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Solar Water Heating System with Phase Change Materials

INVITED PAPER

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Abstract – *Thermal energy storage has always been one of the most critical components in residential solar water heating applications. Solar radiation is a time-dependent energy source with an intermittent character. The heating demands of a residential house are also time dependent. However, the energy source and the demands of a house (or building), in general, do not match each other, especially in solar water heating applications. The peak solar radiation occurs near noon, but the peak heating demand is in the late evening or early morning when solar radiation is not available. Thermal energy storage provides a reservoir of energy to adjust this mismatch and to meet the energy needs at all times. It is used as a bridge to cross the gap between the energy source, the sun, the application and the building. So, thermal energy storage is essential in the solar heating system. Therefore, in this paper, an attempt has been taken to summarize the investigation of the solar water heating system incorporating with Phase Change Materials (PCMs).*

***Keywords**: Solar Water Heating System, Thermal Energy Storage, Phase Change Material, Solar Energy, Latent Heat*

I. Introduction

Over the last two decades a wide variety of solar energy technologies have been developed through research and development, demonstration and large-scale promotion during the eighties and nineties. As a result, some of these technologies have reached maturity and a user-friendly status and are suitable for decentralized applications. One of the most widespread uses of solar thermal technology is solar water heating. India is blessed with good sunshine. The country receives solar radiation amounting to over 5 $x10^{15}$ kWh per annum [1] with the daily average incident energy varying between 4-7 kWh per m^2 depending on the location [2]. Solar water heating systems (SWHs) have now been used for more than sixty years [1], [3], [4]. In many countries, which include China, Israel, USA, Japan, Australia, South Africa and Cyprus, SWHs are very popular for their use in community, commercial and industrial applications [5]-[11].

The magnitude and importance of solar energy are well known. Solar energy is free, environmentally clean, and therefore is recognized as one of the most promising alternative energy recourses options. Its total available value is seasonal and is dependent on the meteorological conditions of the location. However, being an intermittent energy source, the utilization of solar energy can be more attractive and reliable if associated with a heat storage systems. The scientists all over the world are in search of new and renewable energy sources. One of the options is to develop energy storage devices, which are as important as developing new sources of energy. The storage of energy in suitable forms, which can conventionally be converted into the required form, is at present day challenge to the technologists.

Since the solar energy supply is variable in daytime and zero at night, considerable amount of solar energy should be stored during the daytime to meet the demands at night. Energy storage is, therefore, essential to any system that depends largely on solar energy. It adjusts temporal mismatches between the load and the intermittent or variable energy source, thereby improving the system operability and utility. Solar radiation can not be stored as such, so first of all an energy conversion has to be brought about and, depending on this conversion, a storage device is needed. For this purpose, latent heat of fusion of Phase Change Material (PCM) is of great interest on account of high storage density and its isothermal nature of the storage process. Solar energy can be stored by thermal, electrical, chemical, and mechanical methods.

Due to the nature of solar energy, two components are required to have a functional solar energy system. These two components are a collector and a storage unit. The collector simply collects the radiation that falls on it and converts a fraction of it to other forms of. The storage unit is required because of the non-constant nature of solar energy; at certain times only a very small amount of radiation or no radiation will be received. The storage of thermal energy as latent heat of fusion has attractive features over the sensible heat due to its high storage density and isothermal nature of storage process at melting temperature. The phase change from solid to liquid or vice-versa is preferred because the operating pressure is lower than liquid to gas or solid to gas phase change. In practice several PCMs are known, such as:

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paraffin's, fatty-acids, organic and inorganic salt hydrates, organic and inorganic eutectic compounds. A comparison of the advantages and disadvantages of organic and inorganic is shown in Table I.

TABLE I
COMPARISON OF ORGANIC AND INORGANIC MATERIALS FOR HEAT STORAGE [16], [19]

Organics	Inorganics
Advantages	Advantages
Chemical and thermal stability, Suffer little or no supercooling, Non-corrosives, Non-toxic, High heat of fusion and low vapour pressure	High heat of fusion, Good thermal conductivity, Cheap and non-flammable
Disadvantages	Disadvantages
Low thermal conductivity, High changes in volumes on phase change, Inflammability, Lower phase change enthalpy	Phase decomposition and suffer from loss of hydrate, lack of thermal stability, Supercooling, Corrosion

The PCM to be used in the design of any thermal storage systems should have high latent heat of fusion, high heat conductivity (more than 0.5 W/m^{o}C), material's melting temperature should be in the functional interval if it stores solar energy, congruent melting, minimal supercooling, chemical stability, economic efficiency and aspects of environmental protection. A large number of solid–liquid PCMs have been investigated for heating and cooling applications [12]–[20]. The PCM to be used in the design of any thermal storage systems should pass desirable thermophysical, kinetics and chemical properties which are given in Table II.

