



PHASE CHANGE MATERIALS FOR RENEWABLE ENERGY STORAGE UTILISATION

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Abstract

Solar energy is employed in various thermal storage applications globally. To effectively store renewable energy, the exceptional thermal properties of advanced materials, such as phase change materials, are crucial for optimising solar energy utilisation and enhancing the energy and exergy efficiency of solar absorption systems. This chapter addresses the fundamentals of phase change materials, including selection criteria, operational mechanisms, differentiation of thermal energy storage systems, commercially available PCMs, and the development of PCM thermal properties and durability. This chapter addresses phase change materials (PCM) in solar water heating systems for buildings in India, where 20–30% of electricity is consumed for hot water in urban households, residential, and institutional structures. Examined flat plate collectors (FPC) extensively, which are appropriate for generating warm water at household temperatures of 55 to 70 °C, as they are more cost-effective than evacuated tube collectors (ETC), concentrated collectors (CC), and the integration of various phase change materials (PCM) in solar water heating systems.

1. INTRODUCTION

Renewable energy is an inexhaustible resource that can influence the balance between energy supply and energy demand. Solar energy is a prominent renewable resource alongside wind, hydropower, wave energy, tidal energy, and geothermal energy (Sharma et al, 2007). Most countries receive 5×10^{15} kWh annually, corresponding to an average incident solar energy of between 4 and 7 kWh per m². This can be achieved in various solar energy domains, including solar water heating systems, desalination, solar-thermal collectors, building heating and daylighting, and photovoltaic (PV) cells, among others. Technologists and researchers are

endeavouring to harness greater renewable energy for various devices and systems to mitigate the global energy crisis (Dharma et al, 2016). Thermal energy storage (TES) systems can facilitate the utilisation of renewable energy to mitigate greenhouse gas (GHG) emissions and conserve fossil fuels. It plays a crucial role in the conversion of free energy to mitigate energy consumption (Murray et al, 2014). Thermal energy storage (TES) can be categorised into sensible heat, latent heat, and thermochemical energy (Cot-Gores et al, 2012).

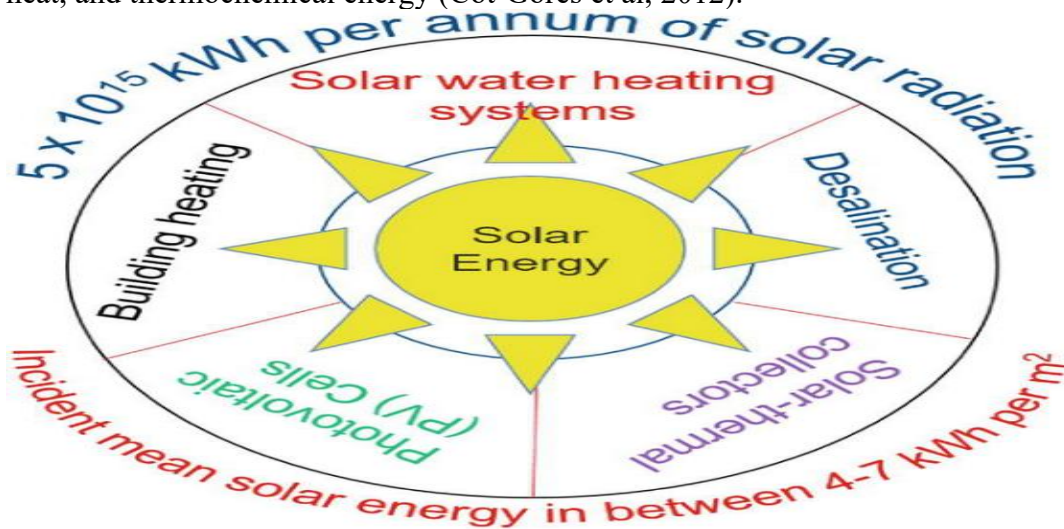


Figure 1. Application of solar energy in different fields.

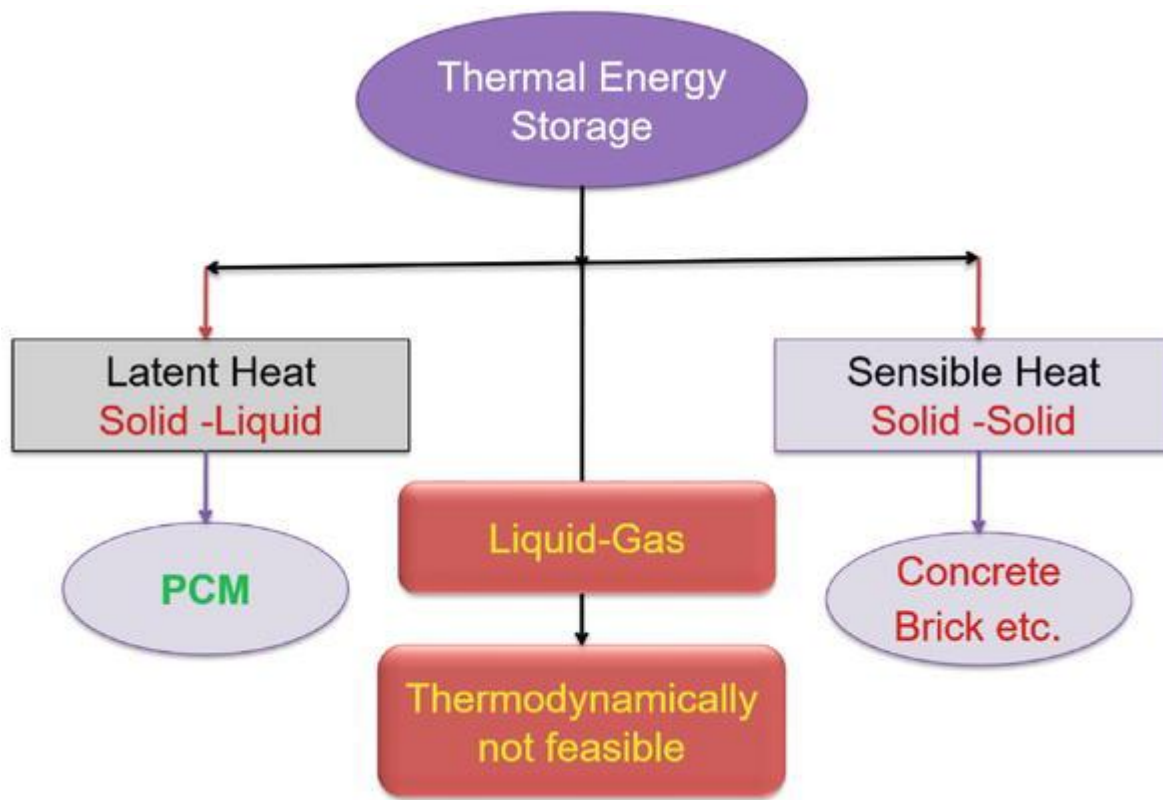


Figure 2. Types of thermal energy storage.

