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Chapter

Phase Change Materials for Renewable Energy Storage Applications

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Abstract

Solar energy is utilizing in diverse thermal storage applications around the world. To store renewable energy, superior thermal properties of advanced materials such as phase change materials are essentially required to enhance maximum utilization of solar energy and for improvement of energy and exergy efficiency of the solar absorbing system. This chapter deals with basics of phase change material which reflects, selection criteria, PCM works, distinguish thermal energy storage system, commercially available PCM, development of PCM thermal properties and durability of PCM. In addition to this chapter focused on PCM in solar water heating system for buildings particularly in India because 20–30% of electricity is used for hot water in urban households, residential and institutional buildings. Discussed Flat plate collectors (FTC) in detail which is suitable for warm water production in household temperature 55 to 70 °C owing to cost effective than the Evacuated Tube collectors (ETC), Concentrated collector (CC) and integration of different methods PCM in solar water heating system.

Keywords: Phase change materials, Advanced materials, Solar energy, Renewable energy

1. Introduction

Renewable energy is a free energy that can impact between energy supply and energy demand. One of the prominent renewable source is solar energy among the wind, rain, waves, tides and geothermal energy [1]. Most of countries receives 5 x 10^{15} kWh per annum i.e. incident mean solar energy in between 4 and 7 kWh per m^2 [2]. This can be accomplished in different solar energy fields such as solar water heating systems, desalination, solar-thermal collectors, building heating and day-lighting and Photovoltaic (PV) Cells etc. (**Figure 1**) [3]. Technologists and researchers are trying to utilize more renewable energy for distinguish devices/systems to decrease global energy crisis [4]. Thermal energy storage (TES) systems may assist the renewable energy exploitation for reduction of Green House gases (GHGs) and depletion of fossil fuels [5]. It plays vital role into energy conversation of free energy to reduce energy consumption [6]. TES can be stored in form of sensible heat, latent heat and thermochemical energy [7].

Sensible heat refers to the amount of energy is absorbed without phase change i.e. Solid–solid, liquid –liquid and gas to gas and latent heat refer to the amount of

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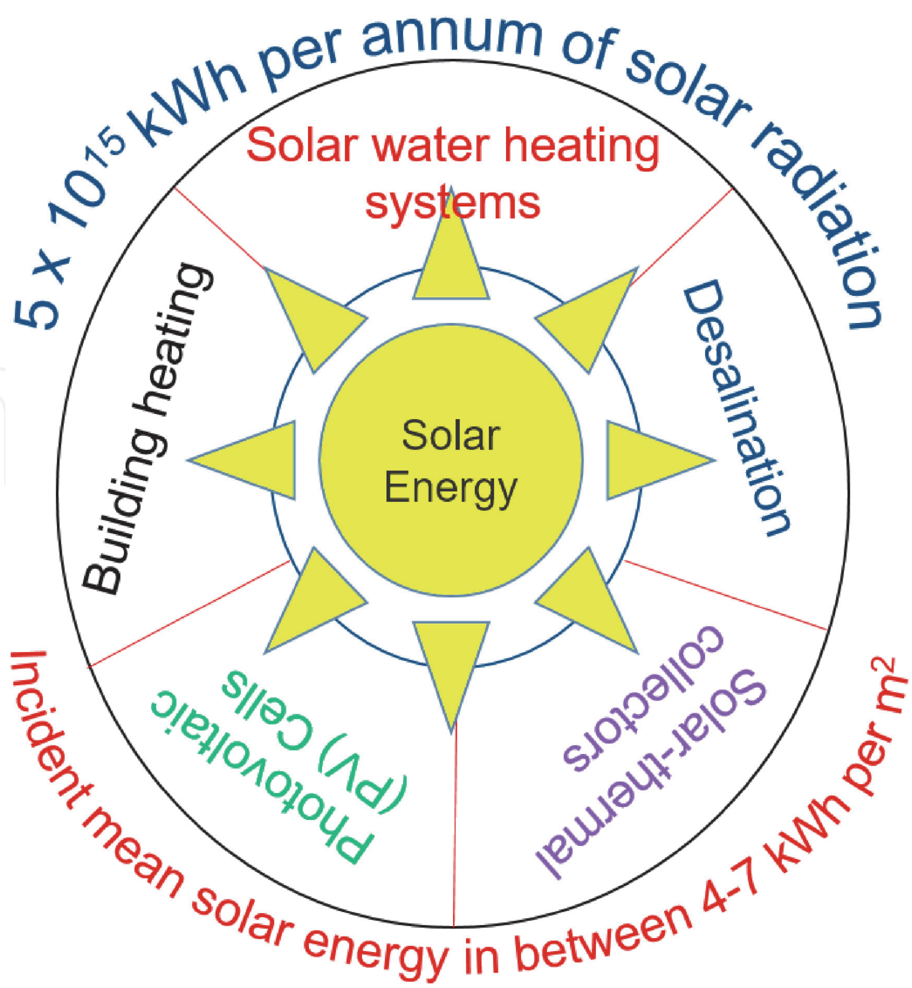

Figure 1.
Application of solar energy in different fields.

energy is absorbed with phase change i.e. solid to liquid, liquid to gas and solid to gas. Thermal chemical energy is energy stored during chemical reaction occurred not only at desired temperature range but also should be reversible reaction and Solid to liquid thermodynamically feasible to solar energy applications [8]. Solid to liquid materials are phase change materials (PCMs) and has the potential to store the energy at constant temperature owing to energy density per unit volume (**Figure 2**) [9].

Avargani et al. [10] installed two consecutive solar collectors with encapsulated paraffin phase change material. The single collector can produce hot water at the temperature of 60°C for 7 hour from midway to midnight. Fazilati and Alemrajabi [11] investigated the effect of PCM in solar water heater. The energy storage density was increased up to 39% and supply of hot water increased 25% as compared to the without PCM. Biwole et al. [12] PCM installed at the back of the solar collector. The solar collector was simulated using CFD model and compared with testing results. Added PCM to the back of solar collector can maintain the hot water temperature under 40°C for 80 min with the constant solar radiation of 1000 W/m^2. Hasan et al. [13–15] have incorporated different types fatty acids in domestic water heating system. The fatty acids such as myristic acid, palmitic acid and stearic acid, with phase transition between 50–70°C are the most promising PCMs for solar water heating. Manirathnam et al. [16] prepared nano-composite such paraffin wax as PCM with one per cent of Sci and CuO. Nano-composite, PCM and without PCM were studied in evacuated tube solar water heater for thermal energy storage. The energy efficiencies for distinguish cases were found to be 33.8%, 38.3%, and 41.7%, respectively corresponding to without PCM, PCM and nano-composite

