>2</sub> O	31+13+16+40	4	234
Na <sub>2</sub> SO <sub>4</sub> +NaCl+NH <sub>4</sub> Cl+H <sub>2</sub> O	32+14+12+42	11	n.a.
C <sub>5</sub> H <sub>5</sub> C <sub>6</sub> H <sub>5</sub> + (C <sub>6</sub> H <sub>5</sub> ) <sub>2</sub> O	26.5+73.5	12	97.9
Na <sub>2</sub> SO <sub>4</sub> +NaCl+H <sub>2</sub> O	37+17+46	18	n.a.
Na <sub>2</sub> S <sub>4</sub> +MgSO <sub>4</sub> +H <sub>2</sub> O	25+21+54	21 – 24	n.a.
C <sub>14</sub> H <sub>28</sub> O <sub>2</sub> + C <sub>10</sub> H <sub>20</sub> O <sub>2</sub>	34 + 66	24	147.7
Ca(NO) <sub>3</sub> .4H <sub>2</sub> O	+ 47 + 53	30	136
NH <sub>2</sub> CONH <sub>2</sub> + NH <sub>4</sub> NO <sub>3</sub>	-	46	95
Mg(NO <sub>3</sub> ) <sub>2</sub> .6H <sub>2</sub> O + NH <sub>4</sub> NO <sub>3</sub>	61.5 +38.4	52	125.5
Mg(NO <sub>3</sub> ) <sub>2</sub> .6H <sub>2</sub> O	+ 58.7 + 41.3	59	132.2
Mg(NO <sub>3</sub> ) <sub>2</sub> .6H <sub>2</sub> O	+ 53 +47	61	148
Mg(NO <sub>3</sub> ) <sub>2</sub> .6H <sub>2</sub> O	+ 59 + 41	66	168
Napthalene + Benzoic Acid	67.1 + 32.9	67	123.4
AlCl <sub>3</sub> +NaCl+ZrCl <sub>2</sub>	79+17+4	68	234
AlCl <sub>3</sub> +NaCl+KCl	66+20+14	70	209
NH <sub>2</sub> CONH <sub>2</sub> + NH <sub>4</sub> Br	66.6 + 33.4	76	151
LiNO <sub>3</sub> + NH <sub>4</sub> NO <sub>3</sub> + NaNO <sub>3</sub>	25 + 65 + 10	80.5	113
AlCl <sub>3</sub> +NaCl+KCl	60+26+14	93	213
AlCl <sub>3</sub> +NaCl	66+34	93	201
NaNO <sub>2</sub> +NaNO <sub>3</sub> +KNO <sub>3</sub>	40+7+53	142	n.a.

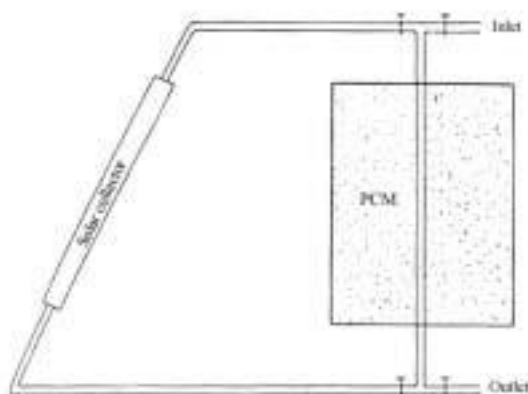
**Table 8.** Melting point and latent heat of fusion of some selected solid - solid PCMs (1, 2, 10, 94- 99)

Name	Melting point (°C)	Latent heat of fusion (kJ/kg)
38.2%NPG/61.8%PE	26 – 32	18 – 75
38.2%NPG/61.8%TAM	22 – 35	27 – 33
76.4%NPG/33.6%TAM	28 – 38	75 – 80
76.4%NPG/33.6%PE	31 – 37	35 – 46
91%NPG/9%PE	31 – 36	68
91%NPG/9%TAM	30 – 39	143 – 150
Neopentyl Glycol(NPG)	43	130
Diamnopentacrythritol	68	184
2-Amino - 2 - Methyl - 1, 3 - Propanediol	78	264
2 - Methyl - 2 - Mtro - 1, 3 - Propanediol	79	201
Trumethylolethane	81	192
Pentaglycerin	81	192
2-Hydroxymethyl-2-Methyl-1, 3 - Propanediol	81	192
Monoaminopentaerythritol	86	192
Cross-Linked Polyethylene	110 – 115	125 – 146
Tris(Hydroxymethyl)Acetic Acid	124	205
2-Amino-2-Hydroxymethyl-1, 3 - Propanediol	131	285
Cross-Linked HDPE	125 – 146	167 – 201
2,2-Bis(Hydroxymethyl) Propionic Acid	152	289
38.2%NPG/61.8%PE	170	147
Penterythritol(PE)	185	303



**Figure 2.** Integrated storage heater with a phase change material layer

Bansal and Buddhi (1992) theoretically examined a cylindrical storage unit within a closed loop using a flat plate collector (Fig. 3) for its charging and discharging modes. A theoretical model for a cylindrical latent heat storage system was constructed. The computations for the interface moving boundary and fluid temperature were conducted utilising paraffin wax (p-116) and stearic acid as phase transition materials. Tiwari et al. (1988) conducted an investigation of a phase change material (PCM) storage system for water heaters, integrating the impact of water flow through a parallel plate situated at the solid-liquid interface. Movable insulation has been developed to minimise nocturnal heat losses from the exposed surface. They determined that the hot water (temperature  $15\text{--}20\text{ }^{\circ}\text{C} > T_a$ ) can be maintained continuously, and that temperature fluctuations diminish as the melted area of the PCM water heater increases. Tayed et al. (1993) devised a home hot water system utilising  $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$  as a phase change material and contrasted it with a simulation model that determines the optimal flow rate of the intake water supply necessary to sustain a constant outlet water temperature. Font et al. (1994) performed an initial investigation into the design of a device for domestic water utilising solid-solid phase change materials (PCM). Numerical simulation was conducted utilising a unidirectional model and validated against the experimental results. The agreement between experimental and simulation data indicates that this model is suitable for investigating the heat transfer phenomenon in the PCM to optimise device design.

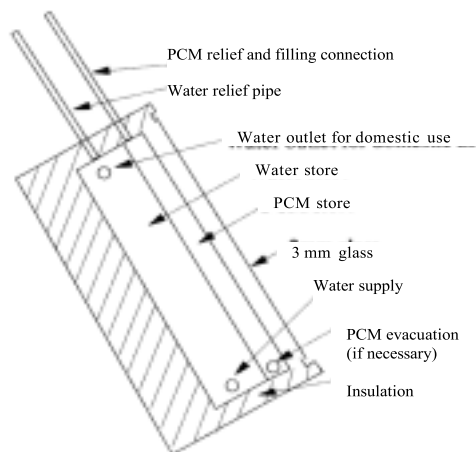


**Figure 3.** A residential hot water system including distinct phase change material (PCM) heat storage.

Chauarsia (1986) and Gu et al. (2004) indicated that paraffin wax may serve as a storage medium for solar water heating. Baran and Sari (2003) indicated that the eutectic mixture of palmitic acid (64.2 wt%) and stearic acid (35.8 wt%), with a melting point of  $52.3\text{ }^{\circ}\text{C}$  and a latent heat of fusion of  $182\text{ kJ/kg}$ , is appropriate for residential water heating applications. Bhargava et al. (1983) employed phase change materials in a solar water heater and determined that the system's efficiency and the outlet water temperature during nighttime hours improve with enhanced

thermal conductivity of the solid-liquid phases of the materials. Hasan et al. (1994) have examined various fatty acids as phase change materials for residential water heating. They suggested that myristic acid, palmitic acid, and stearic acid, which have melting temperatures ranging from 50 °C to 70 °C, are suitable phase transition materials for water heating. The thermophysical properties of the identified phase change materials (PCMs) were assessed using differential scanning calorimetry (DSC). The researchers determined that a minor decrease in latent heat occurred after 450 heating cycles (20–80°C), whereas a drop of up to one-third of the latent heat was observed after 21 heating cycles (20–150°C).

Kurklu et al. (2002) created an innovative water - PCM solar collector, and its short-term thermal performance was examined (Figure 4). The solar collector had two adjacent parts, one containing water and the other containing a phase change material (Paraffin Wax, 45–50 °C). The study's results revealed that the water temperature surpassed 55 °C on a normal day of elevated solar radiation and remained above 30 °C throughout the night. The current solar collector offers significant advantages over conventional solar hot water collectors in Turkey, particularly for overall system weight and cost. This sort of collector may utilise PCM-water solar panels on the southern facades of buildings for energy storage purposes.