Sensible heat denotes the quantity of energy absorbed without a phase transition, i.e. Solid–solid, liquid–liquid, and gas–gas phase transitions, along with latent heat, denote the quantity of energy absorbed during phase changes, specifically from solid to liquid, liquid to gas, and solid to gas. Thermal chemical energy is the energy stored during a chemical reaction that occurs not only within a specified temperature range but also involves a reversible reaction, with solid to liquid transitions being thermodynamically viable for solar energy applications (Cabeza et al, 2021). Phase change materials (PCMs) are solid to liquid substances that possess the capability to store energy at a constant temperature due to their energy density per unit volume (Figure 2) (Silakhori et al, 2021).

Avargani et al. (2021) implemented two sequential solar collectors containing encapsulated paraffin phase change material. The solitary collector can generate hot water at a temperature of 60°C for 7 hours from dusk until midnight. Fazilati and Alemrajabi (2013) examined the impact of phase change materials in solar water heaters. The energy storage density was enhanced by 39%, and the supply of hot water improved by 25% compared to the absence of PCM. Biwole et al (2013) installed phase change material (PCM) at the rear of the solar collector. The solar collector was modelled using CFD and compared with experimental data. The incorporation of PCM at the rear of the solar collector can sustain the hot water temperature below 40°C for 80 minutes under a continuous solar radiation of 1000 W/m². Hasan et al. (1995, 1994, 2021) have integrated various types of fatty acids into home water heating systems. Fatty acids, including myristic acid, palmitic acid, and stearic acid, exhibiting phase transitions between 50–70°C, are the most promising phase change materials for solar water heating. Manirathnam et al. (2021) synthesised a nanocomposite comprising paraffin wax as a phase change material, incorporating one percent of Sci and CuO. Nano-composite, phase change material (PCM), and non-PCM configurations were examined in an evacuated tube solar water heater for thermal energy storage. The energy efficiencies for the distinct cases were determined to be 33.8%, 38.3%, and 41.7%, respectively, corresponding to the absence of PCM, the presence of PCM, and the use of a nano-composite. Xie et al. (2020) developed a cost-effective and environmentally friendly form-stable stearic acid using coconut shell. The thermal characteristics of the SA/CSC15 composite were 76.69 J g⁻¹ and 52.52°C, respectively. The SA/CSC composite exhibits potential for energy storage in solar water heaters.

This paper addresses the fundamentals of phase change materials and succinctly examines the criteria for their selection. This text discusses the efficacy of phase change materials (PCMs) in domestic solar water heaters and elucidates how the low thermal conductivity of PCMs can be improved through the incorporation of supporting materials to enhance the efficiency of solar thermal energy storage systems.

2. OPERATIONAL MECHANISM OF PHASE CHANGE MATERIALS

When the ambient temperature exceeds the PCM melting point, the PCM undergoes a phase transition from solid to liquid, absorbing heat from the water storage tank during the night. Conversely, when the ambient temperature falls below the PCM melting point, the PCM releases heat to the environment or water storage tank as it transitions from liquid to solid. Phase Change Materials (PCMs) are effectively utilised as energy storage systems in applications such as heat pumps, solar engineering, and spacecraft.

As energy is supplied from the source, the temperature of the PCM increases from the initial temperature (T_1) (K) to the final temperature (T_2) (K), during which energy is absorbed as sensible heat, transitioning from solid to solid (Mehling et al, 2008). The sensible heat can be computed according to the following Equation. (1)

$$Q_{\text{sensible heat}} = m \cdot C_{ps} \cdot (T_2 - T_1) \quad (1)$$

where Q represents the quantity of heat retained in the material (kJ), m denotes the mass of the storage material (kg), and Δh signifies the enthalpy of phase change (kJ/kg). Moreover, heat will continue to be absorbed due to the interaction between liquids. The quantity of phase change materials must be tailored according to the application (Figure 3) (Zalba et al, 2003).

$$Q_{\text{latent heat}} = m \cdot \Delta h \quad (2)$$

where Q is the amount of heat stored in the material (kJ), m is the mas of storage material (kg), and Δh is the phase change enthalpy (kJ/kg). Further, heat continues heat will be absorbed due to liquid to liquid. It means that, the amount of phase change materials need to be designed as per the application (Figure 3) (Zalba et al, 2003).