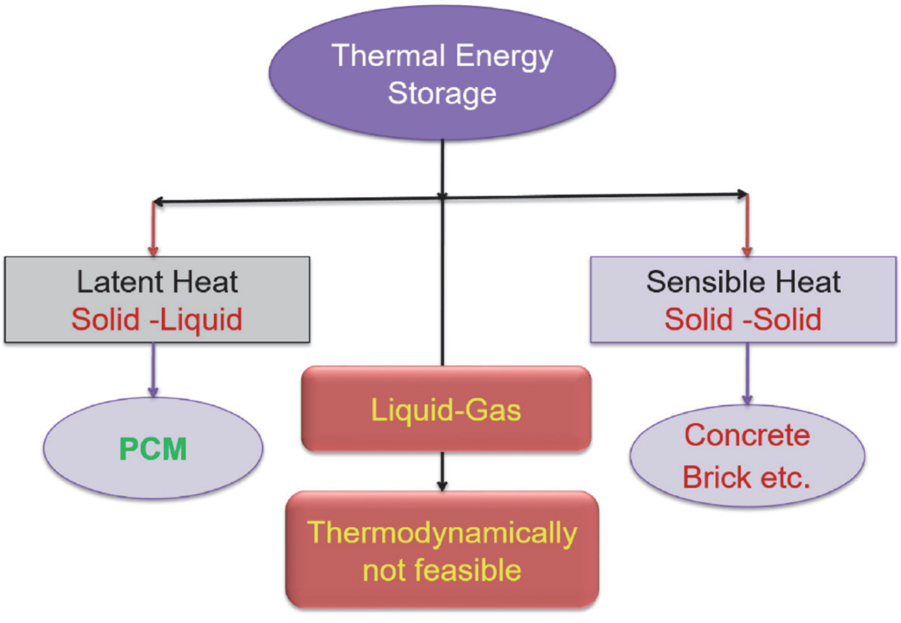

Figure 2.
Types of thermal energy storage.

respectively. Xie et al. [17] prepared cost effective and eco-friendly form shape stabilized stearic acid with coconut shell. The thermal properties of SA/CSC$_{15}$ composite were 76.69 J g^{-1} and 52.52°C, respectively. The SA/CSC composite has potential for solar water heater energy storage.

This book chapter deals with basics of phase change materials and briefly discussed about selection criteria of PCMs. How these phase change materials are effective for solar water heater domestic uses as well as explained how low thermal conductivity of PCMs can be enhanced using supporting materials to increase efficiency of solar systems for thermal energy storage.

1.1 Working principle of phase change materials

When surroundings temperature above the PCM melting point, the PCM becomes phase change from solid to liquid and absorbs the heat from water storage tank during night, when surroundings temperature below the PCM melting point, the PCM desorbs heat to ambient/water storage tank, during the material changes phase from liquid to solid. The PCMs are being successfully used as energy storage devices such as heat pumps, solar engineering, space craft etc. [18].

When energy continues from the source, then PCM temperature rises from initial temperature (T_1) (K) to final temperature (T_2) (K) and during this period energy is riveted due to the sensible heat i.e. solid to solid [19]. The sensible heat can be calculated as per following Eq. (1)

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

where Q is the amount of energy stored in the material (J), m is the mas of storage material (kg), C_{ps} is the specific heat of the storage material of solid state (J/kg·K). From temperature (T_2) (K), the heat is continuously absorbed until the solid turns into the liquid due to the latent heat. The latent heat of system can be determined as per the following Eq. (2)

$$Q_{\text{latent heat}} = m.\Delta h \tag{2}$$

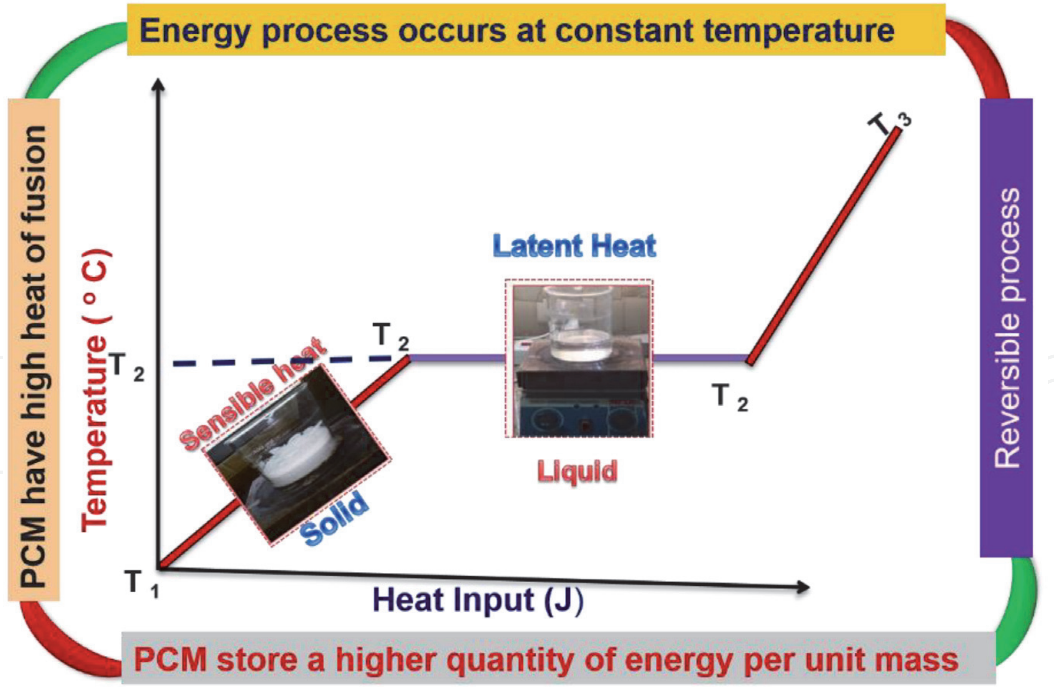

Figure 3.
Working of phase change material.

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**) [20].

$$\text{Total amount energy stored by PCM (Q)} = Q_{\text{sensible heat}} + Q_{\text{latent heat}} + m\ C_{pl}\ (T_1\text{–}T_2) \tag{3}$$

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

2. Selection of phase change materials

Selection of PCMs for solar energy applications need to be considered the following properties.