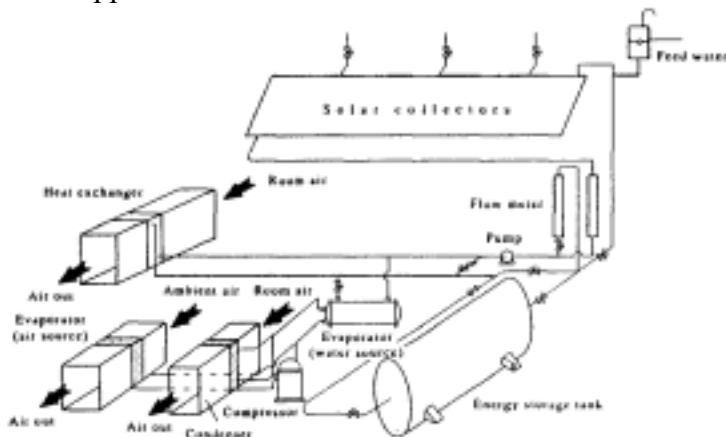


**Figure 4.** Water - Phase Change Material Solar Collector

## 10.2 Heating

Jurinak and Khalik (1978) and Khalik et al (1978) have examined the impact of phase change materials on the efficacy of an air-based solar heating system. The primary finding was that the phase change material (PCM) should be chosen based on its melting temperature rather than its latent heat, as the melting temperature significantly influences system performance. They also indicated that systems employing  $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$  necessitate approximately half the storage volume of a traditional water tank system. An efficient heat capacity for the latent heat storage unit was derived as a function of its mass, latent heat, specific heat, and melting temperature. The effective heat capacity can be employed to assess the thermal performance of the system utilising phase change materials (PCM). Klein and Beckman (1979) conducted simulation research on a closed-loop solar thermal system applicable for several uses, including room heating, absorption air conditioning, and certain forms of process heating. This design methodology can be employed to evaluate the long-term efficacy of such systems. Bulkin et al. (1988) proposed a mathematical model for the design of a solar heating and hot-water supply system utilising solar absorbers and a heat pump with two thermal-storage tanks, considering the system's interaction with external climatic conditions and the serviced room. Ghoneim et al. (1979) examined the impact of assumptions in previous models on the proportion of the demand satisfied by solar energy and the necessary storage capacities.

Kaygusuz et al. (1991) created an experimental model to analyse the dynamics of a solar-assisted heat pump, collectors, drier, and energy storage tank utilised for grain drying. Kaygusuz et al (1995) examined the efficacy of a dual-source heat pump system for domestic heating (Figure 5). In the dual-source configuration, the evaporator is engineered to harness energy from either the atmosphere or the solar energy reservoir. He determined that the dual source system could conserve more energy than both the parallel and series systems. Kaygusuz (1995) performed both experimental and theoretical investigations to assess the efficacy of phase-change energy storage materials, as well as the fluctuation of outlet fluid temperature corresponding to varying NTU (number of transfer units of the storage unit) values in water-based solar heating systems (Figure 6). This system comprises a solar collector, energy storage tank, water-to-air heat exchanger, auxiliary electric heater, water circulation pump, and additional measurement and control apparatus.



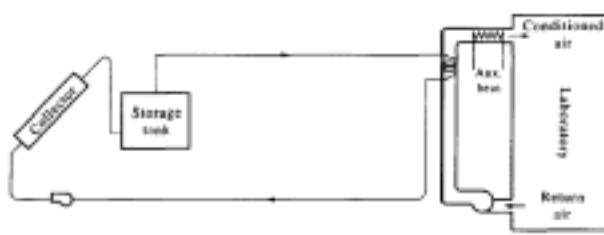
**Figure 5.** Solar-assisted heat pump system connected to energy storage tank

Solar energy is gathered and directed to the energy storage tank, which contains 1500 kg of encapsulated phase change material (PCM), while the heat transfer fluid (water) circulates alongside it (Figure 7). Through experimental and theoretical analyses, they determined that heat storage is a crucial element in temperate climates (e.g., Trabzon, Turkey), and that  $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$  or  $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$  can serve as phase change materials, offering a favourable alternative to rock and water storage systems. PCM storage is more advantageous as a heat source for a heat pump compared to water and rock storage, as the energy storage temperature of PCM is approximately 25-35°C for both  $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$  and  $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$ . This temperature range is appropriate for solar-assisted heat pump applications in Turkey. Mehmet (Mehmet et al, 2000) examined the thermal efficacy of a solar-assisted latent heat storage system employed for space heating in conjunction with a heat pump, utilising 1090 kg of encapsulated phase change material ( $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ ). He determined that the shorter and narrower pipe should be utilised for optimal heating at the outset of the studies. Faith et al. (1995) designed a straightforward solar air heater coupled with a thermal energy storage device, as illustrated in the Figure 8. Heat storage materials were introduced into the tubes and designated as the absorber of the collector. Paraffin wax (melting point 50 °C, latent heat of fusion 190 kJ/kg) and  $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$  (melting point 32 °C, latent heat of fusion 251 kJ/kg) are utilised as phase change materials (PCMs). These systems augment the heat transfer area, enhance the coefficient, and diminish radiation and convection losses. Through a fundamental transient analysis, precise formulas for the temperatures of the heater absorber and glass cover, effective heat gain, outlet air temperature, and heater efficiency have been formulated as a function of time. The system with integrated PCM can deliver heat load continuously for 24 hours a day at a nearly constant temperature. The daily average efficiency of paraffin wax is around 63.35%, in contrast to 59% for sand as the storage medium and 38.7% for the traditional flat plate heater system.

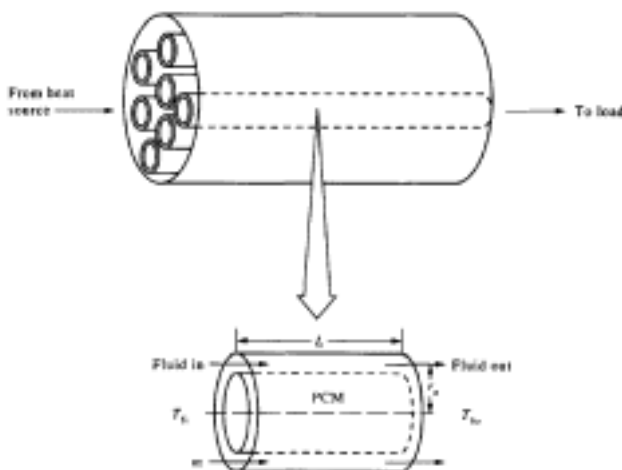
Strith et al. (2002) employed Transparent Insulation Material (TIM) and transparent phase change material (PCM) within the wall to heat the air for residential ventilation. Paraffin wax (melting point 25-30 °C, latent heat of fusion 150 kJ/kg) served as a phase change material, with

60 kg incorporated into a panel for space heating. The average efficiency of solar energy absorbed by the PCM and subsequently transferred to the ventilation air was 45%. Manz et al. (1997) have performed a similar work utilising a different phase change material ( $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ ). He created a numerical simulation that aligns closely with experimental findings. He also indicated that the greatest time ratio parameter may be attained with a mean melting temperature of roughly 20 to 21°C when the building does not experience energy loss through the south-facing TIM-PCM wall.

Arkar et al. (2002) developed a solar-assisted ventilation system utilising phase change material (PCM) storage. He suggested that paraffin spherical encapsulations create a uniform porosity effect in ventilation ducts, hence enhancing the thermal conductivity of paraffin. He stated that ambient air temperature could decrease by 3 to 4 K on a clear summer night.



**Figure 6.** Schematic representation of the fundamental solar energy system



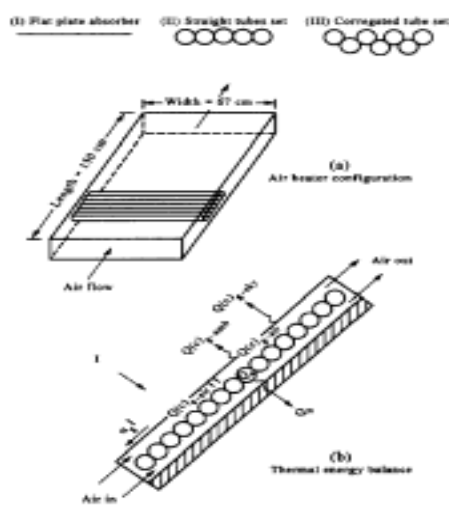
**Figure 7.** Schematic representation of the latent heat storage tank

Ismail and Alves (1986) reported a theoretical model of a shell-and-tube phase change material storage unit. The energy equation for the phase change material (PCM) is expressed in terms of enthalpy. The numerical findings demonstrate the influence of the Biot number, the relative diameters of the tubes, and the inlet fluid temperature on the thermal performance of the system. Visser (1986) formulated a component model for the numerical characterisation of two distinct short-term heat storage vessels. In both containers, energy is stored as the latent heat of phase change materials (PCMs). The transient simulation program was employed to evaluate the efficacy of the cylindrical energy storage tank utilised in the solar-assisted residential heating system with a heat pump. Yimmer et al. (1989) created a numerical model to optimise a fundamental one-dimensional shell-and-tube thermal energy storage system. An enthalpy method was utilised for the phase change material (PCM). A parametric analysis was conducted to evaluate the impact of the inner tube and outer shell radii, as well as the thermal conductivity of the liquid phase of the PCM, on the unit's performance. Lacroix (1993) constructed a theoretical model to forecast the transient behaviour of a shell-and-tube storage unit, with the phase change material on the shell side and the heat transfer fluid cycling within the tubes. Subsequently, parametric studies are conducted to evaluate the impact of diverse thermal and geometric parameters on the heat transfer process and the system's behaviour.