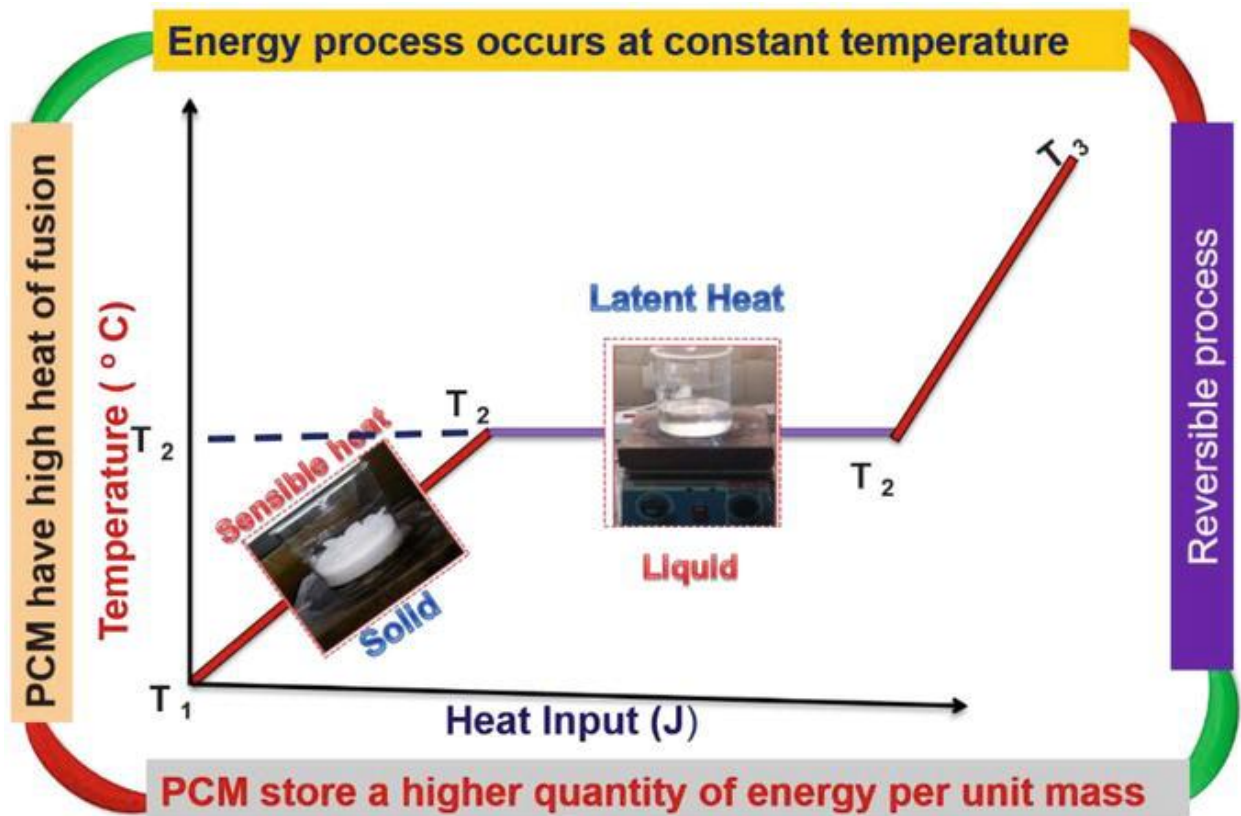


Figure 3. Working of phase change material.

$$\text{Total amount energy stored by PCM (Q)} = Q_{\text{sensible heat}} + Q_{\text{latent heat}} + m C_{pl} (T_1 - T_2)$$

C_{pl} is the specific heat of the storage material of liquid state (J/kg·K).

3. SELECTION OF PHASE CHANGE MATERIALS

The selection of phase change materials for solar energy applications must take into account the following qualities.

3.1 Thermal Perspective

Phase Change Materials (PCMs) must exhibit elevated thermal conductivity during the transitions from solid to liquid and from liquid to solid for effective thermal cycling. Phase Change Materials (PCMs) must possess a high latent heat of fusion to store the appropriate energy while minimising the vessel's volume requirements.

3.2 Physical Perspective

Phase Change Materials (PCMs) must possess a high specific heat capacity to effectively absorb greater amounts of heat during the transition from solid to solid, known as sensible heat. Phase Change Materials (PCMs) must possess elevated energy density per unit volume.

3.3 Kinetic Perspective

Phase change materials must exhibit a high nucleation rate to prevent supercooling during the transition from liquid to solid. Elevated crystal growth rates complicate heat recovery.

3.4 Chemical Perspective

Phase Change Materials (PCMs) must exhibit reversible freeze/melt cycles. PCMs must exhibit chemical stability, meaning the functional groups within the PCMs remain unchanged after multiple temperature cycles. Phase Change Materials (PCMs) must be non-toxic, non-flammable, and non-explosive to ensure safety, as well as non-corrosive to construction materials.

3.5 Economic Perspective

Phase Change Materials (PCMs) should be readily accessible and inexpensive to reduce the overall cost of solar energy systems.

3. CLASSIFICATION OF PHASE CHANGE MATERIALS [24]

Phase transition materials are classified into three categories: (i) Organic, (ii) Inorganic, and (iii) Eutectic combination.

4.1 Organic Phase Change Materials

The organic phase change materials exhibit chemical stability, lack supercooling, are non-corrosive, and are non-toxic. Organic phase change materials (PCMs) are categorised into two groups: (i) paraffins and (ii) non-paraffins. Paraffins exhibit chemical inertness, possess low heat conductivity, and undergo significant volumetric variation. Non-paraffins, such as fatty acids, exhibit a higher heat of fusion than paraffins and demonstrate minimal volume change.

4.2 Inorganic Phase Change Materials

Inorganic phase change materials exhibit a high latent heat of fusion, excellent thermal conductivity, cost-effectiveness, and non-flammability. The majority of them are corrosive to metals. Most inorganic phase change materials are hydrated salts. Hydrated salts possess elevated

energy density and superior thermal conductivity. The disadvantage is that it experiences supercooling.

4.3 Eutectic Mixture

An eutectic mixture comprises multiple phase change materials (PCMs). Eutectic mixes possess a distinct melting point, and their energy density is marginally superior to that of organic phase change materials (PCMs). Eutectics are categorised into three groups: (i) Organic – Organic, (ii) Inorganic – Inorganic, and (iii) Organic – Inorganic (Batens et al, 2010). The optimal temperature range for a eutectic mixture in solar energy applications can be formulated based on Schroder’s Equation. (3) (Shilei et al, 2005).

$$\ln X_A = \frac{\Delta H_A}{R} \left(\frac{1}{T} - \frac{1}{T_f} \right) \quad (4)$$

X_A and ΔH_A represent the molar percentage and latent heat of fusion (kJ/kg) of chemical A, respectively. T and T_f represent the melting temperatures in degrees Celsius of the mixture and compound A, respectively. R is the gas constant, 0.8314 kJ/K. molecular.

4.4 Biological Phase Change Material

Bio-PCM consists of bio-based materials derived from organic sources. It exhibits lower flammability compared to commercially available phase change materials. The bio-PCM can be formulated within a temperature range of -22.7°C to 78.33°C, contingent upon diverse weather circumstances. These materials are encapsulated in sheets resembling bubbles. Bio-PCM exhibits enhanced thermal characteristics, including specific heat and latent heat of fusion (Murnganatham et al, 2010). Classified phase change materials are being utilised in several domains, including passive and active systems (Figure 4).

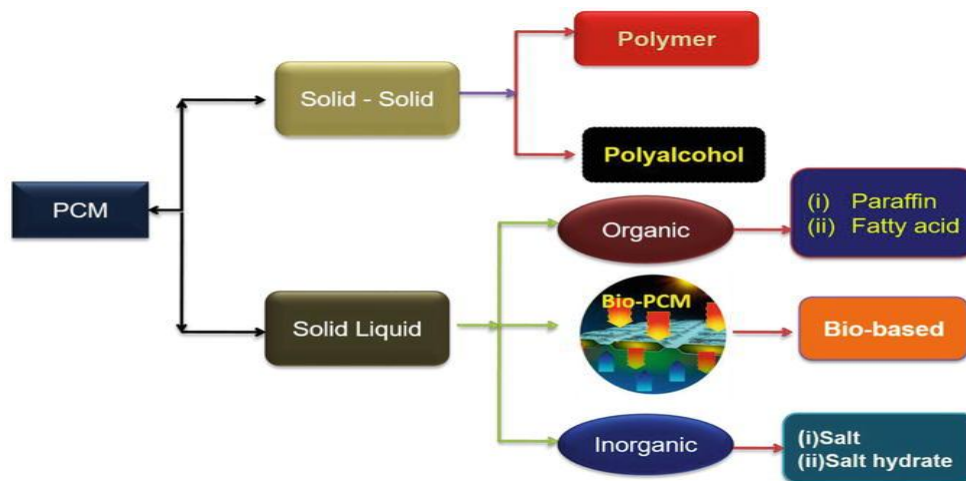


Figure 2. Types of thermal energy storage

Table 1. Differentiate between raw PCMs.