2.1 Thermal point of view

PCMs should have high thermal conductivity during solid to liquid and liquid to solid for thermal cycling. PCMs should have high latent heat of fusion to store amount of energy required volume of the vessel prerequisite is less.

2.2 Physical point of view

PCMs should have high specific heat to absorb more heat during solid to solid i.e. sensible heat. PCMs should have high energy density per unit volume.

2.3 Kinetic point of view

PCMs should have high nucleation rate to avoid super cooling during liquid to solid. High crystal growth rate hassles for heat recovery.

2.4 Chemical point of view

PCMs should be reversible freeze/melt cycle. PCMs should be chemical stability i.e. functional groups contained in PCMs does not change after repeated thermal cycle. PCMs should be non-toxic, non-flammable and non-explosive materials for safety and Non-corrosiveness to the construction materials.

2.5 Economic point of view

PCMs should be easily available and low cost owing to minimize total cost of solar energy system.

3. Classification of phase change materials

Phase change materials are divided into three categories (i) Organic (ii) Inorganic (iii) Eutectic mixture.

3.1 Organic PCMs

The organic phase change compounds are chemically stable, no super cooling, non-corrosive and nontoxic. Organic PCMs are subdivided in two groups (i) Paraffins (ii) Non paraffins. Paraffins are chemically inert, have low thermal conductivity and large volume change. The non paraffin's such as fatty acids have high heat of fusion than paraffin and small volume change.

3.2 Inorganic PCMs

Inorganic PCMs have high heat of fusion, good thermal conductivity, are cheap and non-flammable. Most of them are corrosive to metals. Most inorganic PCMs are hydrated salt. Hydrated salts have a high energy density and high thermal conductivity. Disadvantage is that undergoes super cooling.

3.3 Eutectic mixture

Eutectic mixture is a mixing of more than one PCM material. Eutectic mixtures have sharp melting point and energy density is slightly higher than that of organic PCMs. Eutectics are divided in three groups (i) Organic – Organic (ii) Inorganic – Inorganic (iii) Organic – Inorganic [21]. The desired temperature range of eutectic mixture for solar energy applications can be designed according to Schroder's Eq. (3) [22].

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

Where X_A and ΔH_A are the molar fraction and latent heat of fusion kJ/kg of compound A, respectively. T and T_f are the melting temperature °C of the mixture and compound A. R is gas factor 0.8314 kJ/K. mol.

3.4 Bio-PCM

Bio-PCM is bio based materials which are derived from organic - based materials. It is less flammable than the commercial available PCMs. According to various

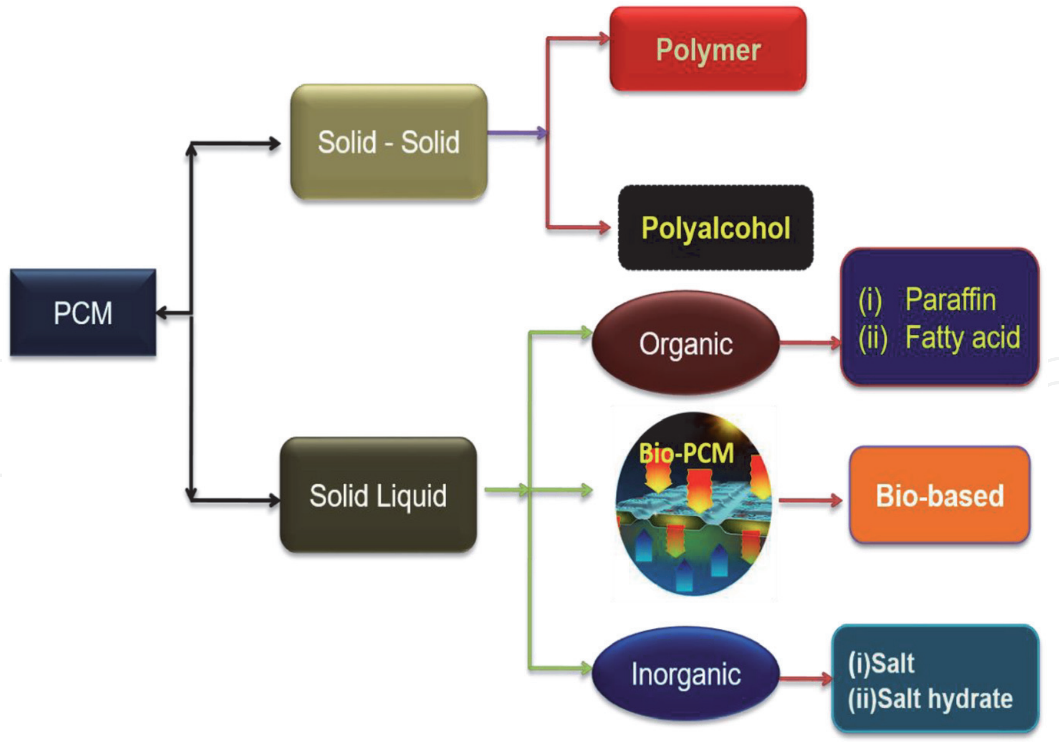

Figure 4.
Classifications of PCMs [24].

Paraffin	Fatty Acid	Eutectic mixture
• Low thermal conductivity • Low latent heat of fusion at desired temperature range.	• High thermal conductivity • High Latent heat of fusion • Small Volume Change	• Eutectics have sharp melting point similar to pure substance • Volumetric storage density is slightly above organic compounds
Disadvantages		
• 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.

Table 1.
Differentiate between raw PCMs.

weather conditions, the bio-PCM can be prepared from - 22.7°C to 78.33°C. These materials are wraps in sheets as bubble. Bio-PCM has superior thermal properties such as specific heat and latent heat of fusion [23]. Classified PCMs are applying into different fields such as passive systems and active systems (**Figure 4**).

The active systems are waste heat recovery, solar water heater, desalination etc. The passive systems are directly added into the building components such as gypsum, mortar, concrete and brick. These two systems are employing in buildings to reduce energy burden in the buildings. Buildings are more responsible 40% of total energy consumption.

Comparison of different PCMS for renewable storage applications have provided in **Table 1** which helps for selection PCMs for thermal energy storage.