TABLE II
MAIN DESIRABLE PROPERTIES OF PHASE CHANGE MATERIALS [2], [19]

Thermal properties	Suitable phase-transition temperature, High latent heat of transition, High thermal conductivity in both liquid and solid phases, Good heat transfer
Physical properties	Favorable phase equilibrium, High density, Small volume change, Low vapor pressure
Kinetic properties	No supercooling, Sufficient crystallization rate
Chemical properties	Long-term chemical stability, Compatibility with materials of construction, No toxicity, No fire hazard
Economic Properties	Abundant, Available, Cost effective

The ideal PCM to be used for latent heat storage system must meet following requirements: high sensitive heat capacity and heat of fusion; stable composition; high density and heat conductivity; chemical inert; non-toxic and non-inflammable; reasonable and inexpensive.

In the nature, the salt hydrates, paraffin and paraffin waxes, fatty acids and some other compounds have high latent heat of fusion in the temperature range from 30ºC to 80ºC that is interesting for solar applications.

Recently, the incorporation of PCM in different applications has grown interest to the researcher.

This paper is a compilation of much of practical information on few selected PCMs used in a solar water heating systems. This review article is an effort to provide practical information on various PCMs and it will also help to provide a variety of designs to store solar thermal energy using PCMs for solar water heating systems.

II. Solar Water Heating System with Latent Heat Storage Materials: a Review

Integrating solar energy collection system into the building shell and mechanical systems may reduce the cost of the solar energy systems as well improve the efficiency of the collection.

Therefore, research in building integrated solar thermal design has started in the early 1940s and is continuing today [21].

Solar water heater is getting popularity [22], [23] since they are relatively inexpensive and simple to fabricate and maintain. Bhargava [24] utilized the PCM for a solar water heater and concluded that the efficiency of the system and the outlet water temperature during the evening hours increases with the increase in the thermal conductivity of the solid-liquid phases of the materials. Hot water can be obtained throughout the day if water pipes are placed near the surface of the storage material. The outlet water temperature curve becomes flat if the pipes are placed near the bottom of the storage material. Prakesh et al. [25] analyzed a novel built in storage type water heater containing a layer of PCM filled capsules at the bottom (Fig. 1).

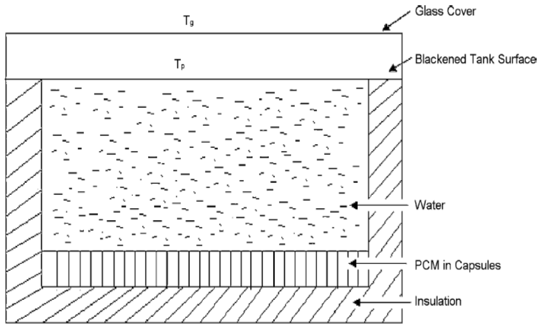


Fig. 1. Solar water heater [25]

During the sunshine hours, the water gets heated up which in turn transfers heat to the PCM below it.

The PCM collects energy in the form of latent heat and melts. During off sunshine hours, the hot water is withdrawn and is substituted by cold water, which gains energy from the PCM.

The energy is released by the PCM on changing its phases from liquid to solid. This type of system may not be effective due to the poor heat transfer between PCM and water. Tiwari et al. [26] presented an analysis of PCM storage for a water heater by incorporating the effect of water flow through a parallel plate placed at the solid-liquid interface. In order to reduce the night heat losses from the exposed surface, a provision of covering the system by movable insulation was made. They concluded that the hot water (temperature 15–20°C>ambient air temperature) can remain throughout the day and night, and the fluctuations in water temperature decrease with an increase in the melted region of the PCM water heater.

A comparison has been made between different sized latent heat storage vessels and sensible heat storage in a water tank with different degree of stratification [27]. The storage vessel consists of a number of closed cylindrical pipes filled with the phase change medium (Fig. 2).

These pipes were surrounded by heat transfer fluid. A cylindrical storage unit in the closed loop with a flat plate collector has been theoretically studied by Bansal and Buddhi [28] for its charging and discharging mode. The calculations for the interface moving boundary and fluid temperature were made by using paraffin wax (p-116) and stearic acid as PCMs.

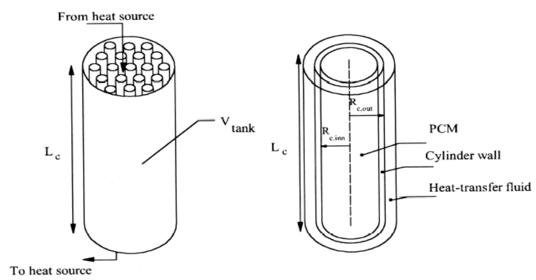


Fig. 2. A cylindrical shell with PCM storage

Tayeb [29] developed a system for domestic hot water using $Na_2SO_4.10H_20$ as a PCM and compared it with the simulation model that gives the optimum flow rate of the inlet water supply required to maintain the constant-temperature water at the outlet. Later, Tayeb [30] conducted study on the mixtures of organic-inorganic substances for their performance as energy storage media.