Paraffin	Fatty Acid	Eutectic mixture
<ul style="list-style-type: none"> • Low thermal conductivity • Low latent heat of fusion at desired temperature range. 	<ul style="list-style-type: none"> • High thermal conductivity • High Latent heat of fusion • Small Volume Change 	<ul style="list-style-type: none"> • Eutectics have sharp melting point similar to pure substance • Volumetric storage density is slightly above organic compounds
Disadvantages		
<ul style="list-style-type: none"> • Low thermal Conductivity • Have large volume change 	Lack of materials with phase transition around the thermal comfort	Only limited data is available on thermo-physical properties as the use of these materials.

4. ACCESSIBILITY OF PHASE CHANGE MATERIALS

1. It is available in encapsulated and unencapsulated phase change materials (PCMs) on the market. The unencapsulated PCMs, such as Indiamart and Alibaba, are manufacturing companies. Commercial encapsulated phase change materials (EPCMs) such as Microtek-BASF, Cristopia, Climator, and Rubitherm are marketed under designations such DS5001X, RT 5, and RT 25, operating within a temperature range from below ambient to above 100°C (www.cristopia.com, www.teapcm.com, www.climator.com, www.rubitherm.de, www.basf.com). The enclosed PCM is a minuscule particle including a core of PCMs, while the shells consist of polymers and inorganic substances (Figure 5).



Figure 5. Encapsulated phase change materials are commercially available (Waqas et al, 2013).

5. TECHNIQUES FOR INTEGRATING PHASE CHANGE MATERIALS INTO RENEWABLE ENERGY STORAGE SYSTEMS

Phase Change Materials (PCMs) can be integrated through two methods: macro-encapsulation and microencapsulation for thermal storage units.

5.1 Macro-encapsulation

In macro-encapsulation techniques, PCM is positioned in sizes exceeding 1 mm. This technology allows for a substantial amount of PCM to be contained within a sealed vessel for later utilisation in thermal storage components (Waqas et al, 2013).. To enhance energy efficiency, researchers are experimenting with various arrangements, including raw PCM in metal balls, aluminium panels, polypropylene flat panels, and tube encapsulation. Nevertheless, metal balls and aluminium panels possess greater thermal qualities, specifically thermal conductivity, compared to polypropylene flat panels and tube encapsulation. Exergy and energy efficiency, along with the duration of hot water output, can be enhanced (Schosiq et al, 2005).

5.2 Microencapsulation

Encapsulation refers to a minuscule particle with a size of less than 1 mm, whereby phase change material (PCM) serves as the core, encased by an inorganic shell composed of materials such as titanium or silica. Polymers including Melamine-formaldehyde (MF), Urea-formaldehyde (UF), Polystyrene (PS), Polyurethane (PU), and Methyl methacrylate (MMA), among others. Microencapsulation of phase change materials can be achieved using two methods: the physical approach and the chemical way (Figure 6) (Borreguero et al, 2010).

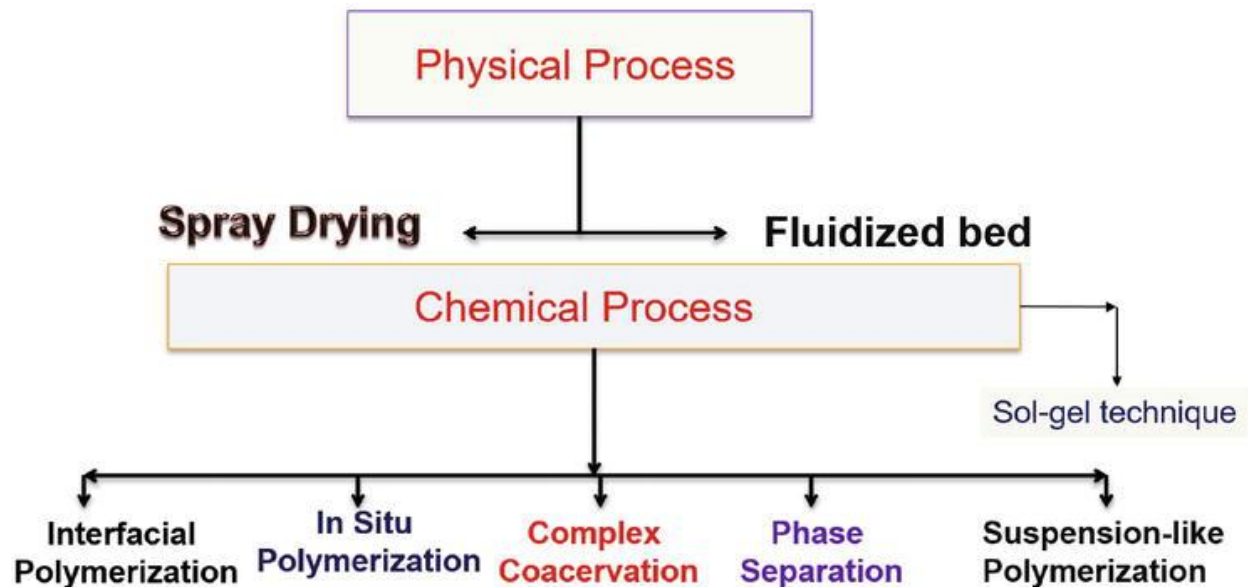


Figure 6. Techniques for the preparation of microencapsulation of phase change materials (PCM).

This approach regulates volume alterations during the solid-to-liquid transition, mitigates environmental interactions, and amplifies the heat transfer surface area (Fang et al, 2008). Inorganic shells can enhance the effective thermal conductivity of organic phase change materials (PCMs). Effective thermal conductivity plays a crucial role in energy storage units (Srinivasaraonaik et al, 2020).

The use of 2–4% high thermal conductivity material into the PCM can enhance its thermal characteristics, as illustrated in Figure 7 (Tangsiriratana et al, 2019). It will enhance the performance of the energy storage unit.

