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Application of Phase Change Materials in Solar Water Heating Systems for Thermal Energy Storage

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Abstract. One of the major drawbacks of solar water heating systems is unable to supply hot water during night time or off sunshine hours. The integration of phase change material with solar water heating systems is cost effective and efficient solution to overcome this major problem associated with solar water heating systems. The phase change material integrated with solar water heating system stores thermal energy during sun shine hours and this stored energy can be recovered during off shine hours or night time to produce hot water. The phase change material can be integrated with water tank of collector, evacuated tubes, external water tank for solar collector and flat plate collector by adding layers at the bottom of absorber plate. The integration of phase change material with SWH system not only overcome the drawbacks of SWH system but also enhance the efficiency of conventional SWH system. Many investigations for the application of TES materials integrated SWH system have been carried out and found a significant enhancement in the performance. This paper presents a comprehensive review of recent advances in the applications of PCM with SWH system for TES.

1. Introduction

As a renewable energy source, solar energy is free, environmentally friendly and available in abundant. Solar energy can be converted into thermal energy using solar collectors. Solar collectors



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are used in many industrial, commercial and domestic applications such as solar water heating, solar space heating, solar drying, solar desalination [1]. Also, there is a consumption of 75% of the total energy for the production of hot water in the domestic, commercial and industrial sectors. There is a huge demand for the production of hot water using solar collectors. Solar water heating (SWH) system is popular as it covers about 80% of the worldwide market of solar systems [2]. However, for the production of hot water, solar energy is relatively being used only to a small extent due to the intermittent availability of solar radiation and uneven load profiles of domestic hot water consumption. There must be deployment of viable technology to mitigate the impact of these factors. Thermal energy storage is a technology that stores the thermal energy in the form of heat during daytime and recovers heat during night time or cold weather conditions. The integration of phase change materials (PCMs) with SWH systems can improve the system's performance by storing solar energy during daytime and recovering the stored heat during night-time [3,4]. In the PCM integrated SWH system, PCM acts as heat-absorbing units and SWH system heat the water. Also, the integration of PCM with SWH helps to increase solar fraction. The rise and drop of water temperature in SWH system throughout the day can be controlled by improving the PCM's characteristics and its configuration. The integration of PCM with novel properties acts as a solution to overcome the drawbacks of SWH system and helps to promote the SWH system in the market worldwide as well as reduce the SWH system costs. This review paper presents a detailed work of the application of the PCM integrated SWH systems. This manuscript provides the ongoing research work opportunities to enhance the performance of SWH system with the use of PCM's materials

2. Phase Change Material

More than 150 potential PCMs are being used as thermal energy storage materials in solar thermal energy systems [5]. Thermal energy storage materials are classified into sensible heat thermal energy storage (SHTES) materials, latent heat thermal energy storage (LHTES) materials and chemical heat storage materials. SHTES materials are those materials that store thermal energy with a rise in its temperature and vice-versa. LHTES materials store heat by changing their phase and vice-versa. Some of the desirable characteristics required for efficient usage of TES are constant operating temperature, high energy density, high heat transfer rate [6]. Of the above-mentioned characteristics, LHTES shows most of them. Therefore, this method of energy storage has attracted a large number of applications. LHTES materials are being used in various applications such as solar thermal energy systems, space heating and cooling, and peak load reduction. When compared to sensible heat storage (SHS) method, the latent heat storage (LHS) method provides enhanced energy storage density with a small temperature difference. Phase change material (PCM) is a type of LHTES material stores and releases thermal energy in the form of heat by changing its phase under nearly constant temperature. There is an availability of a large number of PCMs in required temperature range (-5°C to 190°C). Therefore, PCMs are used in many applications such as solar energy storage, industrial waste heat recovery, heat pumps, spacecraft thermal control applications, thermal storage in satellites, solar heating systems, energy-efficient buildings, heating and cooling of buildings, building air conditioning, central air-conditioning systems, indoor temperature controlling, underfloor heating system, building envelope, refrigeration system, temperature-adaptable greenhouses, electronics cooling, protective clothing, textiles, thermo-regulating fibres, preservation of food. Some of the novel thermo-physical properties of PCM are such as favourable phase equilibrium, high density, small volume change, low vapour pressure, no supercooling, sufficient crystallization rate, long-term chemical stability, compatibility with materials of construction, non-toxic, non-fire hazard, abundantly available, cost-effective. PCMs are being selected on the basis of their thermo-physical properties, kinetic properties, chemical properties, and economics. There are three categories of PCM which are solid-solid phase-changing materials, solid-liquid phase-changing materials, solid-gas phase-changing materials. Of all the three categories, there is wide use of solid-liquid PCMs. For any effective application, the required thermal properties of PCM are high latent heat of fusion, high thermal conductivity, less volume change during phase transition, little or no supercooling, low vapour pressure in the melt, chemically inert and stable,