Sagara et al. (1994) evaluated the long-term efficacy of an air-based solar heating system utilising a phase change material (PCM). Theoretical heat transmission models within spherical capsules containing the PCM were examined. The impact on the overall COP was analysed concerning the volume of the PCM storage tank, melting temperature, collector area, and airflow rate. The simple uniform temperature model is deemed beneficial for long-term system simulations. Sari and Kaygusuz (2002) formulated a eutectic mixture comprising 75.5 wt% lauric acid and 24.5 wt% stearic acid for space heating applications. Eutectic melts were developed at 37°C with a latent heat of 183 kJ/kg, rendering them an appealing phase change material for passive solar space heating applications, including building and greenhouse heating, in relation to climatic circumstances. Vakialtojar (2001) created computational models to assess thermal energy storage systems for space heating and cooling applications. The impact of PCM slab thickness and fluid passage gap on storage performance was examined. He populated the phase change materials ( $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$  and  $\text{KF} \cdot 4\text{H}_2\text{O}$ ) in slender, flat containers, allowing air to circulate through the interstices between them. He determined that the air velocity profile at the entrance does not significantly influence the heat transfer characteristics or the outlet air temperature. Utilising reduced air gaps and thinner PCM slabs can enhance performance; however, this results in an increased quantity of PCM containers and an augmented overall volume of the storage system, consequently leading to a larger pressure drop across the system.

### 10.3 Refrigeration

The predominant storage medium for space cooling are water, ice, and phase change materials, sometimes referred to as eutectic salts. Phase Change Materials (PCMs) have been utilised for diverse thermal storage applications since the 1800s; nevertheless, their applicability as a medium for space cooling has emerged only recently. Currently, the predominant phase change materials for cool storage are inorganic salt hydrates, organic paraffin waxes, and their combinations. Literature on thermal storage at temperatures below ambient, aside from ice, is few. Solomar et al. (Solomar et al, 1989) reported a theoretical simulation of cool storage. BoHe et al. (2002) examined the feasibility of employing cool storage systems utilising phase change materials, along with a discussion of static and dynamic cool storage processes. The Rubitherm RT5 (melting point 7 °C, latent heat of fusion 158.3 kJ/kg) has been identified as a superior candidate for phase change material (PCM) in cool storage due to its cost-effectiveness, congruent melting behaviour, self-nucleation capability, absence of supercooling, and stability throughout multiple cooling and heating cycles.



**Figure 8.** Configuration of a solar air heater with a series of phase change material tubes

A literature review of commercial chemical products related to phase change materials for cool storage within the temperature range of 15 to 23 degrees Celsius was conducted (Kagaku et al, 1998). Nagano et al. (2003) examined the thermal properties of manganese (II) nitrate hexahydrate (melting point 25.8 °C, latent heat of fusion 125.9 kJ/kg) as a phase change material for cooling systems. It was discovered that nearly all chlorides effectively modulated the melting point of  $\text{Mn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ .  $\text{MnCl}_2 \cdot 4\text{H}_2\text{O}$  was an excellent additive for modifying the melting point, decreasing supercooling, and reducing the heat of fusion. The temperature differentials necessary for melting and solidification, as determined by differential scanning calorimetry (DSC), are approximately 6 °C for the melting process and 4 °C for the solidification process of the  $\text{Mn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$  mixture with 4.0 wt% of  $\text{MnCl}_2 \cdot 4\text{H}_2\text{O}$ . Indoor air at 28 °C during the day and external cool air at night below 16 °C can be employed to facilitate the melting and solidification of this mixture. Farid et al. (1998) investigated the viability of cold storage employing dimethyl sulfoxide (melting point 16.5 °C) as a phase change material in a rectangular container. According to the experimental findings and model forecasts, dimethyl sulfoxide can serve as a phase change material for thermal energy storage. The results indicate that the cooling extraction duration is contingent upon the quantity of solidified phase change material (PCM). The cooling extraction phase concluded when the outlet air temperature from the PCM section attained 25°C. This temperature is regarded as the maximum at which humans may experience comfort.

Saitoh and Hirose (1986) conducted an experimental and theoretical investigation of the thermal properties of an encased thermal storage tank. They utilised  $\text{Na}_2\text{HPO}_4 \cdot 12\text{H}_2\text{O}$  as a phase change material to fill cylindrical capsules with an internal diameter of 70.7 mm. The primary elements influencing the charging process were determined to be capsule size, coolant flow rate, coolant temperature, and capsule material. Kondepudi et al. (1988) examined the influence of the Biot number, Stefan number, and Fourier number on the thermal efficiency of cold storage. Laybourn (1988) employed a thermal resistance approach that incorporated convective resistance, wall resistance, and ice layer resistance to determine the cold storage capacity of the tank containing rectangular capsules. Arnold (1990) examined heat transport throughout the freezing and melting processes through a series of charging and discharging tests. Chen (1991) formulated a comprehensive lumped model to forecast the thermal efficiency of a cold storage system. The findings indicated that the lump model is an efficient and straightforward approach for assessing the thermal performance of cold storage systems. Ryu et al. (1991) utilised a rectangular storage tank with a copper tube container and performed a series of experiments employing both vertical and horizontal orientations to examine the heat transmission characteristics. Chen (1999) performed a series of experiments to examine the subcooling phenomenon and the freezing probability of water, both with and without nucleation agents, within a cylinder. The incorporation of nucleation agents has been confirmed as an efficient method to enhance the subcooling phenomenon. Chen et al., (2000) conducted an experimental investigation on the pressure drop within an encased thermal storage tank during the charging phase. The cylindrical capsules within the thermal storage tank employ water infused with nucleation agents as the phase change material, while the coolant consists of an aqueous ethylene glycol solution. They determined that elevated cold storage may be achieved by utilising a lower inlet coolant temperature in conjunction with a high flow rate. The heat transfer coefficient rises with an increase in coolant flow rate. The pressure loss across the tank increases as the coolant flow rate rises throughout the charging operation.

#### **10.4 Greenhouse Heating**

Solar agricultural greenhouses have been extensively utilised over the past two decades to enhance plant quality and productivity while decreasing fossil fuel demand for heating and cooling. Optimal greenhouses necessitate regulation of temperature, humidity, sun irradiance, and internal gas composition while ensuring efficient energy use. Investigations in this domain, focussing on novel materials, thermal storage, and heat exchange apparatus, have yielded intriguing demonstration units that subsequently led to swift commercial implementations. The

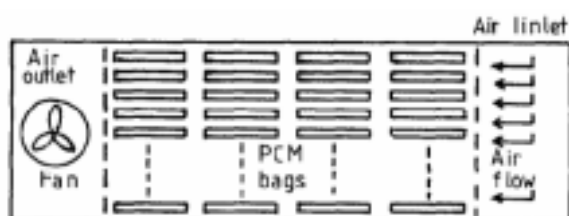
most commonly utilised phase change materials (PCMs) for these applications are  $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ ,  $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$ , polyethylene glycol (PEG), and paraffins.

Nishina and Takakura (1984) conducted research utilising  $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$  with various additives to inhibit phase separation and degradation for greenhouse heating in Japan. Figure 9 illustrates the overall perspective of the experimental configuration. This study revealed that while the internal objective of  $8^\circ\text{C}$  was attained, only 40-60% of the latent heat potential of the PCM was utilised, indicating that nearly half of the PCM was inefficiently employed throughout the energy exchange processes. Takakura et al. (1981) evaluated polyethylene glycol and  $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$  as phase change materials for greenhouse heating over a ground area of  $7.2 \text{ m}^2$ . They contrasted a normal greenhouse with a PCM storage-type greenhouse. The efficiency of the greenhouse, incorporating phase change material (PCM) storage with a solar collector, was 59% and successfully maintained an internal temperature of  $8^\circ\text{C}$  during the night, despite an external temperature decrease to  $-0.6^\circ\text{C}$ . A microcomputer control system has been created to provide enhanced precision and sophistication in the management of solar greenhouse systems.

CNRE-France executed a study employing a glass-covered multi-span greenhouse with a ground area of  $500 \text{ m}^2$ , specifically for rose cultivation, utilising 13.5 tonnes of  $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$  (melting at  $28^\circ\text{C}$ ) as referenced by Jaffrin and Cadier (Chen, 1999) and Jaffrin (1982, 1987). The thermal and agricultural performance of this greenhouse was compared with that of an air-bubble double plastic-covered greenhouse and a regular greenhouse. Figure 10 illustrates the configuration of the PCM containers underground. The containers were positioned on concrete shelves comprising five layers within semi-circular tunnels, utilising air for heat transfer. The study concluded that this technology achieved propane gas savings of 80% and 60% compared to traditional and double-covered greenhouses, respectively. The electricity consumption of the fans was found to be under 10% of the greenhouse's heating demand.

Levav and Zamir (1987) conducted experiments using  $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$  in a greenhouse setting. The necessary air temperature in the greenhouse was attained without any rise in relative humidity. The primary disadvantage of the technology was emphasised as the  $\$1.1/\text{kg}$  expense of the PCM. Moreover, they noted that the  $24^\circ\text{C}$  melting temperature of the PCM may be excessive for certain crops.