4. Availability of PCMs

In the market, it is available in encapsulated and un-encapsulated PCMs. The un-encapsulated PCMs such as Indiamart, Alibaba etc. are the manufacturing

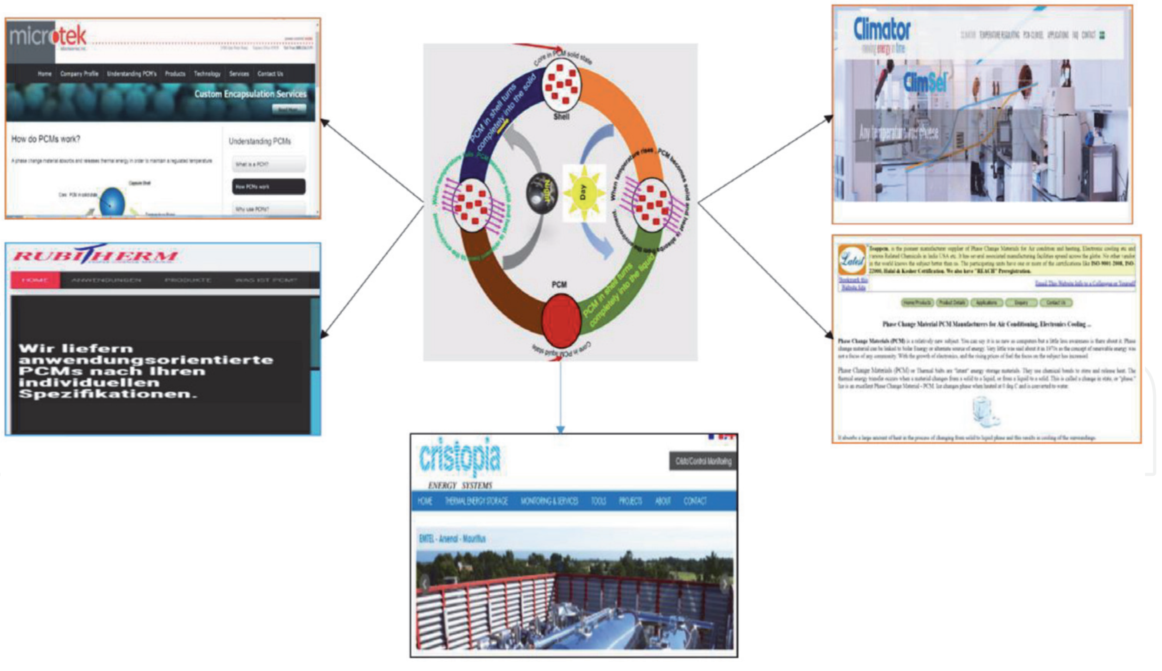

Figure 5.
Commercially available of encapsulated PCMs [30].

companies. The encapsulated PCMs such as Microtek-BASF, Cristopia, Climator and Rubitherm are commercializing encapsulated PCMs (EPCMs) with the name of DS5001X, RT 5, and RT 25 etc. within temperature range of below ambient to above 100°C [25–29]. The encapsulated PCM is a tiny particle which contains core as PCMs and Shells are the polymers and inorganic substances (**Figure 5**).

5. Methods of incorporation of PCMs into renewable storage systems

PCMs can be incorporated into two ways one is macro-encapsulation and microencapsulation for thermal storage unit.

5.1 Macro-encapsulation

In macro-encapsulation methods, PCM has placed in size >1 mm. In this technique, a significant quantity of PCM can be packed in a closed container for subsequent used in thermal storage elements [30]. For better improvement of energy efficient, researchers are being positioned in various configurations such as Raw PCM in Metal ball, aluminum panels, Polypropylene flat panel, tube encapsulation. However, Metal ball and Aluminum panels have the superior thermal properties i.e. thermal conductivity than Polypropylene flat panel, tube encapsulation. It can be improved exergy and energy efficiency as well as duration of hot water outlet [31].

5.2 Microencapsulation

Encapsulation is a tiny particle has the particle size <1 mm where in PCM as a core material which is surrounded by inorganic shell such as Titanium, Silica etc. Polymers such as a Melamine – formaldehyde (MF), Urea Formaldehyde (UF), Poly-styrene (PS), Polyurethane (PU), Methyl methacrylate (MMA) etc. Microencapsulation of phase change materials can be prepared in two methods one is physical method and chemical method (**Figure 6**) [32].

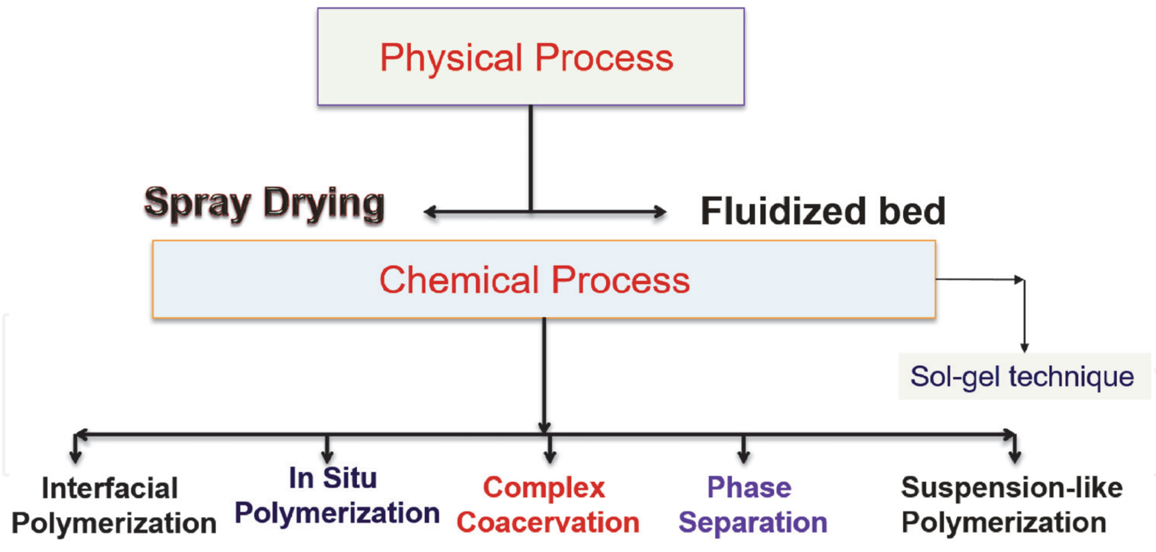

Figure 6.
Methods for preparation of microencapsulation of PCM.