self-nucleating, no phase segregation. Solid-liquid PCMs consists three groups of which are organic, inorganic and eutectic solid-liquid PCMs. Organic solid-liquid PCMs includes paraffin, fatty acids, and sugar alcohols [7,8]. Inorganic solid-liquid PCMs includes salt hydrates, salt solutions, and metals. Eutectic solid-liquid PCMs are developed according to the requirement for desired operating temperature of an application. Some of the characteristics of the inorganic group of solid-liquid PCMs which makes it less reliable than organic solid-liquid group of PCMs are super-cooling, phase segregation and nucleation [9]. The advantage of organic solid-liquid PCMs are non-corrosive, chemically stable, exhibit little or no sub-cooling, compatible with most building materials, high latent heat per unit weight, low vapour pressure. Organic solid-liquid PCMs also possesses some of the drawbacks such as low thermal conductivity, high changes in volume on phase change, flammability. Among the organic solid-liquid PCMs, paraffin has been widely used due to its advantageous characteristics such as high enthalpy of phase change, small segregation of components, and small changes in structure during repeated phase transitions, negligible supercooling, low vapour pressure, self-nucleating behaviour, and low cost. The melting temperature range of paraffin is 25-100°C [10,11,12]. Capric acid, lauric acid, myristic acid, stearic acid, palmitic acid are some of the fatty acids comes under the same class of organic solid-liquid PCMs. Where stearic acid and palmitic acid have superior properties such as easy availability, congruent melting/ freezing, good thermal and chemical stability, non-toxicity, and suitable phase change temperature. In spite of these desirable properties of the mentioned fatty acids, high phase change temperature, corrosiveness, bad odour (especially sublimating during heating), poor thermal stability, and thermal conductivity limit are some disadvantages. Therefore, PCMs possess many advantages and disadvantages due to which their application is in limited use. Many researchers are working on material characteristics of PCMs to enhance their performance for the efficient use of PCMs. The novel properties of PCM act as a solution to remove the drawbacks of SWH system [13,14,15].

3. Application of PCM in SWH Systems

There are various research studies are available on the applications of phase change materials integrated SWH system. The studies revealed that thermal performance of SWH system can be enhanced by integration of PCM storage unit with high latent heat and a large area for heat transfer. Al-Kayiem et al. [16] experimentally investigated the performance of flat plate solar collector (FPSC) based SWH systems by integrating nanocomposite PCMs at various inclination angles with SWH system as shown in the Fig. 1. As a nanocomposite PCM, a mixture of paraffin wax and 20-nm copper nanoparticles of 1wt% is considered in this study as shown in the Fig. 2. They considered three cases comprising of SWH without PCM, SWH with PCM and SWH with Cu-Paraffin wax nanocomposite and performed different observations at 10°, 20°, 30° inclination angles of FPSC, respectively. They found that the water flow rate of 0.5kg/min and inclination angle of 10° is the optimal operation conditions for the high performance of the system. The results indicated that the obtained water tank temperatures of SWH without PCM, with paraffin wax as PCM and with Cu-paraffin wax as PCM were 35.1°C, 40.1°C and 40.7°C respectively. The efficiency of SWH (at 10° inclination angle) without PCM, with paraffin wax, with Cu-paraffin wax were 47.6%, 51.1%, 52%, respectively. They found a significant enhancement in the efficiency of SWH system with paraffin wax used as PCM compared to SWH system without PCM. Further they found that there was no significant enhancement in the efficiency of SWH system was observed when Cu-paraffin wax used as PCM. They recommended that further investigation should be done at various flow rates. They also found an enhancement in the thermal conductivity of Cu-paraffin wax nanocomposite compared to paraffin wax. There is an efficiency rise of 6.9% and 8.4% when solar collector integrated with paraffin wax and Cu-paraffin wax nanocomposite as PCM respectively. During morning time, they found that the SWH with paraffin wax and SWH with Cu-paraffin wax produced hot water of 40.1°C, 40.7°C.