Mixtures of both types of PCMs, in different ratios, were investigated for the object of determining that optimum composition which stores a higher amount of energy and, meanwhile, releases it at a constant temperature or within a narrow range of temperature. Glauber's salt ($Na_2SO_4.1OH_2O$) and stearic acid were used as a PCM in different proportions. The effect of cooling fluid flow rate and ambient temperature as well as the effect of addition of a nucleating agent was also studied. The experimental results showed that the highest amount of energy stored could be obtained from a mixture containing 40% stearic acid and 60% Glauber's salt. The addition of a nucleating agent is very essential in the case of samples containing stearic acid, but it is not as important for samples of pure Glauber's salt. Font et al. [31] conducted a preliminary study for the design of a device for a domestic water heater using a solid-solid PCM. Numerical simulation has been made using a unidirectional model and verified with the experimental results. The concordance between both experimentally and simulation results shows that this model is available to study the heat transfer phenomenon in the PCM in order to optimize the design of the device. Hasan et al. [32]-[34] has investigated some fatty acids as PCMs for domestic water heating. They recommended that myristic acid, palmitic acid and stearic acid, with melting temperature between 50°C-70°C are the most promising PCMs for water heating. They concluded that a little reduction of the latent heat was found after 450 heating cycles. Al-Jandal and Sayigh [35] studied the combination of solar collector and PCM in one unit. The performance characteristics of the proposed Solar Tube Collector (STC) were being analyzed analytically and experimentally. Fundamental experiments were performed to simulate a direct contact solar storage system; using two vertical cylindrical concentric tubes with the annular space between them filled Stearic acid. For the heat charging mode, the experimental results for different types of fin structures have shown that the effect of melting process is strongly affected by the variation of the imposed conditions, in addition to the different trends of the melting profiles along the axial direction due to the effect of natural convection.Kaygusuz [36] had conducted an experimental and theoretical study to determine the performance of phase change energy storage materials for solar water heating systems. $CaCl_2.6H_2O$ was used as PCM.

Author also compared the performance of PCM, water and rock based storage system (Fig. 3). Whenever solar energy is available, it is collected and transferred to the energy storage tank that is filled by 1500 Kg encapsulated PCM. It consisted of a vessel packed in the horizontal direction with cylindrical tubes. The energy storage material ($CaCl_2.6H_2O$) is inside the tubes (the tube container made of PVC plastic) and heats transfer fluid (water) flow parallel to them.

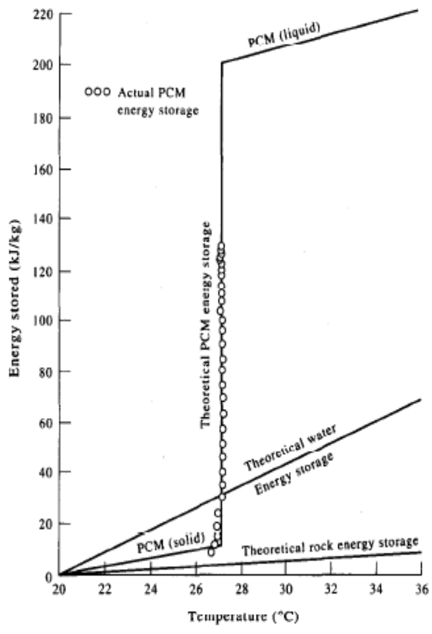


Fig. 3. Performance comparison of PCM, water and rock storage system

The integrated collector storage (ICS) concept is considered to be a promising direction for increasing the economic feasibility of low temperature solar systems for heating water for domestic, agricultural and industrial applications. A system of this type combines collection and storage of thermal energy in a single unit. Compared with the conventional domestic water heating system, the integrated collector has the advantage of simplicity, both in erection and in operation.

Boy et al. [37] proposed an integrated collector storage system based on a salt-hydrate as an appliance for providing hot water instantaneously.

They demonstrated that the thermal efficiency of such system could be improved significantly by incorporating an appropriate PCM device.

However, in their system the salt-hydrate PCM was encapsulated in a special corrugated-fin heat ex exchanger, which increased the cost of the system.

Rabin et al. [38] developed new integrated collector storage (ICS) concept for low-temperature solar water heating system.

The solar energy was stored in a salt-hydrate used as a PCM held in the collector and was discharged to cold water flowing through a surface heat exchanger located in a layer of stationary heat transfer liquid, floating over an immiscible layer of PCM.

The results of parametric studies on the effect of the transition temperature and of the thickness layer of the salt-hydrate PCM on the thermal performance of the charging process are also presented (Fig. 4).

Bajnoczy et al. [39] studied the two grade heat storage system (60°C – 30°C and 30°C – 20°C) based on calcium chloride hexahydrate and calcium chloride tetrahydrate.