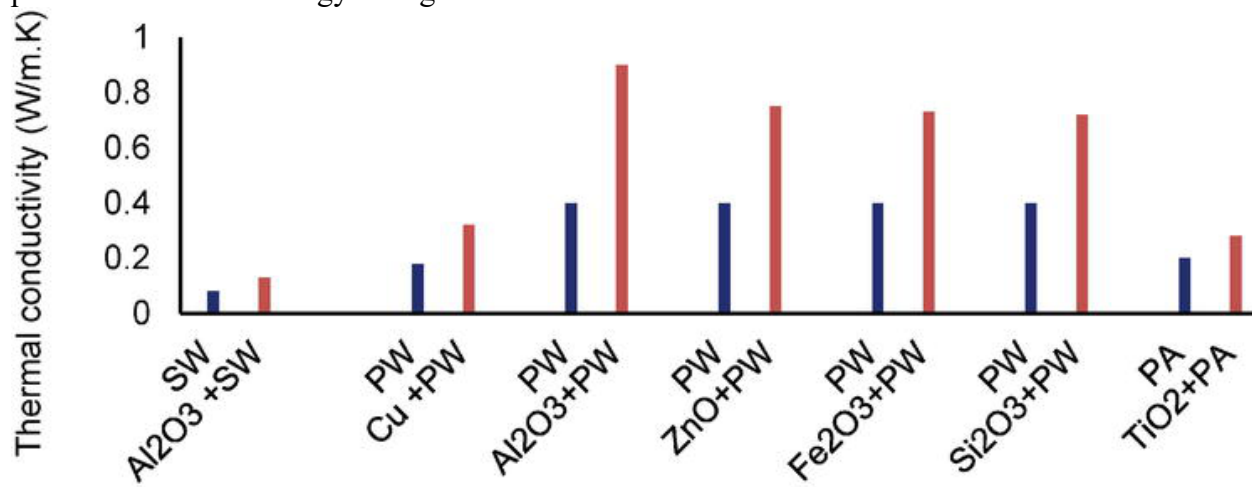


Figure 7. Enhancement of effective thermal conductivity of phase change materials for energy storage. *SW: Sugar Wax, PW: Paraffin Wax, PA: Palmitic Acid.

6. DURABILITY OF PHASE CHANGE SUBSTANCES

An accelerated thermal cycle test is important prior to application in solar water heaters and solar air conditioners. The thermal cycle test involves heating from ambient temperature to the melting point of a phase transition until the substance is fully liquefied, followed by cooling below the melting point until it solidifies. The combined duration of the heating and cooling periods is referred to as an accelerated test. It operates once daily and illustrates the characteristics of phase change materials (Figure 8). Silakhori et al. (2013) performed accelerated testing on paraffin wax, determining its melting point and latent heat of fusion after 1000 cycles. 1.6–7% of the melting point of paraffin wax was recorded. Alkan et al. (2009) performed a thermal cycle test on microencapsulated docosane to assess its thermal stability in conjunction with polymethyl methacrylate (PMMA). No major changes occurred in crucial parameters during 5000 cycles. Ahmet Sari et al. (2009) conducted an accelerated heat cycling test on microencapsulated n-octacosane for 5000 cycles. No alterations were identified in the chemical structures of the microcapsules. Sude Ma et al. (2011) conducted thermal cycling tests of paraffin wax with PMMA for up to 1000 cycles. No alteration was detected in the thermal stability of the microcapsules.

Currently, the use of fossil fuels significantly affects the environment, prompting research in commercial refrigeration, heating and cooling systems in buildings, solar heating, electronics, textiles, and energy conservation in buildings. Phase Change Materials (PCMs) with an operating temperature range of +40°C to +80°C are utilised for solar heating, hot water generation, and electronic applications, while the range of +80°C to +1200°C is employed for absorption cooling, waste heat recovery, and concentrated solar applications.

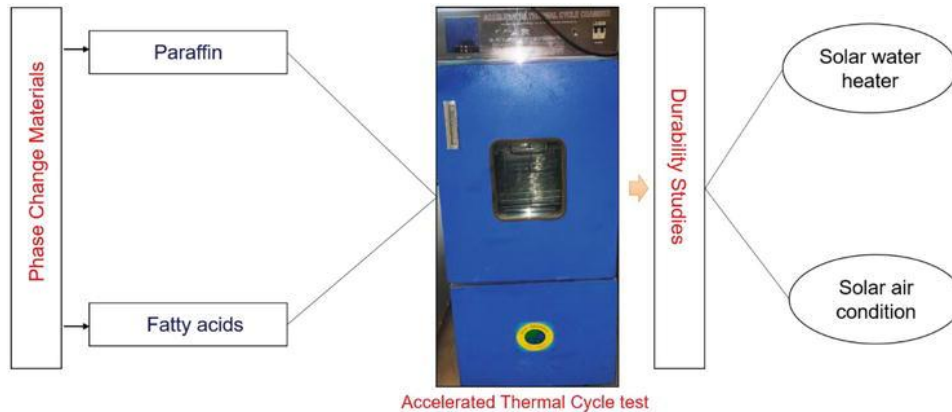


Figure 8. Execution of accelerated thermal cycling test.

Yang et al. (2019) conducted an accelerated test on various fatty acids, including lauric acid, myristic acid, palmitic acid, and stearic acid, across 10,000 heat cycles. The thermal characteristics of fatty acids have remained mostly unchanged over multiple cycles. Sheili et al. (2005) conducted thermal cycle tests on a eutectic mixture of capric and lauric acid. No significant alterations in the eutectic mixture following 360 cycles. Chinnasamy V and Appukuttan S (2019) assessed the thermal characteristics of a eutectic mixture of lauric acid and myristyl alcohol over 1000 cycles. It was concluded that no alterations were seen in the thermal characteristics. Zuo et al. (2011) discovered that the eutectic mixture of lauric acid and 1-tetradecanal exhibited stable thermal characteristics up to 90 thermal cycle tests. Zhang et al. (2013) formulated a ternary fatty acid mixture of phase change materials comprising lauric acid, myristic acid, and palmitic acid. The melting point and heat of fusion remained consistent for up to 50 cycles.

7. PHASE CHANGE MATERIAL FOR VARIOUS APPLICATIONS IN ENERGY STORAGE UNITS

Based on the identified phase transition temperature range, they are utilised in many applications such as solar energy, buildings, and cars to reduce greenhouse gas emissions and regulate thermal conditions (Figure 9). The temperature varies from -20°C to $+5^{\circ}\text{C}$ for household or commercial refrigeration. The temperature range for the second phase transition, from $+5^{\circ}\text{C}$ to $+40^{\circ}\text{C}$, is utilised for heating and cooling applications in buildings.