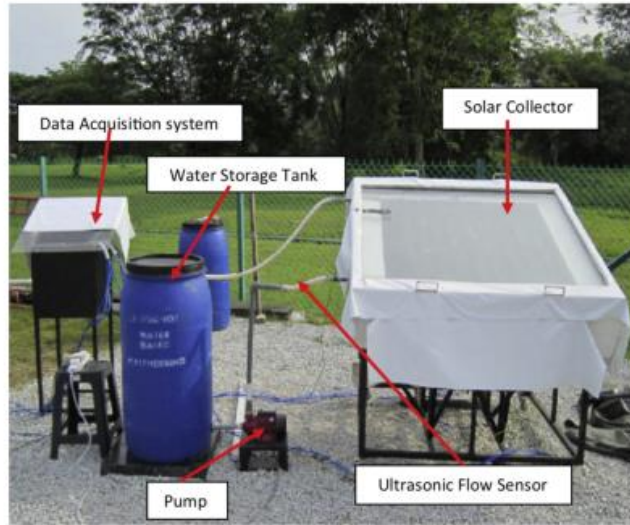


Figure 1. Solar water heating system [16].

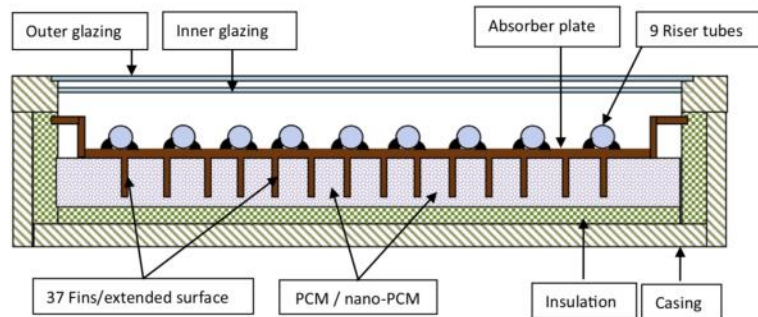


Figure 2. Flat plate collector filled with Cu-paraffin nanocomposite [16].

Due to the large demand for hot water in residential buildings, more attention is being paid to solar water heating systems. In China, there is a wide use of centralized solar water heating systems due to the consumption of huge amounts of hot water in multi-story buildings. In the same context, Zhou et al. [17] experimentally investigated the performance of a centralized solar water heating system by retrofitting phase change materials (PCMs) as a thermal energy storage (TES) unit as shown in the Fig.3. The TES unit comprised of paraffin wax which was packed in stainless steel ball. Also, expanded graphite was added in order to enhance the rate of heat transfer. They selected two PCMs with a melting temperature of 55°C and 60°C according to the operating temperature range of SWH system. At different values of solar radiations, they investigated the heat storage, heat-releasing and insulation properties of water tank equipped with paraffin heat storage unit. Depending on the users demand, the solar fraction of the PCM-SWH system is also calculated. The heat storage time for paraffin with melting temperatures 55°C and 60°C was about 2-4.5 hours. When SWH integrated with a PCM with melting temperature of 55°C, the rate of heat release and solar fraction were 78% and 75%, respectively. When SWH integrated with a PCM with melting temperature of 60°C, the rate of heat release and solar fraction were 83% and 80%, respectively. They found a performance enhancement in a centralized solar water heating system integrated with paraffin as PCM compared to the system without PCM. By Analysing the experimental results, they recommended using paraffin with 60°C melting temperature in centralized solar water heating systems. They also stated that there is an effective rise in the heat storage rate of paraffin when it is changed from PVC unit to stainless steel ball unit along with expanded graphite.

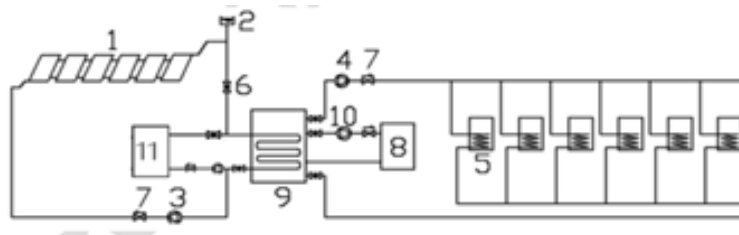


Figure 3. Centralized solar hot water heating system in residential building [17].