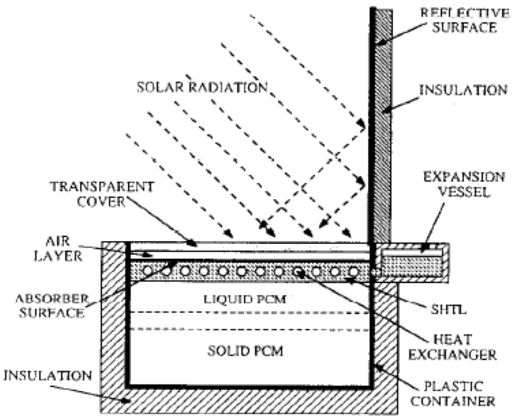


Fig. 4. Schematic presentation of the integrated solar collector storage system based on a phase-change material

Authors also studied the storage capacity changes during the cycles and possible use of a solar energy storage system for domestic water heating system. A possible scheme of a storage system is represented in Fig. 5. Authors reported that the PCM should be located in the upper part of the storage tank. Later Bajnoczy et al. [40] investigated a two grade PCM based on $CaCl_2$-water system in a PCM-water heat exchanger. The crystallization of different hydrates of $CaCl_2$ extended the temperature range of heat storage and the storage stability was achieved by the application of wood chips as thickening agent. A short section of the heat exchanger tube (a few cm) can be characterized by a maximum curve of heat transfer coefficient in function of cooling time. Longer sections (a few meter) showed nearly constant heat transfer coefficient in the range of 115 ± 25 W/m^{2}K. The heat storage system was to be applied to store solar energy and the stored heat was used to preheat the water input of domestic hot water supply system.

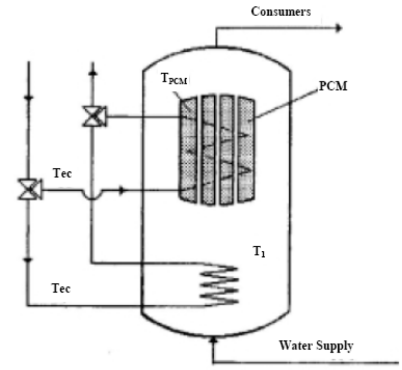


Fig. 5. Scheme of a storage tank (Tec: temperature of energy carrier, T_I: temperature of the water, T_{PCM}: temperature of the PCM)

A comparative study of solar energy storage systems based on the latent heat and sensible heat technique has been carried out to preserve the solar heated hot water for night duration by Chaurasia [41]. For this purpose, two identical storage units were used. One storage unit contained 17.5 kg paraffin wax (m.p. about 54°C) as the storage material packed in a heat exchanger made of the aluminum tubes and another unit simply contained the water as a storage material in a GI tank. Both units were separately charged during the day with the help of the flat plate solar collectors having same absorbing area. This study has revealed that the latent heat storage system comparatively yields more hot water on the next day morning as compared to sensible storage system.

Kurklu et al. [42] designed & developed a new type of solar collector with PCM. The solar collector, which exhibited a net solar aperture area of 1.44m^2, consisted of two adjoining sections one filled with water and the other with a PCM with a melting and freezing range of about 45–50°C, i.e. paraffin wax in this study (Fig. 6). The PCM functioned both as an energy storage material for the stabilization, theoretically, of the water temperature and as an insulation material due to its low thermal conductivity value. The results of the study indicated that the water temperature exceeded 55°C during a typical day of high solar radiation and it was kept over 30°C during the whole night. Covering the collector surface with an insulation blanket at a time when the water temperature was at its maximum improved the energy conservation of the water significantly. The instantaneous thermal efficiency values were between about 22% and 80%.

The present solar collector was much advantageous over the traditional solar hot water collectors in Turkey in terms of total system weight and the cost in particular.

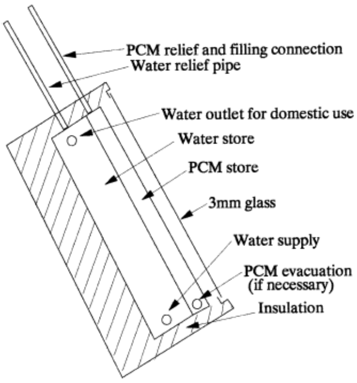
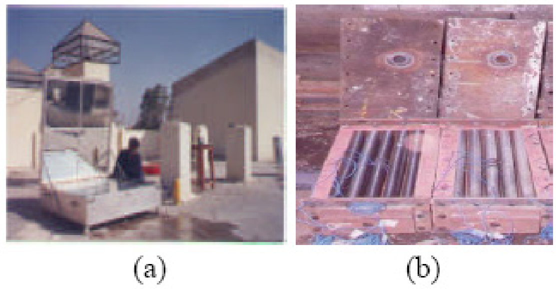