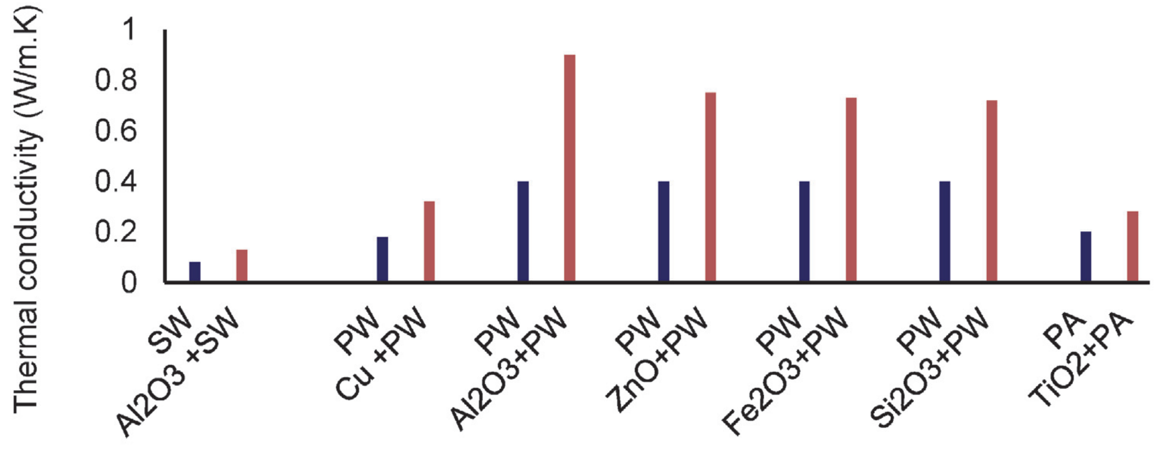

Figure 7.
*Improvement of effective thermal conductivity of PCMS for energy storage. *SW: Sugar WAX, PW: Paraffin wax, PA: Palmitic acid.*

This technique controls the volume change during solid to liquid, resists interaction with environment and enhances the heat transfer area [33]. The inorganic shells can improve the effective thermal conductivity of organic PCMs. Effective thermal conductivity is plays vital role in energy storage unit [34].

Addition of 2–4% of high thermal conductivity material to the PCM can be enhance its thermal properties [35] as shown in **Figure 7**. It will be helpful better performance of energy storage unit.

6. Durability of phase change materials

Accelerated thermal cycle test is essentially required for before applying in solar water heater and solar air conditioner. Thermal cycle test is referring to heating from ambient temperature to melting point of phase transition until completely becomes liquid and cools down to below melting point until becomes the solid. The total heating period and cooling period is called accelerated test. It works once in a day and reflects life of the phase change materials (**Figure 8**). Silakhori et al. [36] conducted accelerated test for paraffin wax and determined melting point and

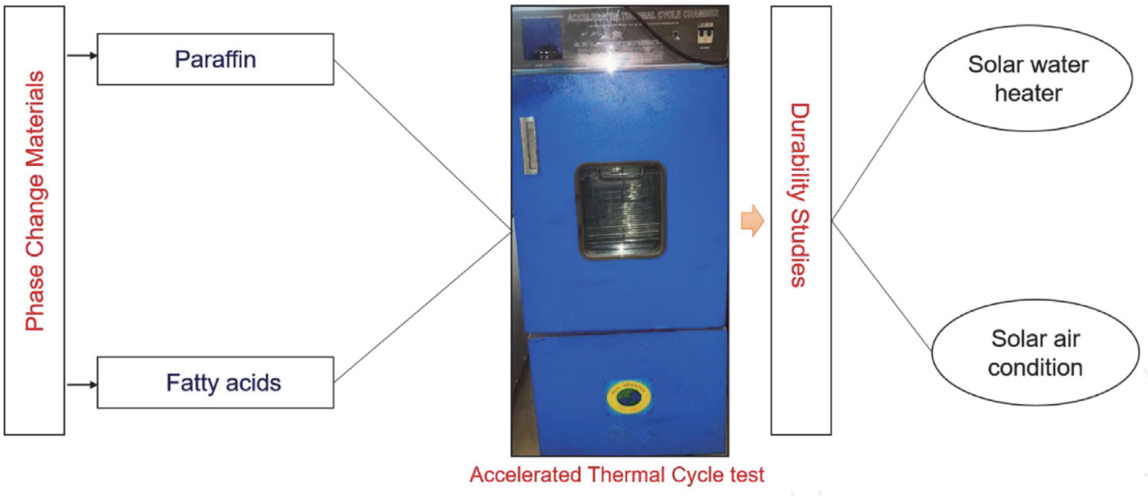

Figure 8.
Performance of accelerated thermal cycle test.

latent heat of fusion after 1000 cycles. 1.6–7% of melting point of paraffin wax was observed. Alkan et al. [37] conducted thermal cycle test of microencapsulated docosane for thermal stability with polymethyl methacrylate (PMMA). There is no significant changes occurred in key parameters 5000 cycles. Ahmet Sari et al. [38] performed the accelerated thermal cycling test for microencapsulated n-octacosane for 5000 cycles. There is no change observed in chemical structures of microcapsules. Sude Ma et al. [39] carried out conducted the thermal cycling test of paraffin wax with PMMA up to1000 cycles. No change in observed in thermal stability of microcapsules.

Yang et al. [40] performed accelerated test of different fatty acids such as lauric acid, myristic acid, palmitic acid and stearic acid for 10,000 thermal cycles. Thermal properties of fatty acids have not changed significantly after repeated cycles Sheili et al. [22] performed thermal cycle test of eutectic mixture of capric and lauric acid. no substantial changes in eutectic mixture after 360 cycles. Chinnasamy V and Appukuttan S [41] determined thermal properties of eutectic mixture of lauric acid /myristyl alcohol after 1000 cycles. It was determined that, there was no changes observed in thermal properties. Zuo et al. [42] found that eutectic mixture of lauric acid/1-tetradeconal were stable thermal properties were stable up to 90 thermal cycle tests. Zhang et al. [43] prepared ternary fatty acid mixture of PCMs with lauric acid, Mysteric acid, and palmitic acid. Melting point and heat of fusion were stable up to 50 cycles.

7. Phase change material for different solicitations for energy storage unit

Based on distinguish phase transition temperature range, these are incorporating in different solicitations are solar energy, building and vehicles for plummeting greenhouse gases (GHGs) and thermal management (**Figure 9**). The temperature ranges from −20°C to +5°C for domestic or commercial refrigeration. The second phase transition temperature range from +5°C to +40°C is applied for heating and cooling applications in buildings.