Felinski et al. [18] investigated the performance of heat pipe based evacuated tube solar collector (HP-ETSC) by integrating it with paraffin wax as phase change material as shown in the Fig.4. They conducted experiments to investigate the impact of paraffin wax on the system's performance. They found that operating time of the HP-ETSC system was increased by integration of paraffin wax as PCM. Also, due to the integration of paraffin wax, they found less heat loss from the system due to the decrease in the mean temperature of the system and the temperature of the water can be brought up to 45°C. Depending on the water flow rate during discharge cycle, the amount of useful heat from the paraffin-HPETSC was increased by 45-79%. PCM was integrated with SWH system to increase the density of stored heat which was obtained from the conversion of solar energy into thermal energy. PCMs are being integrated within the systems such as by inserting PCM in the water tanks of the SWH system, by filling PCM in the Evacuated collector tubes, adding PCM layers in the flat plate collectors; and or filled PCM in an additional external tank. Many researchers are working to develop simple and compact collector-storage systems in order to save space and reduce the heat losses followed by increased system's thermal efficiency. Such a compact collector –storage SWH system, simultaneously absorbs and stores the solar energy. But one of the drawbacks of this collector-storage SWH system is loss of heat during the night time when solar irradiance is unavailable. Various researchers found solutions such as by changing the water tank's shape, inserting baffled plates, insulating with transparent or non-transparent material. They found that the system's thermal efficiency of 62.6% was obtained at conditions when the paraffin's weight is 13.82 kg, collector inclination angle is 60°, and solar radiation is 900 W/m². They also performed an experiment on the same type of SWH system without paraffin (PCM) to investigate the impact of paraffin wax on SWH system. They conducted simultaneous experiments on ETC/Storage system and ETC system without storage. They followed two measurement procedures which were (i) heat reception-heating medium passing through the heat collection unit, (ii) without heat reception-heating medium bypassing the heat collection unit as shown in the Fig.5. In the both ETC and ETC/S systems, they maintained a flow rate of 0.02kg/sm² during the charging process of paraffin wax for both the tests (with and without heat reception). Whereas, during the discharge cycle in order to investigate the amount of heat recovered from the paraffin during night time, they conducted a series of experiments containing with and without heat reception as shown in the Fig.3. Since at higher operating temperature, the rate of heat loss was more, therefore working temperature of 45°C was required to obtain useful heat for water heating for domestic purposes. As shown in Fig. 6, during the charge cycle for up to 250 minutes, the rate of increase in the heating medium's mean temperature and the final mean temperature values were higher in case of ETC system compared to ETC/S system. It was observed that ETC/S could able to generate hot water up to 45°C only after 200 minutes in comparison to heat reception due to the presence of paraffin as PCM in the system. Therefore, the proposed ETC/S can be utilized to obtain the desired temperature of about 45°C after 200 minutes. They observed that after the completion of 250 minutes of study, there was a reduction in the heat losses by 31% and 32% in case of without and with heat reception modes of ETC/S system, when compared to the ETC system without storage. Compared to ETC system without PCM, depending on the flow rates, the amount of useful heat received was 45-79% higher than ETC/S system.



Figure 4. Evacuated tube collector-storage system [18].

Abokersh et al. [19] developed a compact SWH system comprised of U-pipe ETC integrated with paraffin (ALEX WAX 600) as a storage unit. The characteristics of paraffin (ALEX WAX 600) organic-PCM are 60°C melting temperature, and 0.21W/mK thermal conductivity. To enhance the rate of heat transfer of paraffin in the collector, a fin of 0.1251m² area was placed inside the collector. In this study, they considered two system comprising (i) finned U-pipe ETC based SWH system and (ii) un-finned U-pipe ETC based SWH system as shown in the Fig. 7.

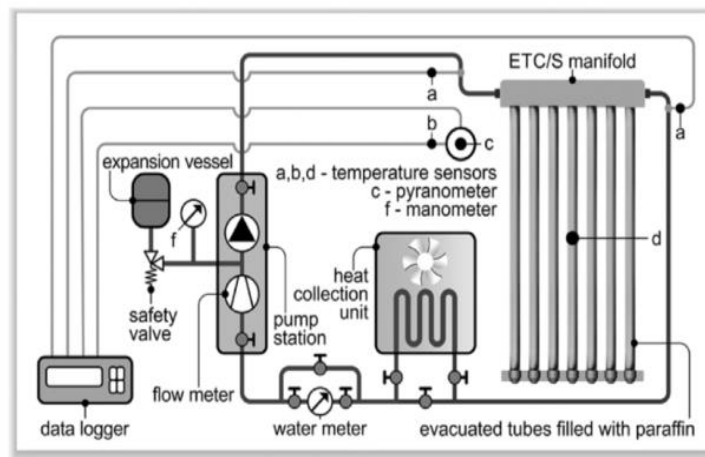


Figure 5. Schematic diagram of the collector-storage SWH system [18].