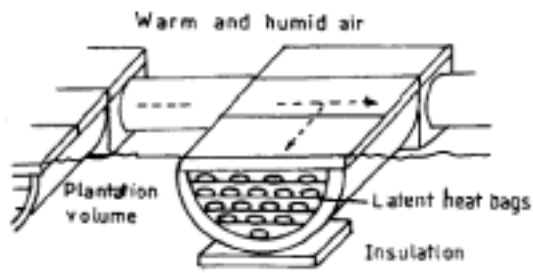
Kern et al. (1979) employed  $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$  as a phase change material in aerosol cans to explore energy storage potential within and outside a  $36 \text{ m}^2$  greenhouse enveloped in fibreglass. The study's results demonstrated that the external unit released approximately 80-90% of the absorbed energy, but the internal energy release ranged from 60-80%. storage facility. Paraffins have also been utilised for energy storage in greenhouses. A study conducted by Bagetinelik et al. (1994) was the sole publication in the literature utilising paraffin ( $48 - 60^\circ\text{C}$ , Latent Heat of Fusion  $190 \text{ kJ/kg}$ ) for greenhouse heating.



**Figure 9.** Overview of the phase change energy storage system

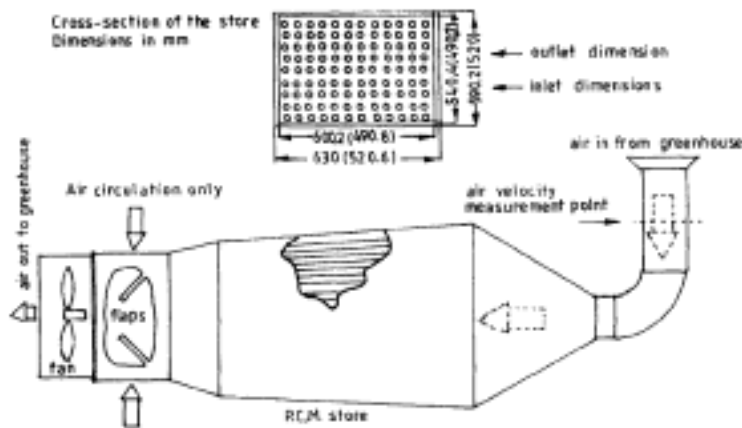
The most recent research on  $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$ -based phase change material applications in greenhouses was conducted by Ktirkliti et al. (1996, 1997). The study utilised two variants of a comparable phase change material (PCM): one with a melting range of  $22 - 25^\circ\text{C}$  for mitigating

peak temperatures during summer, and the other with a melting point of approximately 8°C for frost protection in both greenhouses.



**Figure 10.** Subterranean tunnel: outfitted with a phase change material

Figure 11 illustrates the experimental configuration for both purposes. Results indicated a temperature differential of around 2.5 - 3°C between the PCM greenhouse and the control greenhouse during the experimental duration, with a solar collecting efficiency of 29% based on external solar radiation for the tests utilising PCM with a higher melting point. The temperature differential and sunlight collection efficiency were approximately 22°C and 30%, respectively, during the frost prevention experiment, successfully preventing frost on 7 out of 9 frosty instances. The majority of applications were conducted in either double-covered greenhouses or greenhouses equipped with one or more layers of thermal screens. The sole study that minimally elucidated the impact of the PCM store on the environmental parameters of a greenhouse appeared to be that of Kuruklu et al. (1996, 1997). All studies indicate that phase change materials (PCMs) can be utilised for both energy storage and humidity regulation in greenhouses, contingent upon the appropriate selection and design of the entire system for optimal energy management.



**Figure 11.** Overview of the storage utilised for energy management within the greenhouse

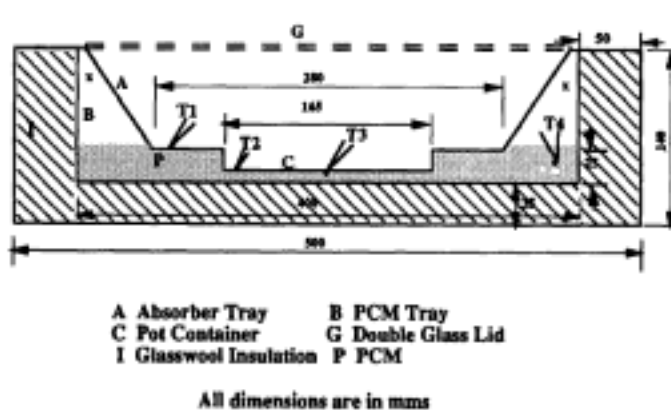
### 10.5 Solar Cooking

Solar cookers are utilised for preparing rice, veggies, meat, and baking cakes, among other foods. The comprehensive design, evaluation, theory, and functionality of box-type solar cookers are thoroughly established (Telkes et al, 1959 – Buddhi et al, 2000). The functionality of these cookers is restricted due to the absence of storage, rendering them unusable on overcast days or during the evening hours. The utilisation of phase change materials (PCMs) for latent heat storage has been acknowledged as a promising approach for creating a compact and efficient storage system, owing to its elevated storage density and stable working temperature (Hoda et al, 1977; Garg et al, 1978).

Buddhi and Sahoo (1997) have designed and constructed a box-type solar cooker with latent heat storage tailored for India's diverse climatic circumstances. Commercial-grade stearic acid (melting point 55 °C, latent heat of fusion 161 kJ/kg) utilised as a latent heat storage medium. Figure 12 illustrates the design of a box-type solar cooker intended for a single vessel, using a phase change material (PCM) for solar energy storage. The cooker comprises an aluminum-absorbing tray designated as 'A'. A cylindrical container with a diameter of 0.165 m and a depth of 0.02 m has been welded at the centre of the absorbent plate (shown as 'C' in Fig. 1), designed to securely hold the cooking pot. This container will facilitate heat transfer from the absorbing plate to the phase change material (PCM). Additionally, aluminium fins were installed on the interior surface of the tray and cylindrical container. The outer tray 'B' is constructed from the identical aluminium sheet. The distance between tray 'A' and tray 'B' was maintained at 0.025 m on the lower side. Tray 'B' contained 3.5 kg of commercial-grade Stearic Acid (PCM), ensuring optimal contact between the PCM and the underside of tray 'A'. The gap between tray 'B' and the casing was filled with glass wool to ensure thermal insulation for the bottom and sides of the solar cooker. A flat glass mirror was secured within an aluminium casing.

function as an insulator and a shield for the glass lid when the cooker is not subjected to sun radiation. The exterior of aluminium tray 'A', cooking pot, and its lid were coated with a matte black paint. The experimental findings indicate the viability of employing a phase change material as the store medium in solar cookers, allowing for meal preparation in the evening with a solar cooker equipped with latent heat storage. It also maintains a virtually uniform plate temperature during the late evening.

Domanski et al. (1995) examined the feasibility of cooking during non-sunlight hours utilising phase change materials (PCMs) as storage mediums. The storage-cooking pot was designed for use during non-sunlight hours (Fig. 13). To achieve this, two concentric cylindrical containers, each 0.0015 m thick and constructed from aluminium, are joined at their tops with four screws, creating a double-wall vessel with an interstitial space between the outer and inner walls. The outer vessel has a diameter of 0.18 m, whereas the inner vessel has a diameter of 0.14 m. The annular space between the outer and inner vessels measures 0.02 m. The gap is sealed with a detachable aluminium cover featuring three circular apertures for the insertion of thermocouples and facilitating direct observation during the filling or extraction of the phase change materials (PCMs). An aluminium circular cover serves as the lid for the interior jar.



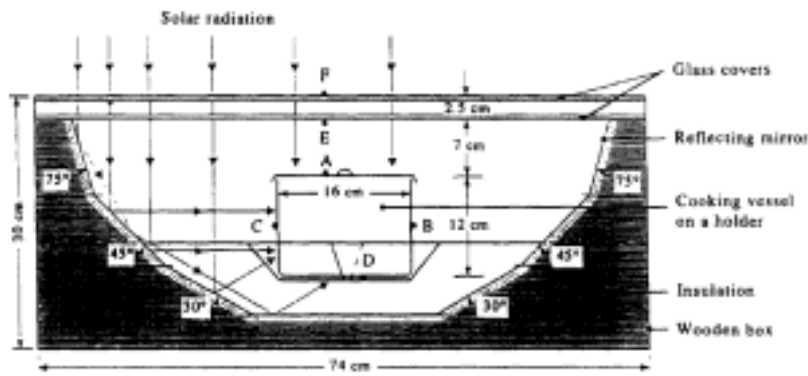
**Figure 12.** Schematic representation of the solar cooker's box with phase change material storage

The external surfaces of the outer vessel and the coverings are coated with standard black paint to optimise the absorption of solar radiation. The interstice between the outer and inner vessels contains 1.1 kilogramme of stearic acid (69 °C, 95% purity) or 2 kg of magnesium nitrate hexahydrate (89 °C, 99% purity), allowing adequate room for the expansion of the phase change materials upon melting. They determined that the cooker's performance was assessed based on the charging and discharging durations of the PCMs under various settings. He stated that performance is contingent upon solar irradiation, the mass of the cooking medium, and the

thermophysical parameters of the phase change material (PCM). The cooker's overall efficiency when discharging was determined to be 3-4 times superior to that of steam and heat-pipe solar cookers, which are suitable for indoor cooking. In this configuration, the rate of heat transmission from the PCM to the cooking pot during the PCM's discharge is sluggish, necessitating more time for preparing the evening meal.