Now days, utilization of fossil fuels creates huge impact on environment and its leads to studies on commercial refrigeration, heating and cooling in building, solar heating and electronics, Textiles, building energy conversation etc. The PCMs

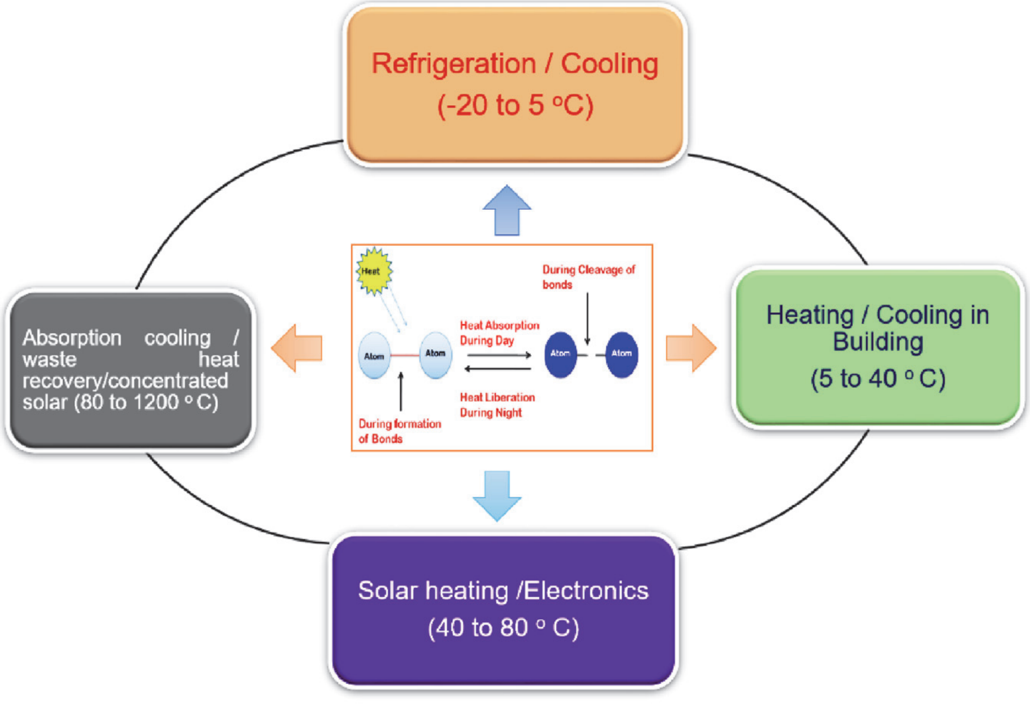

Figure 9.
PCMs are in different applications.

operating temperature range from +40°C to +80°C are used for solar based heating, hot water production and electronic applications and + 80°C to +1200°C range is applied for absorption cooling, waste heat recovery and concentrated solar [44–49].

8. Phase change material into the solar water heating systems

Solar radiation is occurred from the daylight and can be absorbed with solar collectors. These collectors are used for various applications; one of the solicitations is production of outlet hot water. The outlet of the hot water temperature is depending upon different types of collectors (**Figure 10**).

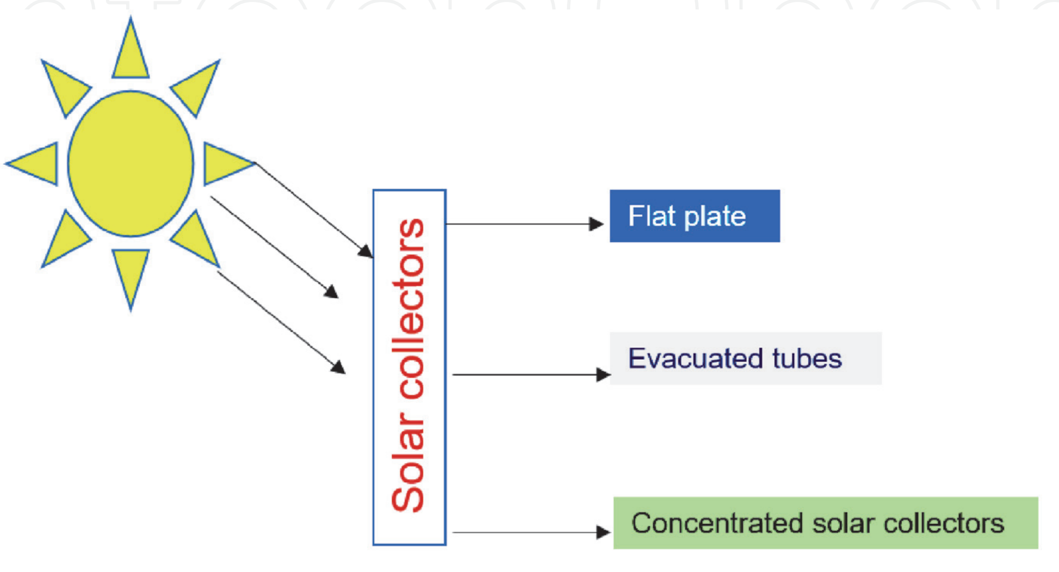

Figure 10.
Different types of solar collectors.

Generally, these solar collectors are mounted on walls for thermal management in the buildings. The thermal power output of the various solar collectors can be determined with product of conversion efficiency and intensity of solar irradiance [44]. The output of thermal power collector can be calculated using following Eq. (4)

$$Q_{KN=}\left(n_0 - \frac{\alpha_1(\theta_K \quad - \theta_u) + (\ \theta_K - \theta_u)^2}{E}\right).E.A_K = m.C_p.(\theta_{KO} - \theta_{KI}) \qquad (5)$$

Q_{KN} Output of thermal power of collector (W), E solar irradiance intensity (W / m^2), A_K Collector area (m^2). Where: n_0: Zero-loss collector efficiency, α_1: Basic heat loss coefficient (W/m^2 K), $\theta_{K:}$ Mean collector temperature (K), θ u: Ambient air temperature (K).$\theta_{KO:}$ Collector outlet temperature (K), $\theta_{KI:}$ Collector inlet temperature (K), m: HTF mass flow rate (kg/s), C_p: heat capacity of HTF (J/kg K).

Among all the solar collector, the flat plate solar collector is discussed in detail owing to Manufacture process is easy, cost effective, maintenance is low and easy installation. This type of Flat plate solar water heater is suitable for urban households (**Table 2**).