Fig. 6. The schematic view of the solar collector and its parts

Sarı and Kaygusuz [43]-[45] recommended myristic acid, Stearic acid and Palmitic acid as a good PCM for energy storage for domestic solar water heating. These fatty acids have a suitable melting point 49-51°C, 60-61°C, 61°C and latent heat of fusion 204.5, 186.5, 203.4 and purity 98%, 90%, 97% respectively. These fatty acids do not exhibit any subcooling. Baran and Sari [46] also developed a eutectics mixture of palmitic and stearic acids in ratio of 64.2:35.8 wt%, which melts and solidifies at an approximately isothermal phase transition temperature of 52.3°C and 181.7 kJ/kg latent heat of fusion. There was no subcooling find during the solidification. Thus, author concluded that the phase transition temperature and latent heat of fusion of the developed mixture can be very fruitful to use for heat storage in passive solar space building heating applications and solar domestic water heating with respect to the climate conditions.

Sharma et al. [47] designed, developed and performance evaluate of a latent heat storage unit for evening and morning hot water requirements, using a box type solar collector. Paraffin wax (m.p. 54°C) was used as a latent heat storage material and found that the performance of the latent heat storage unit in the system was very good to get the hot water in the desirable temperature range (Figs. 7). Authors also reported that to get the hot water in the desirable temperature range more fins may be provided to increase the effectiveness of the storage unit. Suat et al. [48] presented a conventional open-loop passive solar water-heating system combined with sodium thiosulfate pentahydrate (PCM) was experimentally investigated during November and then enhancement of solar thermal energy storage performance of the system by comparing with those of conventional system including no PCM was observed. Heat storage performances of the same solar water-heating system combined with the other salt hydrates-PCMs such as zinc nitrate hexahydrate, disodium hydrogen phosphate dodecahydrate, calcium chloride hexahydrate and sodium sulfate decahydrate (Glauber's salt) were examined theoretically by using meteorological data and thermophysical properties of PCMs with some assumptions.



Figs. 7. Camera photograph of the box type solar collector with heat exchangers

It was obtained that the storage time of hot water, the produced hot water mass and total heat accumulated in the solar water-heating system having the heat storage tank combined with PCM were approximately 2.59-3.45 times of that in the conventional solar water-heating system having the heat storage tank including no PCM. It was also found that the hydrated salts of the highest solar thermal energy storage performance in PCMs used in theoretical investigation were disodium hydrogen phosphate dodecahydrate and sodium sulfate decahydrate (Fig. 8). Authors also reported that the additional cost of solar thermal energy storage system including PCM used in the present study has been estimated as US$ 0.5 per the unit volume of the heat storage tank in liter. However, the volume of hot water tank required to store the same heat in energy storage system including PCM will be smaller than that of conventional solar energy storage system. Therefore, it is obvious that the use of PCM in the system may not cause an important increase in cost.

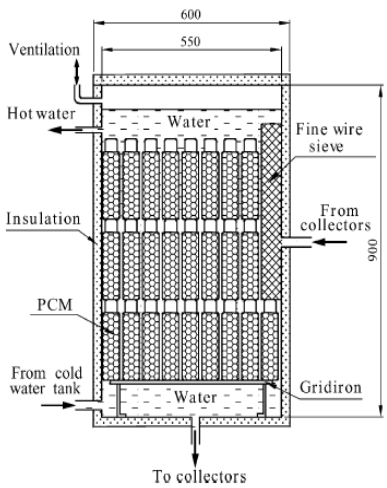


Fig. 8. Detailed cross-sectional view of the cylindrical heat storage tank combined with PCM

Mettawee & Assassa [49] investigated the thermal performance of a compact PCM solar collector based on latent heat storage. In this collector, the absorber plate–container unit performs the function of both absorbing the solar energy and storing PCM. The solar energy was stored in paraffin wax, which was used as a PCM, and was discharged to cold water flowing in pipes located inside the wax. The collector's effective area was assumed to be 1m^2 and its total volume was divided into 5 sectors. The experimental apparatus was designed to simulate one of the collector's sectors, with an apparatus-absorber effective area of 0.2m^2. Outdoor experiments were carried out to demonstrate the applicability of using a compact solar collector for water heating. The time-wise temperatures of the PCM were recorded during the processes of charging and discharging. Experiments were conducted for different water flow rates of 8.3-21.7 kg/h. The effect of the water flow rate on the useful heat gain was also studied. The heat transfer coefficients were calculated for the charging process. The propagation of the melting and freezing front was also studied during the charging and discharging processes. The experimental results showed that in the charging process, the average heat transfer coefficient increases sharply with increasing the molten layer thickness, as the natural convection grows strong. In the discharge process, the useful heat gain was found to increase as the water mass flow rate increases (Fig. 9).