8. INCORPORATION OF PHASE CHANGE MATERIALS INTO SOLAR WATER HEATING SYSTEMS

Solar radiation originates from sunlight and can be captured using solar collectors. These collectors are utilised for multiple applications; one of the purposes is the generation of output hot water. The exit temperature of the hot water is contingent upon various types of collectors (Figure 10).

Typically, these sun collectors are affixed to walls for thermal regulation within structures. The thermal power output of different solar collectors can be calculated by multiplying the conversion efficiency by the intensity of solar irradiation (Douvi et al, 2021). The output of a thermal power collector can be determined using the following Equation (4).

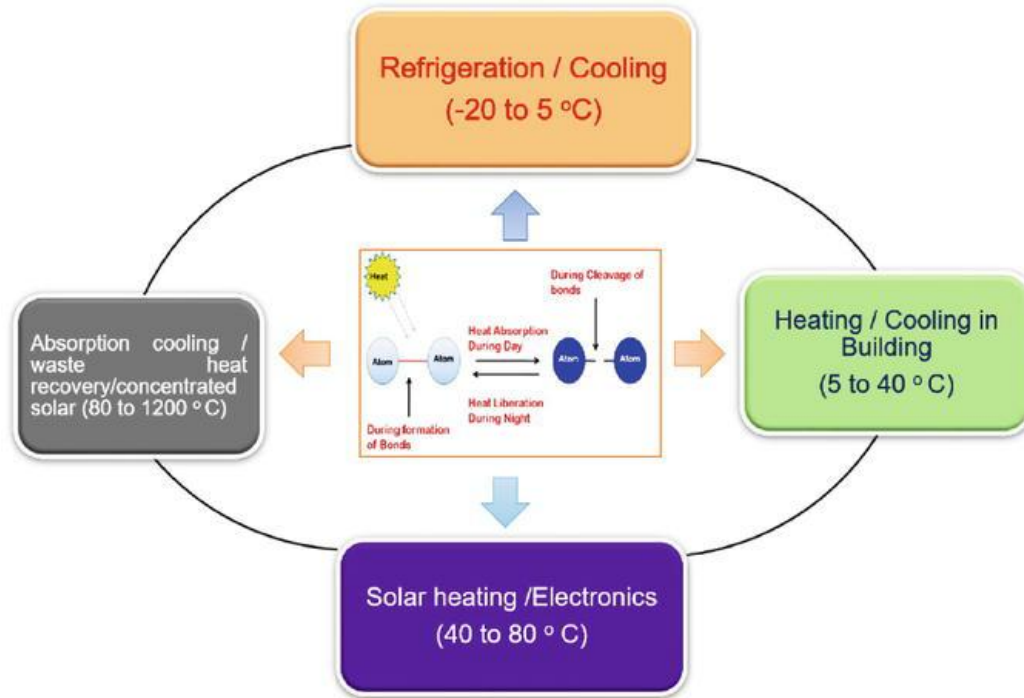


Figure 9. Phase Change Materials (PCMs) are utilised in various applications.

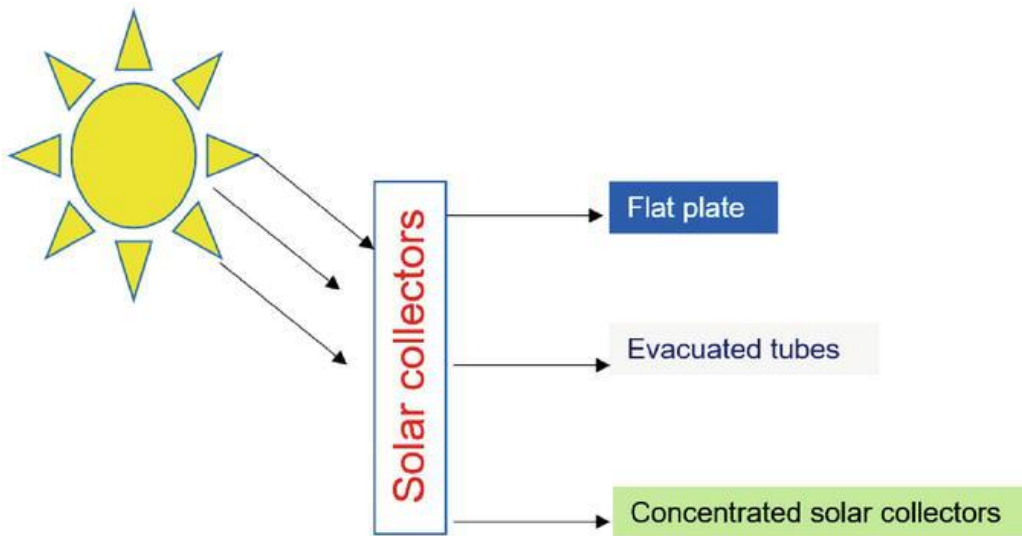


Figure 10. Diverse varieties of solar collectors.

$$Q_{KN} = \left(\eta_0 - \frac{\alpha_1(\theta_K - \theta_u) + (\theta_K - \theta_u)^2}{E} \right) \cdot E \cdot A_K = m \cdot C_p \cdot (\theta_{KO} - \theta_{KI}) \quad (5)$$

Q_{KN} denotes the thermal power output of the collector (W), E represents solar irradiance intensity (W/m^2), and A_K signifies the collector area (m^2). Where: η_0 : Zero-loss collector efficiency; α_1 :

Basic heat loss coefficient ($\text{W/m}^2 \text{ K}$); θ_K : Mean collector temperature (K); θ_u : Ambient air temperature (K).

K_O : Collector outlet temperature (K), θ_{KI} : Collector intake temperature (K), m : Heat transfer fluid mass flow rate (kg/s), C_p : Heat capacity of heat transfer fluid (J/kg K).

The flat plate solar collector is examined in detail due to its straightforward manufacturing process, cost-effectiveness, low maintenance requirements, and ease of installation. This variant of flat plate solar water heater is appropriate for urban residences (Table 2).