8.1 Flat plate

Flat plate is one type of heat exchanger for solar collector that converts radiant energy from sunlight into heat energy. This plate is generally used for low and moderate temperature applications i.e. <80°C. This type of collector contains one is case, second is absorbers like copper or aluminum positioned in the heat exchanger owing to good conductors for heat, the heat transfer fluid and insulation materials. To improve thermal efficiency, need to be minimizing the thermal losses and integrate the superior thermal properties of PCM. The thermal storage materials can be integrated either in the collector or separate thermal storage tank. Flat plate collectors are used in hot water production and space heating, and air conditioning system [50, 51]. For solar water heating, the flat-plate collectors are installed at the optimum angle is Latitude +10°. Water is transport fluid in solar water heating and it has good thermodynamic properties such as high heat capacity, high energy density and incompressible.

Disadvantage of water as transport fluid is damage the collector when it is freeze in winter. The damage can be managed by positioning collector at low solar inputs and need to be add antifreeze mixtures to improve above mentioned problems. The usual antifreeze substances are ethylene glycol or propylene glycol. These chemicals are variegated with water and proper discarding due to toxicity. The durable of antifreeze chemicals is about 5 years [52].

In Flat plate solar water heater, PCM can be equipped in two ways (i) Flat plate integrated solar collector (ii) Flat plate non-integrated solar collector.

Solar collector type	Solar collector efficiency	Heat loss coefficient (W/m^2.K)
Unglazed absorber	0.91	12.0
Flat-plate, single glazing, non-selective absorber	0.86	6.1
Flat-plate, Single glazing, selective absorber	0.81	3.8
Flat-plate, double glazing, selective absorber	0.73	1.7
Vacuum	0.80	1.1

Table 2.
Performance data for distinguish solar collectors [45].

8.1.1 Flat plate integrated solar collector

In Flat plate integrated solar collector, PCM can be positioned like aluminum honeycomb structure and PCM modules for frost protection under the absorber plate (**Figure 11**). PCM integrated solar collectors are increased thermal stability and extended for hot water outlet. However, advanced insulation materials are to be attached to minimize the heat losses otherwise may reduce efficiency of the system [53].

8.1.2 Flat plate non: integrated solar collector

In Flat plate non – integrated solar collectors connected to PCM storage unit. The PCM storage unit is placed on upper of an inclined collector, near the solar collector or under the solar collector. To avoid the leakage, the PCMs are encapsulated in rectangular, cylindrical, and spherical container (**Figure 12; Table 3**).

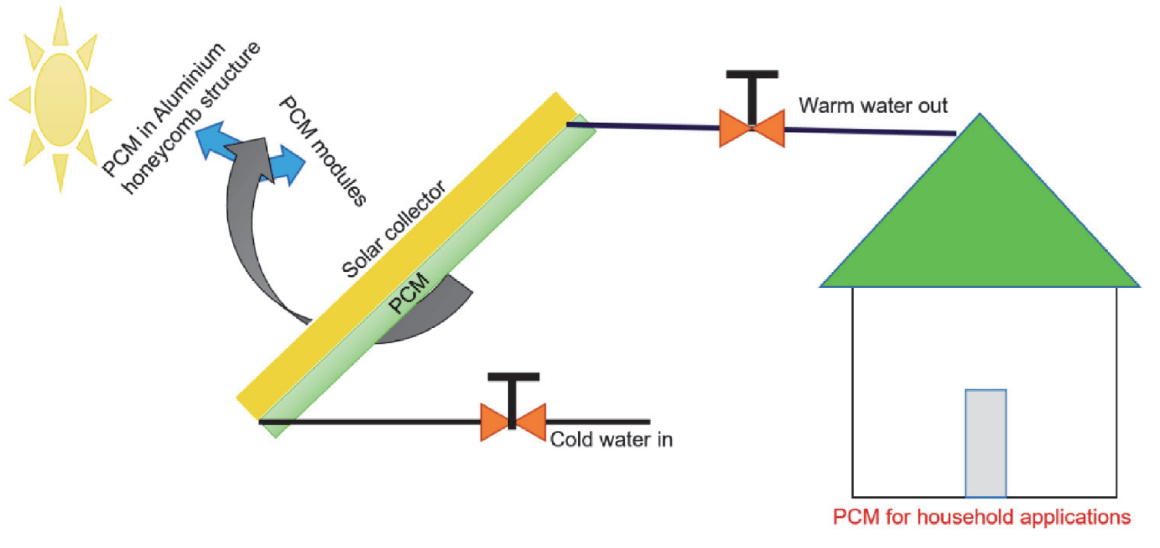

Figure 11.
PCM in flat integrated solar collector.

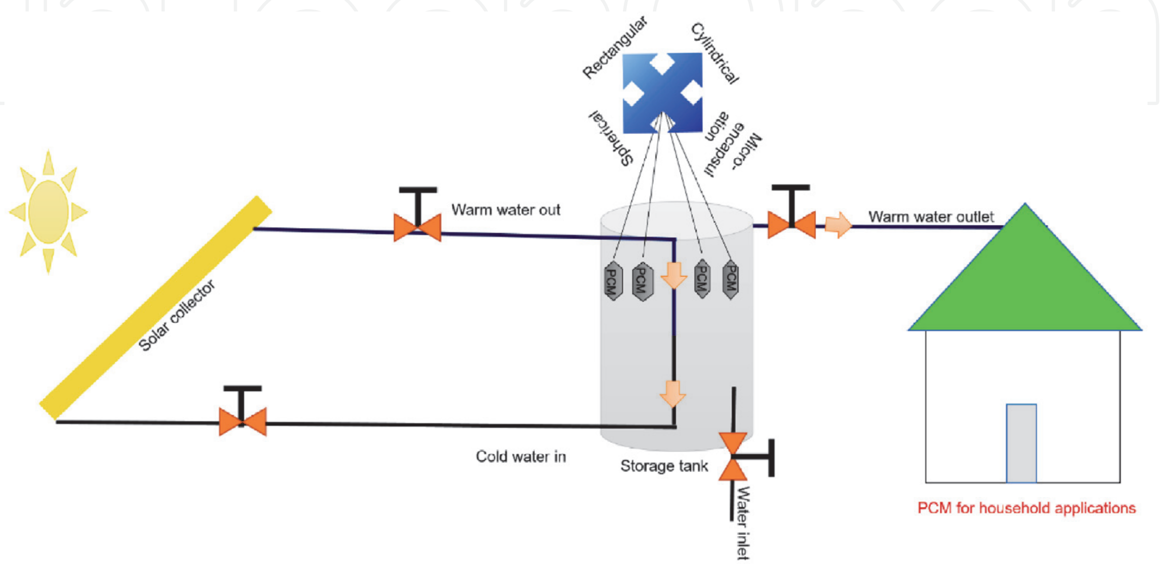

Figure 12.
PCM in in flat non-integrated solar collector.