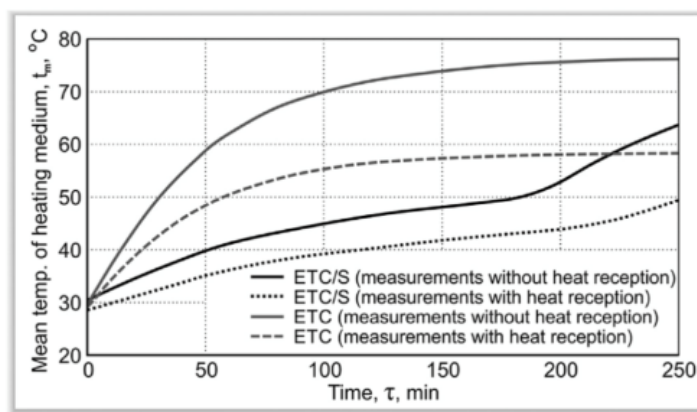


Figure 6. Mean temperature of heating medium during charge cycle [18].

They also compared the performance of these two systems with a typical forced recirculation solar water heating (FSWH) system under same operating conditions. They found that due to lower thermal inertia, there was an enhancement in the performance of two compact systems over a typical SWH system operating under forced recirculation mode tested at various operating conditions. Also, the arrangement of fin enhanced the rate of heat transfer of paraffin which further increased the stability of compact SWH system. They also found that the amount of energy discharge from the finned and un-finned U-pipe ETC based SWH system was 35.8% and 47.7% higher, respectively in comparison to the FSWH system. They stated that efficiency of finned, un-finned and typical SWH system were 85.7%, 71.8%, and 40.5% respectively. The solar fraction of finned, un-finned and typical SWH system were 40.1%, 50.5%, and 32% respectively.

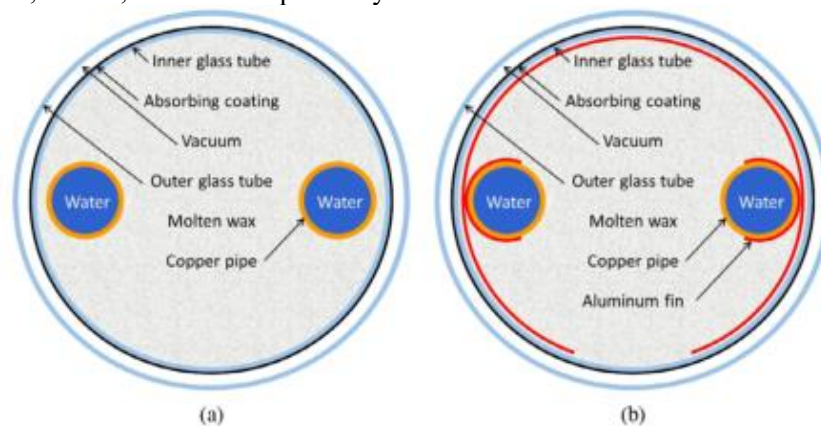


Figure 7. (a) un-finned and (b) finned based U-pipe ETC [19].

Kanimozhi et al. [20] developed an experimental setup of an SWH system integrated with TES system and used paraffin wax as LHS material and honey wax as SHS material to enhance the heat transfer rate and energy storage of TES system as shown in the Fig. 8. In this study, TES system is a cylindrical tank fixed where copper tubes were filled with the paraffin and honey waxes as shown in the Fig. 9. It was found that this TES system is beneficial for both isothermal and non-isothermal storage processes. This TES system improved the heat transfer rate of water passing from the water tank of SWH system to the waxes in the cylindrical unit. They examined the charging and discharging processes of PCMs and observed enhancement in heat absorption, heat transfer, and heat rejection. They found an enhancement of 40% in the heat absorption, heat transfer, and heat rejection processes.