Sharma et al. (2000) engineered a cylindrical phase change material storage unit for a box-type solar cooker to facilitate food preparation in the late evening. The device encircles the cooking vessel, resulting in an elevated rate of heat transfer between the phase change material and the food, hence facilitating speedier cooking. A PCM container was developed and constructed to accommodate the cooking vessel, as illustrated in the figure. Fourteen. It comprises two hollow concentric aluminium cylinders with diameters of 18 cm and 25 cm, each 8 cm in depth and 2 mm in thickness. The interstitial space between the cylinders was occupied by acetamide (melting point 82 °C, latent heat of fusion 263 kJ/kg) serving as a phase change material (PCM). The pot utilised for cooking measures 17.5 cm in diameter and 10 cm in height, allowing it to fit within the PCM container for culinary applications. To improve the heat transfer rate between the PCM and the inner wall of the PCM container, eight fins (1x3 cm) were affixed to the inner wall of the container. It was observed that utilising 2.0 kg of Acetamide as a latent heat storage medium enables the cooking of the second batch of food if loaded prior to 3:30 P.M. in the winter season. The melting temperature of a PCM is advised to be between 105 and 110 °C for evening cooking. Consequently, it was necessary to select a storage material with an adequate melting point and sufficient quantity to prepare the food in the late evening. To accumulate a greater volume of heat in a phase change material, an increased amount of solar radiation input would be necessary. Consequently, Buddhi and Sharma (2003) employed a latent heat storage unit for a box-type solar cooker including three reflectors. Acetanilide (melting point 118 °C, latent heat of fusion 222 kJ/kg) was utilised as a phase change material for nocturnal cooking. A double-glazed box-type solar cooker, including a 50 cm x 50 cm aperture area and a depth of 19 cm, was employed to perform the cooking trials with the PCM storage unit. This solar cooker features three reflectors, with the central reflector affixed to a hinge allowing rotation solely across the horizontal axis. The remaining two reflectors were secured by a ball-and-socket mechanism on the left and right sides of the reflector. This pair of reflectors possesses three degrees of freedom, allowing movement along the horizontal and vertical axes, as well as rotation about both axes. Through these methods, attempts were undertaken to maintain the reflected solar irradiance on the absorber surface to augment the incident solar radiation on the glass cover during the sunlight exposure trials.

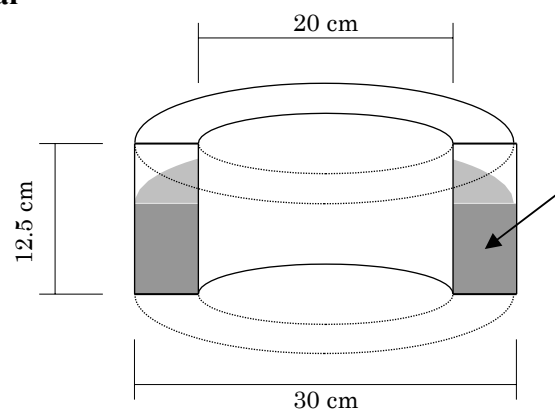
In accordance with Sharma et al. (2000), a cooking apparatus incorporating latent heat storage was built and constructed for nocturnal or late evening food preparation. The unit has two hollow concentric aluminium cylinders with diameters of 20 cm and 30 cm, each 12.5 cm in depth and 2 mm in thickness. The interval between the cylinders was occupied with 4.0 kg of phase change material to facilitate the cooking trials with all three reflectors. The pot utilised for cooking measures 19 cm in diameter and 15 cm in height, allowing it to fit within the PCM storage unit for culinary applications. To improve the heat transfer rate between the PCM and the inner wall of the PCM container, eight fins (1 cm x 3 cm) were affixed to the inner wall of the container. The experimental results indicate that the cooking trials were effectively executed until 8 P.M. use 4.0 kg of phase change material during the winter season in India.



**Figure 13.** Solar Cooker Featuring a Phase Change Material Cooking Container

Sharma et al. (2004) devised a solar cooker utilising an Evacuated Tube Solar Collector (ETSC) with phase change material (PCM) storage, as seen in Fig. Fifteen. The system comprises an ETSC, a closed-loop pumping line carrying water as the Heat Transfer Fluid (HTF), a phase change material (PCM) storage unit, a cooking unit, a pump, a relief valve, a flow meter and a stainless steel tubing heat exchanger. The PCM storage unit comprises two hollow concentric aluminium cylinders, with inner and outer diameters of 304 mm and 441 mm, respectively, and a depth of 420 mm, featuring a thickness of 9 mm (Fig. 16). The interstice between the cylinders was occupied by 45 kg of erythritol (melting point 118 °C, latent heat of fusion 339.8 kJ/kg), utilised as the phase change material (PCM). A pump sends the heated water (HTF) from the ETSC through insulated pipes to the PCM storage unit via a stainless steel tubing heat exchanger that encircles the cooking unit in a closed loop. During daylight hours, warm water transfers its thermal energy to the PCM and is stored as latent heat via a stainless steel tube heat exchanger. The stored heat is employed to prepare food throughout the evening or when solar intensity is inadequate for cooking. They determined that cooking occurred twice daily, at midday and in the evening. Midday cooking did not influence evening cooking, and evening cooking utilising PCM storage was determined to be more efficient than midday cooking. Experiments and analyses demonstrated that the prototype solar cooker exhibited good performance despite suboptimal heat transmission; the revised design of the heat exchanger in the thermal storage unit will improve the heat transfer rate in the current configuration.

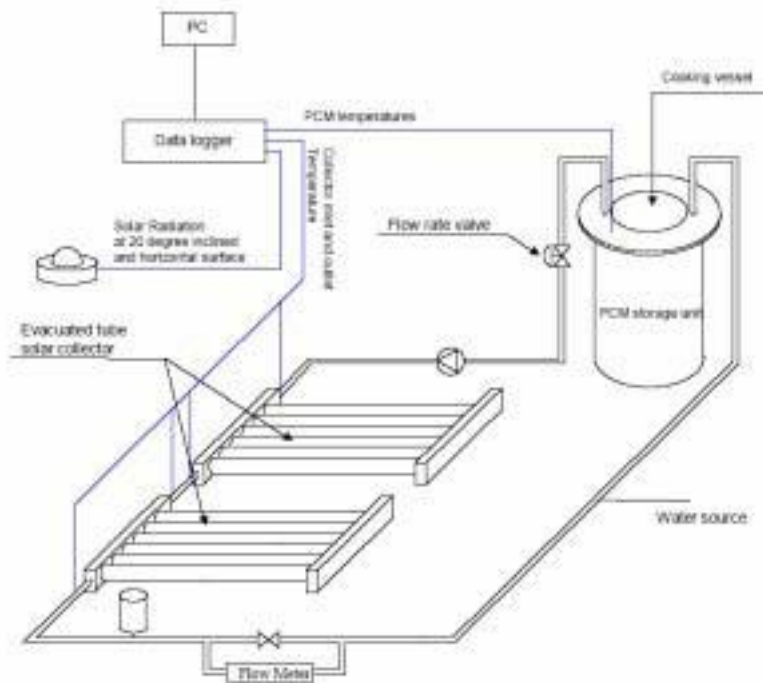
### 10.6 Phase Change Material



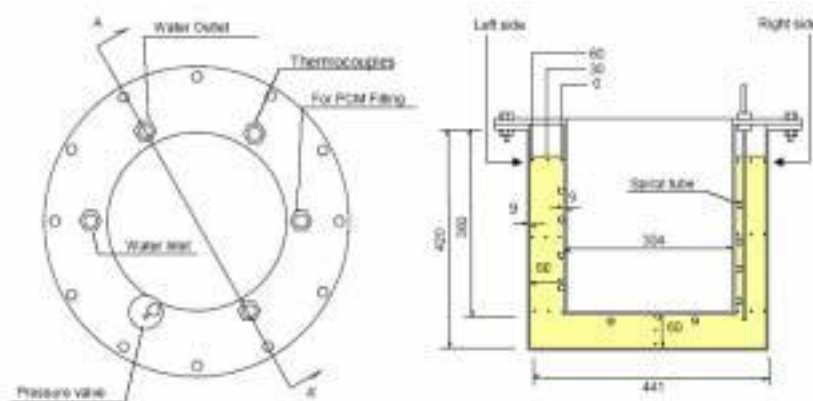
**Figure 14.** A schematic representation of the latent heat storage unit

Ramadan et al. (1987) developed a basic flat-plate solar cooker incorporating focussing plane mirrors and energy storage materials. The incorporation of a half-centimeter thick sand jacket surrounding the cooking pot has significantly enhanced the performance of the cooker. They determined that a cooking duration of six hours per day has been documented. Approximately three hours of indoor cooking each day has been accomplished. An overall energy conversion efficiency of up to 28.4% has been achieved. The feasibility of employing a PCM as a storage

media to achieve extended cooking durations was examined. A thin layer of the salt hydrate  $Ba(OH)_2 \cdot 8H_2O$  was proposed as a jacket surrounding the cooking kettle. Bushnell (1988) introduced a prototype for solar ovens utilising pentacrythritol as a solid-solid phase change material (PCM). He delineated the performance through efficiency assessment and the establishment of a figure of merit.