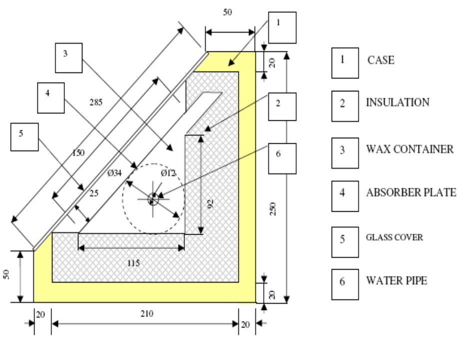
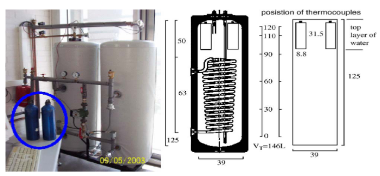


Fig. 9. Schematic of the experimental apparatus cross section

Cabeza et al. [50] constructed solar pilot plant at the University of Lleida to test the PCM behavior in real conditions, which could work continuously with the solar system, or could also work with an electrical heater. Figs. 10 show pictures of the installation. The stand had two thermal solar collectors, two hot-water tanks of 146 L and an electrical heater outside the tanks which allowed electrical heating with a known power when needed. The two water tanks were identical, but one had been modified to insert the PCM module. The right tank was equipped with thermocouples as indicated in Fig. 10(b) to measure the temperature in the water at different levels. This allowed to check whether the water in the tank is still stratified. The thermocouples were fixed to the vertical pipe that extends over most of the tank interior and acts as cold-water inlet. The PCM module geometry adopted was to use several cylinders at the top of the water tank. Therefore, several experiments with two, four and six PCM modules were carried out in the real installation built in the University of Lleida. The modules used were commercial aluminum bottles filled with almost identical amounts of the PCM–graphite composite material. The dimensions of the PCM modules were 8.8-cm-diameter and 31.5-cm-height, giving 1.5 L capacity. Authors reported that as in any other application, the selection of the PCM to be used is a crucial point. The temperature of water to be stored as domestic hot-water is about 60°C; therefore, the melting temperature of the PCM should be around 60°C. In the market, different PCMs with this melting temperature can be found [51]. Experiments with paraffin's, sodium acetate trihydrate and even fatty acids have been carried out in the laboratory [52], [53] and, finally, sodium acetate trihydrate was chosen for the experiments. High heat transfer rate in the PCM is also crucial for the performance of this new concept [53]. Former experiments at laboratory showed that even though there were many ways to enhance heat transfer in PCMs, graphite is the best option in this kind of applications [54]. Therefore a granular PCM-graphite compound of about 90 vol.% of sodium acetate and 10 vol.%. graphite was chosen as a PCM. It was also chosen for its suitable thermal data, described below, and its low price. Data of the PCM graphite compound were given by the manufacturers with density of 1.35-1.4 kg/L, a melting point of 58°C, a heat capacity of 2.5 kJ/kgK, an enthalpy of 180-200 kJ/kg and a thermal conductivity of 2-5 W/mK. The melting point and enthalpy were tested in our laboratory with a Mettler Toledo DSC 822.

Authors concluded that the inclusion of a PCM module in water tanks for domestic hot-water supply is a very promising technology. It would allow to have hot-water for longer periods of time even without exterior energy supply, or to use smaller tanks for the same purpose.

(a)



(b)

Figs. 10. (a) Solar thermal collectors, (b) Hot-water tanks from Lapesa and PCM modules

Tarhan et al. [55] designed, developed and tested three trapezoidal built in storage solar water heaters to find the possible contributions of the PCM use in terms of the PCM types (i.e. myristic acid and lauric acid) and the location of the PCM storage units (i.e. together with absorbing plate and together with baffle plate) to the water temperature rise and drop characteristics in their tanks. Lauric acid, stored in a storage unit that was also used as a baffle plate, considerably reduced the peak temperatures during the trials but had small effects on the dip temperatures.

Therefore, lauric acid can be used to stabilize the temperature and reduce the necessary volume of the water tank during the day. It could not be very effective to retain the water temperature during the night.

On the other hand, myristic acid, stored in a storage unit that was also used as an absorbing plate, was more effective to retain the water temperatures during the night since it solidified at 51–52 ^{o}C water temperature and acted as a thermal barrier against heat loss during the night time because of its relatively high melting temperature and low heat conduction coefficient in its solid phase.

The ability of the myristic acid storage unit to retain the water temperatures got more remarkable, especially at the middle portion of the water tank.

The myristic acid storage increased the dip temperatures by approximately 8.8% compared to the control heater. The experimental results have also indicated that the thermal characteristics of the PCM and the configuration of the PCM storage unit can result in advantageous control of the water temperature rise and drop during both day and night time.

Lee et al. [56] experimentally studied a latent heat storage unit (LHSU) in a two-phase thermosyphon solar water heater.

Three PCMs were used as energy storage materials: tricosane, water, and sodium acetate.