8.1 Flat Plate

A flat plate is a form of heat exchanger utilised in solar collectors to transfer radiative energy from sunlight into thermal energy. This plate is typically utilised for applications involving low to moderate temperatures, specifically below 80°C . This form of collector comprises a casing, absorbers such as copper or aluminium situated within the heat exchanger due to their excellent thermal conductivity, the heat transfer fluid, and insulation materials. To enhance thermal efficiency, it is essential to minimise thermal losses and include the better thermal capabilities of phase change materials (PCM). Thermal storage materials can be incorporated within the collector or in a separate thermal storage tank. Flat plate collectors are utilised for hot water generation, space heating, and air conditioning systems [www.alternative-energy-tutorials.com, (Badiei et al, 2020)]. For solar water heating, flat-plate collectors are mounted at the optimal angle of Latitude $+10^\circ$. Water serves as the transport fluid in solar water heating due to its favourable thermodynamic features, including high heat capacity, high energy density, and incompressibility.

The disadvantage of using water as a transport fluid is the potential harm to the collection when it freezes in winter. The damage can be mitigated by placing the collector in areas with limited solar exposure and including antifreeze solutions to address the aforementioned issues. The common antifreeze agents are ethylene glycol or propylene glycol. These compounds are diluted with water and disposed of appropriately due to their toxicity. The longevity of antifreeze compounds is around 5 years (kalogirou et al, 2009).

In flat plate solar water heaters, phase change materials (PCM) can be incorporated in two configurations: (i) flat plate integrated solar collectors and (ii) flat plate non-integrated solar collectors.

8.1.1 Integrated Solar Collector with Flat Plate Design

In a flat plate integrated solar collector, phase change material (PCM) can be arranged in an aluminium honeycomb configuration and PCM modules can be utilised for frost protection beneath the absorber plate (Figure 11). PCM-integrated solar collectors enhance thermal stability and prolong the availability of hot water output. Advanced insulating materials must be affixed to minimise heat loss, as failure to do so may diminish system efficiency (Abuska et al, 2019).

8.1.2 Non-integrated flat plate solar collector

Flat plate non-integrated solar collectors linked to a phase change material storage unit. The PCM storage unit is positioned above an inclined collector, adjacent to or beneath the solar collector. To prevent leakage, the phase change materials (PCMs) are enclosed in rectangular, cylindrical, and spherical containers (Figure 12; Table 3).

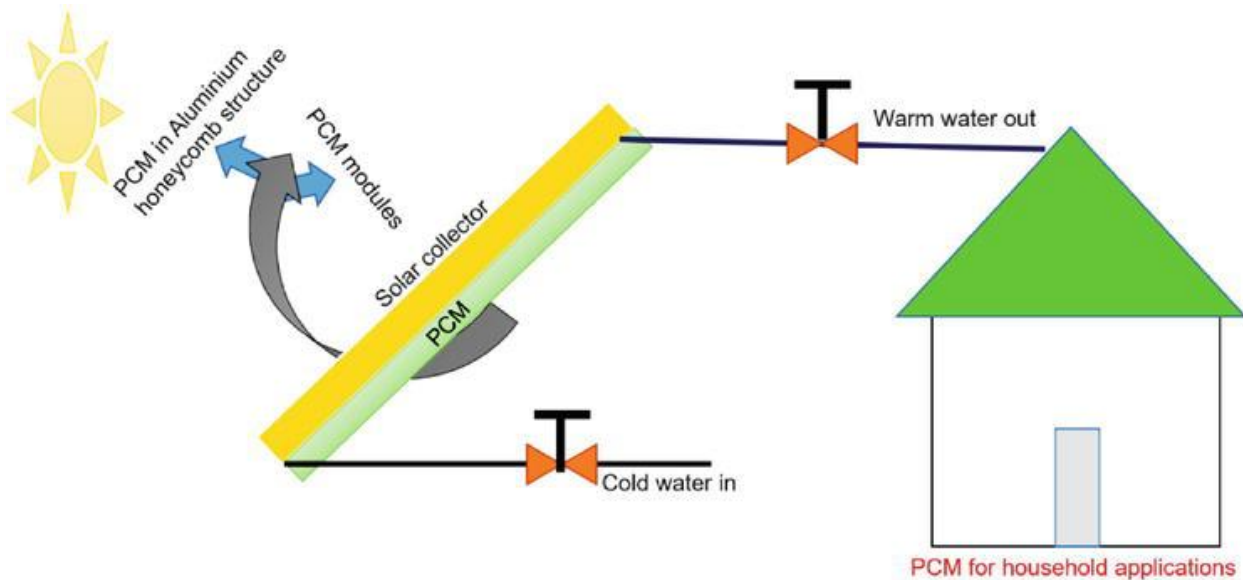


Figure 11. Phase Change Material in flat integrated solar collector.

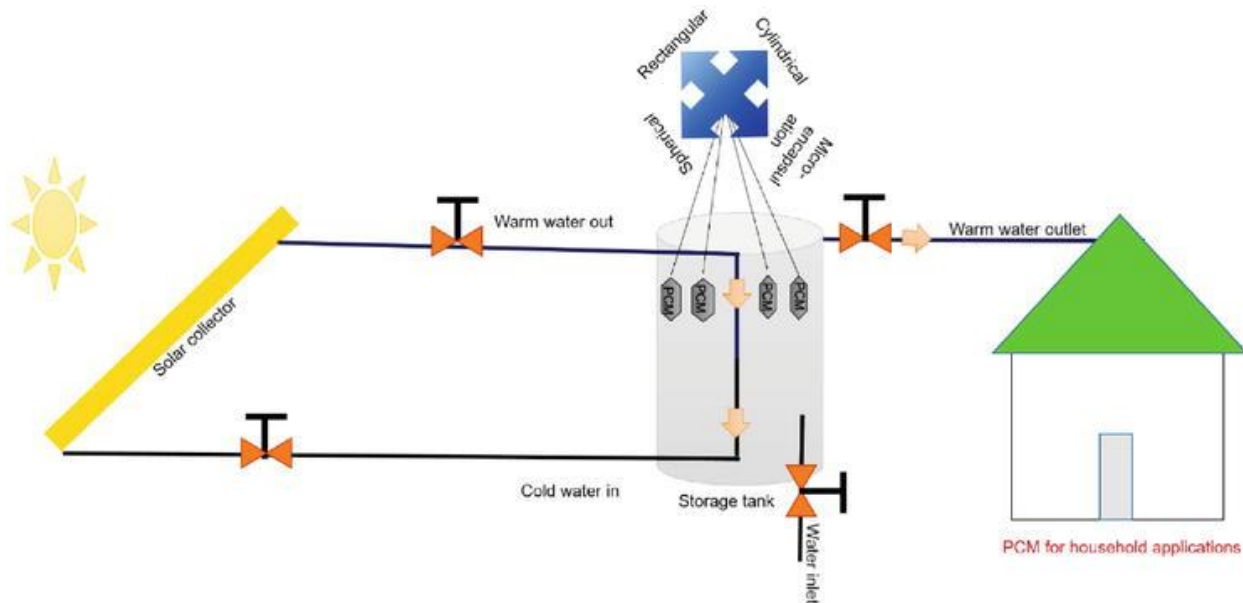


Figure 12. PCM in a flat non-integrated solar collector.