**Figure 15.** Outline of the prototype solar cooker based on evacuated tube solar collector with PCM storage unit



**Figure. 16 (a).** Sectional view of the PCM storage unit. **Figure. 16(b).** Vertical perspective of the PCM storage device

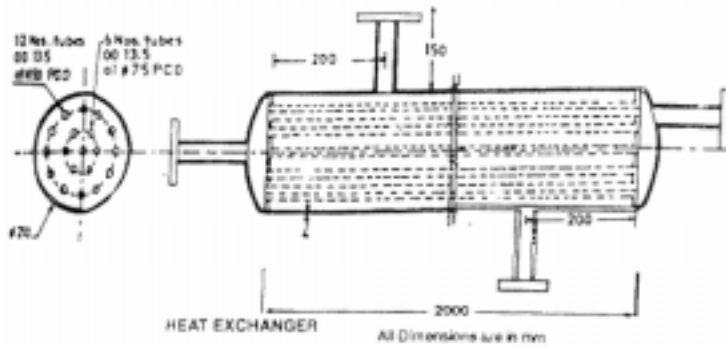
### 10.7 Waste Heat Recovery Systems

The air conditioning system expels both sensible and latent heat, with sensible heat comprising approximately 15-20% of the total heat discharged. The compressor's elevated temperature is rather high ( $< 65\text{ }^{\circ}\text{C}$ ) while utilising Freon as a refrigerant. Consequently, it can be recuperated via an accumulator, resulting in elevated thermal energy. Zu et al. (2004) devised a heat recovery system utilising phase change materials (PCM) to reclaim the expelled heat from air conditioning systems, thereby generating low-temperature hot water for washing and bathing purposes. The study determined that the heat recovery system reduces both the primary energy consumption for

heating residential hot water and the heat dissipation to the environment resulting from air conditioning systems. The efficiency ratio of the system significantly improves when all rejected sensible and latent heat from air conditioning systems is recovered. The technical grade paraffin wax and its mixes with liquid paraffin and lauric acid are suitable as phase change materials for heat recovery in air conditioning systems.

An efficient application of urban waste heat from co-generation systems, generally accessible at temperatures ranging from 60 to 100 °C. Kakiuchi et al. have examined erythritol (melting point 118 °C; latent heat of fusion 339.8 kJ/kg) (Ona et al, 2001, Kakiuchi et al, 1998), which is applicable in high-temperature industrial waste heat processes. A multitude of investigations has been conducted on stearic acid (Buddhi et al, 1999, Sari et al, 2001). This material possesses a melting point ranging from 60 to 70 degrees Celsius and is costly. Its utility in waste heat systems is restricted. Nagano et al. (2004) offered a combination of  $Mg(NO_3)_2 \cdot 6H_2O$  as the primary material, with  $MgCl_2 \cdot 6H_2O$  as an addition to adjust the melting point. It was claimed that the incorporation of 5-10 wt% of  $MgCl_2 \cdot 6H_2O$  can solidify  $Mg(NO_3)_2 \cdot 6H_2O$  (melting point 80 °C, latent heat of fusion 150 kJ/kg). Augmenting the mix ratio had minimal impact on the heat of fusion, although facilitated a reduction in the melting point to approximately 60 °C. No deterioration in the melting point or latent heat of fusion was noted during 1000 accelerated thermal cycles. Yagi et al. (1995) performed foundational research on heat transfer to design a latent heat storage technology for recovering high-temperature waste heat above 500 K. Experiments on heat transfer were conducted for both a single encapsulated phase transition material and a packed bed. The metallic phase change materials demonstrated exceptional efficacy in thermal storage due to their uniform temperature distribution within the capsule. Simulation results indicate that concurrent flow for heat storage and release demonstrates superior efficacy in utilising stored heat compared to counter-current flow.

Buddhi (1997), engineered and constructed a shell and tube heat exchanger for low-temperature waste heat recovery, utilising stearic acid (melting point 59 °C, latent heat of fusion 198 kJ/kg) as a phase transition material for this investigation. The thermal performance of this system was assessed during the charging and discharging processes of the phase change material at various mass flow rates. The schematic diagram of the shell and tube heat exchanger is illustrated in the figure. Seventeen. The utilised phase change material exhibits inadequate thermal conductivity; hence, to improve the system's effective thermal conductivity, the radial spacing between the tubes was maintained at 3 to 4 centimetres. The shell included 50 kg of commercial-grade stearic acid utilised as a latent heat storage medium. The energy-charging test commenced with the circulation of hot water through the HTF tubes, followed by the extraction of stored energy via the introduction of cold water into the HTF tubes. The ambient temperature, flow rate, and phase change material temperatures of the heat exchanger were concurrently recorded at 15-minute intervals. He determined that the experimental findings demonstrate the viability of employing PCM as storage material in heat recovery systems. The suboptimal thermal conductivity of the PCM results in a low total heat transfer coefficient, necessitating the incorporation of fins to enhance the efficiency of the heat exchanger. The spacing between tubes, fins, and mass flow rates must be meticulously chosen to enhance the efficiency of the heat exchanger. Paraffin wax (melting point 54 °C, latent heat of fusion 184 kJ/kg) was utilised in a shell and tube heat exchanger for waste heat recovery (Buddhi et al, 2003). Fins were utilised for efficient heat transfer.



**Figure 17.** Shell-and-tube heat exchanger using latent heat storage material

## 11. LATENT HEAT STORAGE EXCHANGER

Latent heat storage systems primarily rely on the examination of heat storage materials and the advancement of heat exchangers that ensure a high effective heat transfer rate for rapid charging and discharging. A heat exchanger utilising high-temperature phase change materials not only possesses a significant capacity for thermal energy storage but also enhances the applicability of the stored energy. Achieving an adequate rate of heat transfer from latent thermal energy storage devices is consistently problematic due to suboptimal heat exchanger design. Various types of heat exchangers have been developed to address this deficiency. A double pipe heat exchanger for latent thermal energy storage has been examined (Fath et al, 1991). This research indicated that the heat transfer rate can be improved by elevating the air inlet temperature, augmenting the air mass flow velocity, and extending the heat exchanger length. A single full-length heat exchanger demonstrated superior thermal effectiveness compared to two half-length parallel heat exchangers of identical capacity. A direct contact heat exchanger utilising an immiscible heat transfer fluid within the phase change material (PCM) has removed the permanent heat exchange surface and has been validated to inhibit phase separation of the PCM (Farid et al, 1989 – Sokolov et al, 1991).

Classical double-pipe or shell-and-tube heat exchangers have been utilised in energy storage systems, with theoretical and experimental analyses of the phase-change phenomenon limited to the geometry of cylindrical capsules, annular gaps, and spherical or rectangular enclosures. A alternative design incorporates three varieties of phase change materials (PCMs) with distinct melting temperatures (Watame). This facilitates optimal utilisation of the HTF energy. The utilisation of plate heat exchangers was considered to offer a more efficient and compact heat exchange design (Bansal et al, 1992). Erk and Dudukovic (1996) introduced an innovative energy storage technology of n-octadecane held by capillary forces within a porous silica substrate. This arrangement removes the costly heat exchange surface, enhances energy density, and increases the rates of energy storage and release. Lecomte et al. (1985) proposed a design methodology for determining the dimensions of a shell-and-tube latent heat exchanger inside a thermal system under specified thermodynamic parameters. They determined that elevated flow rates were incapable of transferring much heat from the PCM to the load. The transfer of heat from the phase change material (PCM) to the load is contingent upon the efficacy of the heat exchanger and the thermophysical characteristics of the PCM. Bathelt (1980) investigated the thermal transfer throughout the melting process from a horizontal cylindrical heat source exhibiting a homogeneous surface heat flow and temperature, utilising a fluid circulated via a multipass heat exchanger immersed in n-heptadecane and n-octadecane. The instantaneous configuration of the melt volume was documented photographically, and local heat transfer coefficients at the solid-liquid interface were ascertained. In quasi-steady melting, the local and average heat transport is connected in a dimensionless manner. The correlation was utilised to compute the position of the solid-liquid interface, which aligned well with the experimental data.

Saxena et al. (1982) introduced a basic model for calculating potential thermal energy storage in shell and tube heat exchangers. The impact of numerous parameters, including the thermal and physical properties of phase change materials (PCM) and convective fluids, heat exchanger size, and flow rates of heat transfer fluids in both laminar and turbulent regimes on energy storage durations is examined. El - Kassaby et al. (1993) modelled the performance of a low-temperature phase transition material in a heat exchanger for short-term storage. A superior correlation was achieved for the outlet air temperature in comparison to the experimental observations, with discrepancies not surpassing 0.5°C throughout the simulated duration. This simulation method is applicable to any phase change material (PCM) with established thermophysical parameters and can forecast the transient movement of the freezing or melting front, as well as the mass fraction of either the liquid or solid phase relative to the total PCM mass.

Kamimoto et al. (1986) designed a latent heat thermal storage exchanger utilising form-stable high-density polyethylene. In their design, the hot fluid entered the exchanger from the top during the charging operation, while the cold fluid entered from the bottom during the discharging process. No rationale was provided for the adoption of this operational style. Bellecci et al. (1993) conducted numerical simulations of the cyclic thermal processes in a shell-and-tube latent heat thermal storage exchanger. The design incorporated the introduction of hot and cold fluids from the same end of the storage exchanger during the sequential charge and discharge operations. Gong et al. (1994) sought to determine which operational method is superior between Kamimoto (1986) and Bellecci et al. (1993). A finite element model was created to simulate the cyclic thermal process in a shell-and-tube latent heat thermal storage exchanger. This exchanger has a tube encircled by an exterior coaxial cylinder constructed from a phase change material (PCM). A heat-transfer fluid circulates through the tube to either store or remove thermal energy from the phase change material (PCM). Numerical investigations demonstrated that entering the hot and cold fluids from the same end of the storage exchanger is preferable to introducing them from opposite ends. The numerical findings also offer help for selecting the proper mode. The results are confined solely to conduction-controlled melting and freezing heat transfer in the phase change material (PCM).