Types	Advantages	Disadvantages
Rectangular	• Manufacturing process is easy • Small occupied space	• Heat loss rate is high • Thermal stress concentration • Leakage phenomenon may exist
Cylindrical	• Fluid flow can improved • Rate of the PCM is high	• Manufacturing process is not easy
Spherical	• High heat transfer efficiency • Low heat loss rate	• Positioned in storage is complex • Complicated filling process of the PCM is difficult
Micro-encapsulation	• Encapsulation efficiency is high • Particle size is low • High heat transfer area is high	• Manufacturing process is tough • Manufacturing costs is easy

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

Table 3.
Merits and demerits of regular PCM container for different medium [54].

Incorporating solar energy storage system into building may diminish cost of renewable energy storage system and also progress efficiency of the collection. In solar water heating process, the storage unit is filled with PCM for captivating the heat during day from hot water. At night, the absorbed energy supplies to the warm water tank and hot water can be collected for a long time [55, 56]. Kulakarni and Deshmukh [57] studied efficiency of water heating system using paraffin whose melting point was 62°C. Efficiency of solar water heater increased from 31.25% to 44.63%. The storage capacity was enhanced from 3260.4 kJ to 4656.5 kJ. Bhargava [58] utilized three different thermal properties of PCMs such as Na_2SO_4. $10H_2O$ (32 °C and 251 kJ/kg), $Na_2HPO_4.12H_20$ (36.1°C and 279 kJ/kg) and P116 (46.7°C and 209 kJ/kg) Wax were incorporated into storage unit. Determined the efficiency of the system and duration of the outlet water temperature. As thermal conductivity of the materials are increased, Increased duration of outlet hot water temperature during the evening hours. Fazilati and Alemrajabi [59] used Paraffin as storage medium. The melting point and latent heat of fusion were 55°C and 187 kJ/kg. 39%, 16% and 25% improved the energy and exergy efficiency and duration of warm water was improved. Prakash et al. [60] laminated a PCM layer (46.7°C and 209 kJ/kg) at the bottom of the water tank. They concluded that, it was not effective during phase change from liquid to solid due to low heat transfer area. Kaygusuz [61] had studied performance of solar water with $CaCl_2.6H_2O$ (28°C and 45 kcal/kg) as phase change material an experimental and theoretically. Hasan et al. [13–15] incorporated some fatty acids as PCMs such as myristic acid (MA), palmitic acid (PA) and stearic acid (SA) for domestic water heating. They recommended that these fatty acids with melting temperature between 50–70°C were the most auspicious PCMs for water heating. Most of the researchers were studied with different phase transition temperature in solar water heater system. However, as per the Cabinet of Ministers of Latvia, the allowable domestic hot water (DHW) range must be from 55 to 70°C [62]. Literature review given in **Table 4** on phase transition temperature rage in 55 to 70 °C for DHW.

Other than above PCM, some of commercial available within 55–70°C of thermal storage materials are listed out in Zalba et al. [78]. These materials may have applied in Flat Plate Solar water heater for better thermal efficiency, thermal management and longer duration for warm water.

PCM	M.P (°C)	H.F (kJ/kg)	Reference
Two kinds of PCM	70	210	[63]
Paraffin	60	213	[64]
Paraffin and SA	61 & 57	213 & 198	[65]
Salt hydrate	60		[66]
RT 60	60	144	[67]
Nano Cu-PCM (0.5 to 2%)	57.81–59.57	157.3 to 172.2	[68]
RT 65, SA, Pent glycerin	55,66,80	159,207,152	[69]
RT 65 graphite composite	65	—	[70]
Paraffin	70–80	224	[71]
PCM1	60–62	209	[72]
Paraffin	60–70	224	[73]
—	57.34	178.76	[74]
MA, Paraffin, Tristearin	58, 59,56	199,189,191	[75]
Sodium acetate tri-hydrate with graphite	60	180–200	[76]
SA–MA (80–20%)	61–65	190.87	[77]

Table 4.
Literature review on PCM flat plate solar collector for water heater.

9. Conclusion

Phase change materials have high energy density and potential to apply in Flat plate solar collector for production of hot water in urban households. Other than the researchers attempted, there are so many PCMs available commercially in the market for improvement of efficiency of Solar water system. Thermal cycle test is essential for determining durability of paraffin and fatty acid before applying into system. Paraffin and fatty acid have durability to 14 years and 27 years respectively. Higher thermal conductivity of PCMs increased longer duration of hot water however low thermal conductivity materials with high latent heat of fusion of PCMs can be enhanced with addition of high thermal conductivity fillers. Encapsulated PCMs is a tiny particle can easily have applied in storage tanks. PCMs are successfully incorporated in integrated and non-integrated flat plate solar collector. However, non-integrated flat plat solar collector has the higher thermal efficiency than the integrated solar collector because of difference in heat transfer area. There are number of PCMs, commercial methods and designs are available at national and international level. Among them cost effective parameters are selected for effective PCM solar water heating system.

Abbreviations

Q	amount of energy stored in the material (J)
m	mass of storage material (kg)
C_{ps}	specific heat of the storage material of solid state (J/kg·K)
T_1	Initial temperature (K)

T_2	Final temperature (K)
Δh	phase change enthalpy (kJ/kg)
PCM	Total amount energy stored (Q)
C_{pl}	specific heat of the storage material of liquid state (J/kg·K).
X_A and ΔH_A	molar fraction and latent heat of fusion kJ/kg of compound A
T and T_f	melting temperature °C of the mixture and compound A
R	gas factor 0.8314 kJ/ K. mol
Q_{KN}	Output thermal power of collector (W)
E	Solar irradiance intensity (W/m^2)
A_K	Collector area (m^2)
n_0	Zero-loss collector efficiency
α_1	Basic heat loss coefficient (W/m^2 K)
θ_K	Mean collector temperature (K)
θu	Ambient air temperature (K)
θ_{KO}	Collector outlet temperature (K)
θ_{KI}	Collector inlet temperature (K)
m	HTF mass flow rate (kg/s)
C_p	Heat capacity of HTF (J/kg K)

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