The results of a comparative study indicate that tricosane provides many advantages to be the energy storage material in LHSU. Other results show that the LHSU gives optimum charge and discharge performance under 40% alcohol fill ratio and with tricosane used as the energy storage material, and displays an optimum charge efficiency of 73% and optimum discharge efficiency of 81%.

Nallusamy et al. [57] investigated experimentally the thermal behavior of a packed bed of combined sensible and latent heat thermal energy storage (TES) unit.

A TES unit was designed, constructed and integrated with constant temperature bath/solar collector to study the performance of the storage unit (Fig. 11).

The TES unit contains paraffin as PCM filled in spherical capsules, which were packed in an insulated cylindrical storage tank.

The water used as heat transfer fluid (HTF) to transfer heat from the constant temperature bath/solar collector to the TES tank also acts as sensible heat storage (SHS) material.

Charging experiments were carried out at constant and varying (solar energy) inlet fluid temperatures to examine the effects of inlet fluid temperature and flow rate of HTF on the performance of the storage unit. Discharging experiments were carried out by both continuous and batchwise processes to recover the stored heat.

The significance of time wise variation of HTF and PCM temperatures during charging and discharging processes was discussed in detail and the performance parameters such as instantaneous heat stored and cumulative heat stored were also studied. The performance of the present system was compared with that of the conventional SHS system.

It was found from the discharging experiments that the combined storage system employing batchwise discharging of hot water from the TES tank was best suited for applications where the requirement is intermittent.

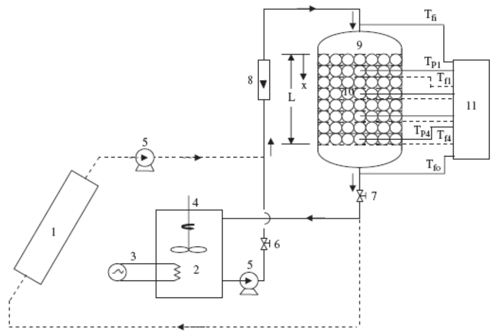


Fig. 11. Schematic of experimental setup: (1) solar flat plate collector (varying heat source); (2) constant temperature bath; (3) electric heater; (4) stirrer; (5) pump; (6 and 7) flow control valves; 8. flow meter; (9) TES tank; (10) PCM capsules; (11) temperature indicator; T_P and T_f - temperature sensors (RTDs)

Hassan and Beliveau [58] presented the development of a newly designed collection system that consists of an integrated flat-plate collector and a PCM storage tank. The designed system provides a substantial cost saving when compared to the traditional solar system design, it appears that the use of this system is promising. Evaluation of the thermal performance using simulation technique indicated that the proposed system could supply a minimum of 88% of the building's space heating and hot water requirements throughout the year saving the homeowner 61.5% of his annual heating bill and reducing the need for non-renewable energy. Experimental evaluation of the proposed system is currently underway.

The automatic control of the solar thermal system is accomplished by continuously controlling the fluid circulation pump as well as the fluid path.

The fluid path is altered based on changes in system and service temperatures or changes in the level of solar radiation and ambient temperatures. Four alternative fluid paths are shown in Figs. 12.

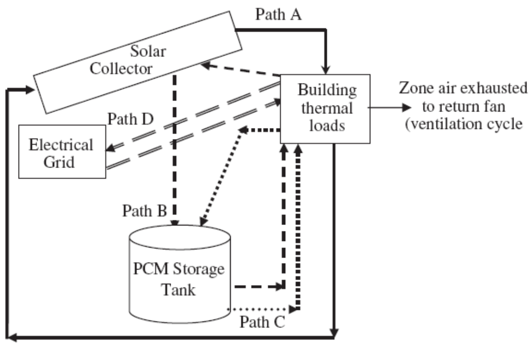


Fig. 12(a)

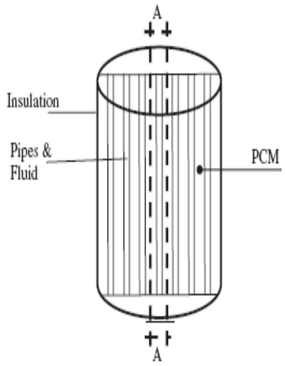


Fig. 12(b)

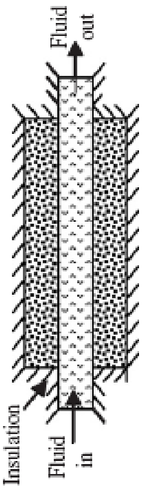


Fig. 12(c)

Figs. 12. (a) Alternative energy supply paths, (b) PCM storage tank & (c) Section A enlarged

If the fluid outlet temperature ranges between 40^{o}C and 60^{o}C, path A becomes operational.

In path A, the hot fluid is circulated between the solar collector and the building thermal zones and hot water tank to satisfy the building's thermal loads and hot water requirements.

As the temperature increases above 60^{o}C, the fluid path is switched to path B.