Integrating a solar energy storage system into a structure may reduce the costs associated with renewable energy storage and enhance the efficiency of energy gathering. In the solar water heating method, the storage unit is filled with phase change material (PCM) to capture heat from hot water during the day. During the night, the stored energy is transferred to the warm water tank, allowing for prolonged collection of hot water Jouhara et al (2018), Taylor et al, (2017). Kulakarni and Deshmukh (2014) investigated the efficiency of a water heating system utilising paraffin with a melting point of 62°C. The efficiency of the solar water heater improved from 31.25% to 44.63%.

The storage capacity increased from 3260.4 kJ to 4656.5 kJ. Bhargava (1983) employed three distinct thermal properties of phase change materials, specifically Na₂SO₄·10H₂O (32 °C and 251 kJ/kg), Na₂HPO₄·12H₂O (36.1 °C and 279 kJ/kg), and P116 Wax (46.7 °C and 209 kJ/kg) were integrated into the storage unit. Assessed the system's efficiency and the duration of the outlet water temperature. As the thermal conductivity of the materials increases, the duration of elevated outlet hot water temperature during the evening hours also increases.

Table 3. Advantages and disadvantages of standard PCM containers for various mediums (Ling X et al, 2019).

Types	Advantages	Disadvantages
Rectangular	<ul style="list-style-type: none"> • Manufacturing process is easy • Small occupied space 	<ul style="list-style-type: none"> • Heat loss rate is high • Thermal stress concentration • Leakage phenomenon may exist
Cylindrical	<ul style="list-style-type: none"> • Fluid flow can improved • Rate of the PCM is high 	<ul style="list-style-type: none"> • Manufacturing process is not easy
Spherical	<ul style="list-style-type: none"> • High heat transfer efficiency • Low heat loss rate 	<ul style="list-style-type: none"> • Positioned in storage is complex • Complicated filling process of the PCM is difficult
Micro-encapsulation	<ul style="list-style-type: none"> • Encapsulation efficiency is high • Particle size is low • High heat transfer area is high 	<ul style="list-style-type: none"> • Manufacturing process is tough • Manufacturing costs is easy

M.P: melting point, H.F.: Heat of fusion, SA: Stearic acid, MA: Myristic acid.

Fazilati and Alemrajabi (2013) utilised paraffin as a storage medium. The melting point and latent heat of fusion were 55°C and 187 kJ/kg, respectively. Energy and exergy efficiency improved by 39%, 16%, and 25%, respectively, along with an enhancement in the duration of warm water. Prakash et al. (1985) incorporated a phase change material layer (46.7°C and 209 kJ/kg) at the base of the water tank. They determined that it was ineffective during the phase transition from liquid to solid due to a limited heat transmission area. Kaygusuz (1995) investigated the performance of solar water utilising CaCl₂·6H₂O (28°C and 45 kcal/kg) as a phase change material through both experimental and theoretical methods. Hasan et al. (1995, 1994, 1994] utilised various fatty acids as phase change materials (PCMs) for domestic water heating, including myristic acid (MA), palmitic acid (PA), and stearic acid (SA). It was suggested that fatty acids with melting temperatures ranging from 50 to 70°C are the most favourable phase change materials for water heating. Most researchers examined various phase transition temperatures in solar water heater systems. According to the Cabinet of Ministers of Latvia, the permissible range for domestic hot water (DHW) is between 55 and 70°C Dzikevics M et al, (2020). The literature review presented in Table 4 indicates a phase transition temperature range of 55 to 70 °C for DHW.

Table 4. Literature review on phase change material flat plate solar collectors for water heating applications.

PCM	M.P (°C)	H.F (kJ/kg)	Reference
Two kinds of PCM	70	210	Zhou F et al, (2019)
Paraffin	60	213	Nallusamy et al, (2007)
Paraffin and SA	61 & 57	213 & 198	Reddy et al, (2012)
Salt hydrate	60		Dzikevics et al, (2020)
RT 60	60	144	Elbahjaoui et al, (2019)
Nano Cu-PCM (0.5 to 2%)	57.81–59.57	157.3 to 172.2	Saw C et al, (2016)
RT 65, SA, Pent glycerin	55,66,80	159,207,152	Hailot et al, (2011)
RT 65 graphite composite	65	—	Hailot et al, (2012)
Paraffin	70–80	224	Chen Z et al, (2010)
PCM1	60–62	209	Yang L et al, (2014)
Paraffin	60–70	224	Chen Z et al, (2010)
—	57.34	178.76	Shirinbakhsh et al, (2018)
MA, Paraffin, Tristearin	58, 59,56	199,189,191	Shirinbakhsh et al, (2018)
Sodium acetate tri-hydrate with graphite	60	180–200	Cabeza et al, (2006)
SA–MA (80–20%)	61–65	190.87	Mazman M et al, (2006)

In addition to the aforementioned phase change materials, several commercially available thermal storage materials within the temperature range of 55–70°C are enumerated in Zalba et al. (2003). These materials may be utilised in flat plate solar water heaters to enhance thermal efficiency, optimise thermal management, and prolong the duration of warm water availability.

9. CONCLUSION

Phase change materials possess high energy density and prospective use in flat plate solar collectors for the generation of hot water in urban residences. In addition to the researchers' efforts, numerous commercially available phase change materials (PCMs) exist to enhance the efficiency of solar water systems. The thermal cycle test is crucial for assessing the durability of paraffin and fatty acids prior to their application in a system. Paraffin exhibits durability for 14 years, while fatty acid endures for 27 years. The elevated thermal conductivity of phase change materials (PCMs) prolongs the duration of hot water, whereas materials with low thermal conductivity but high latent heat of fusion can be improved by using high thermal conductivity fillers. Encapsulated phase change materials are small particles that can be readily utilised in storage tanks. Phase Change Materials (PCMs) are effectively integrated into both integrated and non-integrated flat plate solar collectors. Nonetheless, the non-integrated flat plate solar collector exhibits superior thermal efficiency compared to the integrated solar collector due to variations in heat transfer area. A variety of phase change materials, commercial methods, and designs are accessible both nationally and internationally. Cost-effective settings are selected for an efficient PCM solar water heating system.

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