Hasan (1994) created a straightforward tube-in-tube heat exchanger for thermal energy storage utilising stearic acid as a phase change material (PCM). He discovered that the melting front progresses radially inward and axially downward within the PCM tube. The velocity of the melting front was accelerated by a convection heat transfer mechanism within the melted phase change material (PCM). Phase transition can be expedited by positioning the heat exchanger horizontally instead of vertically. He et al. (2001) conducted a theoretical study and experimental evaluations of an innovative shell-and-tube latent heat exchanger, establishing a foundation for its optimal design and operation. They indicated that some parameters, including inlet temperature, fluid velocity, PCM thickness, and flow channel length, significantly influence the heat transfer performance of the unit. Consistent heat output can be achieved by elevating the inlet temperature of the heat transfer fluid, increasing the thickness of the phase change material, and extending the flow channel length. Banaszek et al. (1999) employed a spiral heat exchanger within a latent heat storage unit. The system's most attractive qualities include compactness, improved heat transfer from centrifugal forces, ease of sealing, an extensive heat transfer surface, and a reduced undisturbed flow length. Qarnia et al. (2001) introduced a mathematical model to simulate the thermal dynamics of a cross-flow heat exchanger, using layers of phase change material (PCM) positioned between the hot and cold air streams to mitigate icing. The mathematical model was corroborated using empirical data. Thermal resistance was shown to impact exchanger performance by diminishing the dimensionless output temperature of the cold air stream.

## **12.0 MEASUREMENT METHODOLOGIES FOR THERMO-PHYSICAL PROPERTIES**

The various measuring techniques currently employed for determining the latent heat of fusion and melting temperature of phase change materials (PCMs) can be categorised as follows: (i) Drop Calorimeter (DC), (ii) Differential Thermal Analysis (DTA), and (iii) Differential Scanning Calorimeter (DSC). The DC approach necessitates considerable time investment, and the precision of the outcomes is suboptimal (Buddhi et al, 1987). In DSC and DTA procedures, sample and reference materials are subjected to heating at a consistent pace. The temperature differential between the two materials is directly proportional to the disparity in heat flow, and this record is referred to as the DSC curve. The suggested reference material is Alumina (Al<sub>2</sub>O<sub>3</sub>). The latent heat of fusion is determined by the area beneath the peak, whereas the melting temperature is assessed by the tangent at the point of maximum slope on the peak's face. A multitude of researchers have employed Differential Scanning Calorimetry (DSC) to assess the thermophysical properties of Phase Change Materials (PCMs) (Flaherty, 1971; Giavarini et al., 1972; Cantor et al., 1978; Elder et al., 1980; Salyer et al., 1986; Bukovec N. et al., 1989; Dunn J.G. et al., 1989; Aboul-Enein et al., 1991; Takahashi Y. et al., 1991; Babich M.W. et al., 1992; Richardson M.J. et al., 1993; Gibbs et al., 1986; Feldman D. et al., 1996; Li W. et al., 1999; Sharma S.D. et al., 1999; Sharma, A. et al., 2002; Liu et al., 2001) (Flaherty et al, 1971 – Liu et al, 2001).

The aforementioned methods are generally regarded as precise for determining the heat of fusion. The thermophysical properties of a minimal quantity (1-10 mg) of the sample phase change material may differ from those of the bulk components, including heterogeneous additions. Zhang developed a T-history approach as an alternative for ascertaining the thermophysical characteristics of PCM, aimed at overcoming the aforementioned limitations of DSC. This method's requirement for a minimal sample volume renders it highly suitable for conducting cycle tests using sealed tubes holding newly developed phase change materials (PCMs). Nonetheless, the original T-history technique is constrained in its accuracy of thermophysical parameters due to the incorporation of some erroneous physical assumptions. Hong et al. (2004) endeavoured to enhance the precision of the T-history approach for quantifying the heat of fusion of diverse materials. Marin et al. (2003) enhanced the methodology of Zhang et al. to ascertain temperature-dependent characteristics. Their analysis indicates that this method facilitates the straightforward acquisition of both characteristics and curves, significantly aiding in the selection of heat storage materials and the subsequent design of thermal energy storage systems. The enthalpy–temperature curves facilitate the acquisition of average material properties by allowing the assessment of thermal property variations with temperature.

## **12. THERMAL CYCLES**

For latent heat storage, commercially available phase change materials (PCMs) with around 95% purity are favoured due to their widespread availability and cost-effectiveness. The thermophysical characteristics and behaviour of commercial-grade materials significantly differ from those reported in the literature for laboratory-grade materials (purity exceeding 99%). Given the scarcity of data about the impact of thermal cycling on commercial-grade phase change materials (PCMs), it is crucial to investigate its impacts on melting temperature, latent heat of fusion, and specific heat of these materials. Sharma et al. (1998, 2002) performed accelerated heat cycle testing on stearic acid, acetamide, and paraffin wax. They determined that commercial-grade phase change materials exhibit no consistent decrease in their melting points after undergoing 1500 heat cycles. Acetamide and paraffin wax exhibit commendable stability during the cycle process and may be regarded as promising phase change materials (PCMs). It is advisable to undertake a heat cycle test on commercial-grade materials intended for use as PCM, as their behaviour may vary. Ting et al. (1987) performed accelerated cycle testing on a phase change material (PCM) unit containing Na<sub>2</sub>SO<sub>4</sub>·nH<sub>2</sub>O at various weight ratios. The researchers examined the impact of 1000 temperature cycles on the container tube, although did not assess

its influence on the thermophysical properties of the PCM. Fernanda (1988) has investigated the thermal reliability of salt hydrate phase change materials (PCMs) with melting temperatures ranging from 15 to 32°C by assessing latent heat of fusion and melting temperature during repeated cycles.

Sharma et al. (2001) examined the impact of thermal cycling on urea and observed that it did not undergo melting after multiple cycles. It was recommended that urea not be utilised as a phase change material (PCM). Hadjieva (1992) computed the enthalpy of three paraffin mixtures, revealing its dependency on oil content and atomic distribution as determined by chemical and gas chromatographic investigations. Thermal cycle testing was conducted on a mixture of technical grade paraffins, which demonstrated stability after undergoing 900 heating and cooling cycles. Gibbs (1995) indicated that paraffin exhibits exceptional heat stability. Kimura and Kai (1984) utilised NaCl to enhance the stability of  $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ , which had a somewhat more amount of water than the stoichiometric ratio. The salt demonstrated exceptional stability after undergoing over 1000 heating and cooling cycles. Porisino (1988) investigated the thermal reliability of salt hydrate phase change materials (PCMs) by assessing the latent heat of fusion and melting temperature during repeated cycles. Wada et al. (1984) examined the diminishing heat storage capacity of  $\text{CH}_3\text{COONa} \cdot 3\text{H}_2\text{O}$  during thermal cycling and conducted calorimetric assessments on three distinct sample types. Hasan and Sayigh (1994) examined the thermal characteristics of certain saturated fatty acids utilising the DSC technique during a medium-term duration that encompasses

Heating and cooling cycles totalling 450 occurrences. The thermal energy storage capability of  $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$  was examined concerning heat cycling as discussed by Marks (1980). Zhang et al. (2001) investigated the solid-liquid phase transitions in lauric, palmitic, and stearic acids, together with their binary systems. They also examined the durability of the thermal properties over multiple heating-cooling cycles, specifically 30, 50, 80, and 100 cycles. Sari (2003, 2003) performed 1200 accelerated thermal cycle tests to investigate the thermal reliability of lauric, myristic, palmitic, and stearic acids. Thermal cycling studies have been performed on wallboards impregnated with 24 wt% PCM. The samples exhibited no propensity for the PCM (paraffin) to migrate within the wallboard, and there was no discernible degradation in the thermal energy storage capacity (Khudhair 2003).

### **13. DETERIORATION OF THE PHASE CHANGE MATERIALS**

Porosini (1988) and Groll et al. (1990) evaluated the corrosion of various salt hydrates and salt eutectics on different container materials, as well as their thermal stability. Recently, Cabeza et al. (2001 - 2001) investigated the corrosion resistance of five prevalent metals (aluminium, brass, copper, steel, and stainless steel) when exposed to molten salt hydrates (zinc nitrate hexahydrate, sodium hydrogen phosphate dodecahydrate, calcium chloride hexahydrate, sodium carbonate, potassium hydrogen carbonate, potassium chloride, water, sodium acetate trihydrate, and sodium thiosulphate pentahydrate) in an immersion corrosion test. Recently, Sari et al. (2003) examined the corrosion resistance of various construction materials to fatty acids (stearic, palmitic, myristic, and lauric acid) for an extended duration. The materials used for the containers were stainless steel (SS 304 L), carbon steel (C<sub>20</sub>), aluminium (Al), and copper (Cu). It can be concluded that stainless steel (SS304L) with a chromium oxide ( $\text{Cr}_2\text{O}_3$ ) surface layer and aluminium (Al) with an aluminium oxide ( $\text{Al}_2\text{O}_3$ ) surface layer are fundamentally compatible with the examined fatty acids, as evidenced by gravimetric and metallographic corrosion test findings. Carbon steel (Steel C<sub>20</sub>) and copper (Cu) are preferentially compatible materials for storage containers.