Path B transports the hot fluid from the solar collector to the storage tank, to store the excess energy ensuring that the fluid's temperature exiting the storage tank is around 50^{o}C by alerting the fluid's mass flow rate.

The fluid is then transferred to the thermal zones and the hot water tank to supply the building's thermal loads before returning to the solar collector. In cases where the change in the fluid temperature while passing through the solar collector equals zero or less, the flow within the solar collector will shut itself off.

During that time, the needed energy will be drawn either from the PCM storage tank (path C), or from the electrical grid if the stored energy is not sufficient (path D). The heating energy is stored in a PCM Rubithern RT 54, which is stocked in a well-insulated cylindrical tank as shown in Fig. 12(b).

The storage tank contains parallel 6.35mm diameter copper pipes.

These pipes were connected to the solar collector and were used to transfer the hot fluid from the solar collector to the PCM to allow for heat transfer. Section A is enlarged in Fig. 12(c). The section represents a copper pipe serving two PCM sections.

Shukla [59] has designed two solar water heaters with paraffin as thermal energy storage material. One system had tank in tank type storage (Fig. 13) and the second had integrated type of storage using a reflector.

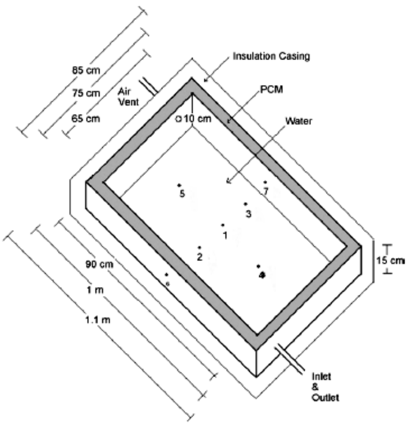


Fig. 13. Solar water heating system

The two systems were able to deliver hot water during the night and in morning on a 24 h cycle basis the two systems were found to be 45% and 60% efficient respectively. Galenen and Vanden [60] also used paraffin for domestic hot waters and space heating.

Mazman et al. [61] were performed tests under real operating conditions in a complete solar heating system that was constructed at the University of Lleida, Spain.

In this work, new PCM-graphite compounds with optimized thermal properties were used, such as 80:20 weight percent ratio mixtures of paraffin and stearic acid (PS), paraffin and palmitic acid (PP), and stearic acid and myristic acid (SM).

The solar domestic hot water (SDHW) tank used in the experiments had a 150 L water capacity. Three modules with a cylindrical geometry with an outer diameter of 0.176 m and a height of 0.315 m were used.

In the cooling experiments, the average tank water temperature dropped below the PCM melting temperature range in about 6-12 h.

During reheating experiments, the PCM could increase the temperature of 14-36 L of water at the upper part of the SDHW tank by 3-4^{o}C.

This effect took place in 10-15 min. It could be concluded that PS gave the best results for thermal performance enhancement of the SDHW tank (74% efficiency).

The effect of using the developed PCM on the thermal performance of the solar domestic hot water tank was also discussed.

EL Qarnia [62] was developed a theoretical model based on the energy equations to predict the thermal behavior and performance of a solar latent heat storage unit (LHSU) consisting of a series of identical tubes embedded in the PCM. During charging mode, a heat transfer fluid (hot water) from the solar collector passes through the tubes and transfers the collecting heat of solar radiation to the PCM. The heat stored in the liquid PCM is next transferred to water during discharging mode to produce heating water. A simulation program based on the finite volume approach was also developed to numerically evaluate the thermal performance of the LHSU. The model was first validated by comparing the results of numerical simulations to the experimental data. A series of numerical simulations were conducted for three kinds of PCM (n-octadecane, Paraffin wax and Stearic acid) to find the optimum design for a given summer climatic conditions of Marrakech city: solar radiation and ambient temperature. Optimization of the LHSU involves determination of the mass of the PCM, the number of tubes, and the flow rate water in solar collector that maximize the thermal storage efficiency. Several simulations were also made to study the effect of the flow rate water on its outlet temperature, during the discharging mode. The analysis of the results obtained in this research work shows that the use of n-octadecane as PCM is not beneficial because the outlet temperature of hot water is never greater than 28^{o}C. On the other hand with paraffin wax (P116), the outlet temperature of hot water varies within the range 36-47^{o}C but a part of the PCM remains liquid. The results also showed that the Stearic acid offers an acceptable range of the outlet temperature of hot water and fully discharge of the storage unit for an optimum mass flow rate of water and hence it is beneficial for the heating water application. Therefore, the selection of PCM should be done carefully in order to produce hot water in acceptable range of temperature.

III. Conclusion

Solar water heating system plays an important role in sustainable energy management in Indian households as well as worldwide. Such an effort will not only be useful in improving the quality of life but also in environmental protection. This review paper is focused on the past & current research of energy storage through PCMs for solar water heating systems. This paper will also help to find the suitable PCM and provide the various designs for solar water heating systems to store the solar thermal energy.

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