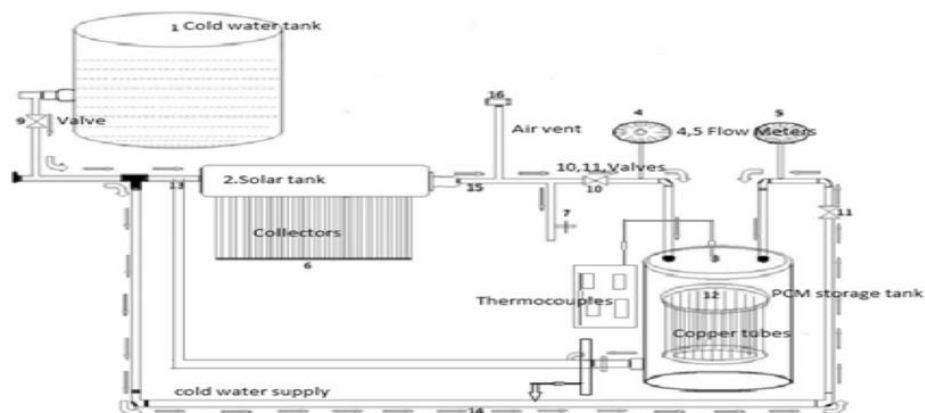


Figure 8. Schematic diagram of experimental setup [20].

They also developed a test rig to measure the system's performance and took total year measurements at all climatic conditions and continued for a couple of successive years. They collected measurements of average efficiency of collector, efficiency of collector, water outlet temperature, coefficient of performance (COP) and made a comparative study of a system without and with PCM. They found that there was an enhancement in the performance of the SWH system with PCM compared to the system without PCM. Compared to the system without PCM, the system with PCM can able to exhibit enhance performance, achieved higher efficiency, hold water at required temperatures, overcome the impact of solar radiation fluctuations. During daytime, they found 30% lesser fluctuations in collector efficiency in the system with PCM compared to the system without PCM.

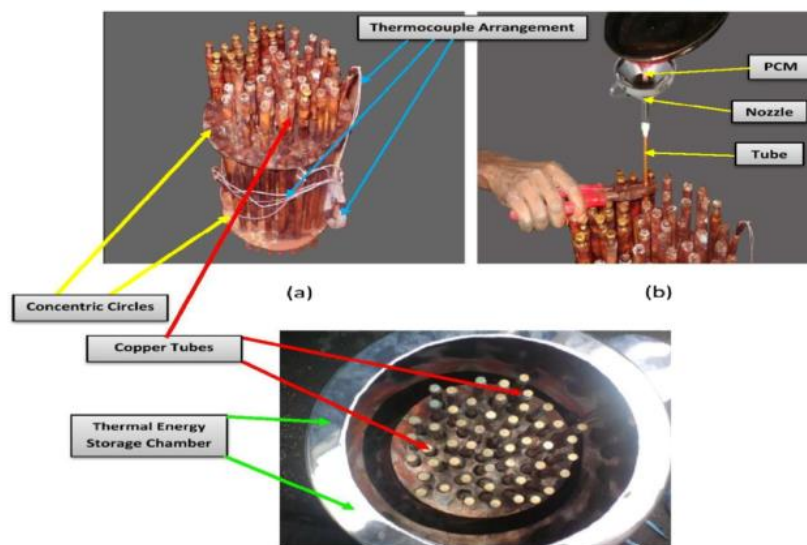


Figure 9. (a) Copper tubes fixed in concentric circles (b) pouring PCM in copper tubes (c) Arrangement of copper tubes in TES system [20].

During summer nights, the system with PCM was able to achieve 50°C water outlet temperature but it was lesser than system without PCM. During winter nights, the COP of system with PCM was 3.0 which made to achieve water outlet temperature of 50°C in less time compared to system without PCM.



Figure 10. Collector-storage based SWH system [21].



Figure 11. Oscillating heat pipe (OHP) [21].

4. Conclusion

The SWH system absorbs solar energy and converts into thermal energy in the form of heat which further utilized to produce hot water. Since solar energy is free available and environmentally friendly which having significant potential for the use to hot water through SWH system. Thermal energy storage (TES) materials are available in the temperature range of 50-70°C temperature ranges which can integrate with the SWH system to store solar energy during daytime and recovered it during night time to produce hot water. This manuscript offers an outline of the latest investigations for SWS system and its performance by the integrating different solar collectors with the PCM unit. This type of new innovative systems has vast possibilities for domestic and industrial sector to reduce energy consumption for hot water production. A collector-storage water heating system is extremely endorsed for low/medium temperature applications as they can store solar energy in the form of latent heat during daytime and can provide heat at night time or unavailability of sun radiation to produce hot water. It was found that the PCM's based Solar Water Heating systems having high potential to replace existing system to enhancing the thermal efficiency of SWH system.

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