### **14.0 ENHANCEMENT OF HEAT TRANSFER**

In a latent heat storage system, the solid-liquid contact recedes from the heat transfer surface during the phase transition. Throughout this process, the surface heat flux diminishes as a result of the escalating thermal resistance associated with the increasing thickness of the

molten/solidified layer. During solidification, conduction serves as the sole transport mechanism, which is often inefficient. During melting, natural convection may arise in the molten layer, typically enhancing the heat transfer rate relative to the solidification process, provided the layer is sufficiently thick to facilitate natural convection. Nevertheless, the typically poor heat transfer rate can be significantly improved with the application of an appropriate heat transfer augmentation technology. Numerous techniques exist to improve heat transfer in an LHTS system. Various researchers have recommended the utilisation of finned tubes with diverse configurations as an effective method to enhance the charge/discharge capacity of an LHTS system (Velraj et al,1997 – Baner et al, 2000). Additional techniques for enhancing heat transfer in latent heat thermal storage (LHTS) systems include the incorporation of phase change materials (PCM) within a metal matrix, the dispersion of PCM with high-conductivity particles, microencapsulation of PCM, the use of an embedded graphite matrix, carbon fibre brushes exhibiting high thermal conductivity (190 W/mK), exfoliated graphite to enhance the thermal conductivity of form-stable P/HDPE composite PCMs, the insertion of copper plates within spherical capsules containing n-octadecane PCM, and the utilisation of metal screens or spheres positioned inside the PCM. Erik and Dudukovic (1996) introduced an innovative energy storage technology including n-octadecane maintained by capillary forces within a porous silica substrate. This arrangement removes the costly heat exchange surface, enhances energy density, and increases the rates of energy storage and release. Leoni and Amon (1996) utilised aluminium foam to improve the heat transmission mechanism in a latent heat storage system.

## **15. NOVEL PCM INNOVATIONS**

Ravankar (2001) introduced an innovative testing methodology for satellite power utilising latent heat storage. PCM transitions to a liquid state at elevated temperatures, thereafter solidifying during prolonged periods of cold darkness and releasing its latent heat. The emitted heat can be utilised to produce electricity by powering thermoelectric equipment. John et al. (2000) developed an innovative nighttime cooling ventilation system, integrating phase change materials and heat pipes as an alternative to air conditioning. The technology provides significant advantages by diminishing or eradicating the necessity for air conditioning. Microencapsulated phase change materials can be integrated into textile fibres, composites, and garments to significantly improve thermal insulation in both hot and cold conditions (Colvin et al, 1998). Cabeza et al. (2002) indicated that phase change materials (PCMs) are effective for delivering temperature-sensitive drugs and food due to their capacity to store heat and cold within a range of several degrees. Numerous firms are involved in the investigation of transporting temperature-sensitive phase change materials for diverse purposes (201 - 205).

Vasiliev et al. (2000) devised a latent heat storage module for motor vehicles, enabling heat retention when the engine is off, which may then be utilised to preheat the engine upon restart. Utilising heat storage enables the engine to attain an optimised operating temperature in a significantly reduced timeframe compared to the absence of heat storage. Pal and Joshi (1996, 1997) advocated for the use of PCM to limit the maximum temperature of electronic components. Tan et al. (2004) performed an experimental investigation on the thermal management of mobile electronic devices and computers, utilising a heat storage unit (HSU) containing n-eicosane as the phase change material (PCM) within the device. The elevated latent heat of n-eicosane in the HSU absorbs heat dissipation from the chips, sustaining the chip temperature below the permissible service temperature of 50 °C for 2 hours during transient operations of the PDA.

Climator (Ulfvengren et al, 2004) has created a cooling vest for athletes to lower body temperature. Phase Change Materials (PCMs) have also been suggested for the cooling of newborns (Olsson et al, 2004). Koschenz et al. (2004) devised a thermally activated ceiling panel for integration into lightweight and retrofitting structures. Simulation studies and laboratory testing indicated that a 5 cm layer of microencapsulated phase change material (25% by weight) and gypsum can maintain a pleasant room temperature in ordinary office buildings. Heptadecane was tested as a phase change material in this prototype configuration. Naim et al. (2002)

developed an innovative continuous single-stage solar still incorporating phase change material (PCM). The productivity of a solar still can be significantly improved through the integration of a phase change material (PCM) with the still. Huang et al. (2004) employed phase change materials for the thermal regulation of building-integrated photovoltaics. Under varying ambient conditions, a PV/PCM system may facilitate the photovoltaic module's operation close to its optimal temperature of 25°C. They created a PV/PCM simulation model and validated it against experimental results. The enhancement in thermal performance attained through the utilisation of metal fins in the PCM container is substantial. The fins facilitate a more consistent temperature distribution inside the PV/PCM system. A comprehensive experimental investigation has been conducted on the thermal properties of a phase change material utilised to regulate the temperature increase of photovoltaic systems in a PV/PCM configuration (Huang et al, 2001- Huang et al, 2002). Tavaranan et al. (2002) proposed the utilisation of phase change materials (PCM) in conjunction with solar (PV) panels and thermoelectric modules (TEMs) for the creation of a portable vaccination refrigerator intended for distant settlements lacking grid electricity. Thermoelectric modules (TEMs), which convert electrical energy into thermal energy through the Peltier effect, serve as effective alternatives for eco-friendly cooling applications, particularly for modest cooling demands and when compactness is essential. Omer et al. (2001) have conducted experimental investigations on thermoelectric refrigeration systems utilising latent heat storage. Duffy and Trelles (2003) proposed a numerical simulation of a porous latent heat thermal energy storage system for thermoelectric cooling, examining various porosities of the aluminium matrix. A porous aluminium matrix was employed to enhance system performance by boosting heat conduction while minimally impacting stored energy.

Weinlader et al. (2004) employed phase change materials in double-glazed façade panels for daylighting and thermal regulation. A façade panel using PCM exhibits around 30% reduced heat loss in south-facing facades. Solar heat gains are diminished by around 50%. Facade panels with phase change materials significantly enhance thermal comfort in winter, particularly during the nighttime hours. During summer, these systems exhibit minimal heat gains, hence diminishing peak cooling demands throughout the day. Evening heat gains can be mitigated with overnight ventilation. Utilising a phase change material (PCM) with a low melting point of up to 30°C will enhance thermal comfort during the day in summer, in contrast to double glazing without or with internal sun protection. Ying et al. (2004) established the testing requirements for PCM fabrics. Three indices have been suggested to define the thermal functional performance of PCM textiles. The index of thermal regulation capability describes the thermal performance of PCM fabrics and is significantly influenced by the quantity of PCM present. Khateeb et al. (2004) developed a lithium-ion battery utilising an innovative phase change material (PCM) for the thermal management system in electric scooters. A developed Li-ion battery was proposed to substitute the current lead-acid battery in the electric scooter, without necessitating any mechanical modifications to the battery compartment.

## **16. CONCLUSION AND FUTURE PERSPECTIVES**

Elevated intake temperatures and increased flow rates of heat transfer fluid systems are necessary for the optimal operation of thermal energy storage (TES). The retrieval time and energy storage capacity are substantial for a system combining Sensible Heat Storage (SHS) and Latent Heat Storage (LHS). Therefore, the implementation of a combined SHS and LHS system is advised. Minimal changes are seen between the use of paraffin and stearic acid as phase change materials during charging and discharging procedures. Nevertheless, variations in latent heat and thermal conductivity demonstrate that paraffin's performance is marginally superior (5-7%). Both PCMs are appropriate for thermal energy storage systems.

The notable benefits of Thermal Energy Storage (TES) systems encompass minimal energy loss during storage, elevated energy densities, and the potential for more compact configurations. Further research is essential to augment the understanding of the engineering and scientific attributes of thermochemical TES systems. The efficacy and execution of these systems can only

be assessed and enhanced through the conduction of such research. Thermochemical materials constitute a crucial element of these systems. The selection of thermochemical materials is influenced by their availability, cost, durability, energy density, degradation, and cyclic behaviour. Additional research is necessary for design elements, safety, dimensions, efficiency, maintenance, economics, and installation. A comprehensive analysis of these systems should be conducted, emphasising the energy and exergy requirements. Such evaluations can facilitate the optimisation and enhancement of design. Numerous endeavours are underway in this domain, and it is anticipated that they will provide significant new discoveries and experimental outcomes.

This review will assist in identifying appropriate phase change materials (PCMs) for diverse applications, various methodologies for measuring the thermophysical properties of PCMs, suitable heat exchangers with strategies to enhance heat transfer, and various designs for heat storage utilising PCMs across applications such as heating, cooling, cooking, greenhouse management, water heating, and waste heat recovery systems. The study examines temperature cycles and corrosion of materials for long-term stability. Recent advancements in PCM applications are highlighted to enhance awareness of novel uses. Additional applications remain to be identified.

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### **Conflicts of Interest**

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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