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REVIEW OF SOLAR THERMAL STORAGE TECHNIQUES

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ABSTRACT

For some time, solar energy has occupied ranked prime position in the renewable energy research field, due to the fact that it is an inexhaustible energy source. However, the main problem of solar energy is that it is an intermittent source, due to it dependence on the period of solar radiation. Consequently, thermal energy storage is considered a perfect option to solve this problem. A thermal energy storage unit works to enhance the conservation of energy and hence, improve the performance of the solar heating system. This paper reviews the literature concerning the usefulness of using the most important two core components in solar heat applications: thermal solar collectors and thermal energy storage systems. It includes a review and discussion of the different kinds of thermal solar collectors and thermal energy storage systems, including a latent heat storage system, a sensible heat storage system, and a hybrid heat storage system. The thermal energy storage systems are studied in terms of efficiency, thermal losses, the thermal conductivity of the material used for storage, and output temperature. The conclusions in this work suggest that latent heat storage through phase change material (PCMs) is better than sensible heat storage, due to the higher thermal energy storage density of PCMs. The conclusions also indicate that the use of paraffin wax as a PCM gives abetter performance compared to other phase change materials. In addition, the thermal performance of the solar heating system can also be enhanced by increasing the thermal conductivity of paraffin wax by adding other materials.

Keywords: thermal energy storage, solar air heater, solar water heater, phase change material.

1. INTRODUCTION

In recent years, the energy crisis and global warming has pushed scientists to search for alternative methods or alternative energy sources to overcome the problems of depleted energy resources. In developed countries, such as those in the European Union, around 40% of consumed energy emits CO2 due to energy consumption in buildings [1]. To solve this problem, renewable energy has been introduced to compensate the energy crisis and reduce the harmful emission effects of gases such as CO2 caused by global warming [2].

The solar energy is considered to be one of the most important sources for renewable energy due to the fact that it is an inexhaustible source. Furthermore, recent studies have confirmed that thirty minute of solar radiation on earth is equal to the world energy request for the whole year [3]. Therefore, solar energy is used in many applications, such as ventilation air preheating, space heating of buildings [4, 5, and 6], drying agricultural crops [7, 8 and 9] and water heaters in homes [10, 11, 12, and 13].

In order to be effective and productive, all the solar energy applications listed above must be integrated with a thermal energy storage unit. The function of a thermal energy storage unit is to absorb and store heat energy. Hence, solar heaters can be operated for a longer period of time during sunset [14]. Consequently, in recent years, several studies have focused on the development of solar energy systems, particularly the optimal use of solar radiation and the best ways to store solar thermal energy.

In this paper, three types of solar air heating systems and solar water heating systems are reviewed: latent heat storage system, sensible heat storage system, and hybrid heat storage system. Moreover, a review of the various storage media systems is presented, which focuses on the storage concepts, classification and materials. In addition, this article presents an exhaustive review of solar heaters integrated with PCMs for the two systems that are presented and discussed. Finally, it suggests directions for future developments.

2. SOLAR ENERGY COLLECTORS

Solar energy collectors work mainly through the absorption of solar radiation, which they turn into heat, after which the heat transfers to water or air mediums. In general, solar energy collectors can be classed into three types: flat-plate collector, evacuated tube collector and concentrating collector.

Solar energy collectors can also be classified based on their method of work, which can be positive or negative. The positive type uses an electric pump to distribute the heat transfer fluid, while the negative type operates without a pump. Consequently, both types may be used in all types of collectors whether they be flat-plate, evacuated tube or concentrating.

The solar energy collectors can also be grouped into direct or indirect types. A direct type of solar water heating system distributes domestic water during collectors but is inappropriate for frigid atmospheres. The indirect type, on the other hand, is used for heat transfer fluid [15]. Figure-1 illustrates a comparison between the collector efficiency for different types of solar energy collectors. The sections below outlines the different types of collectors in more detail.

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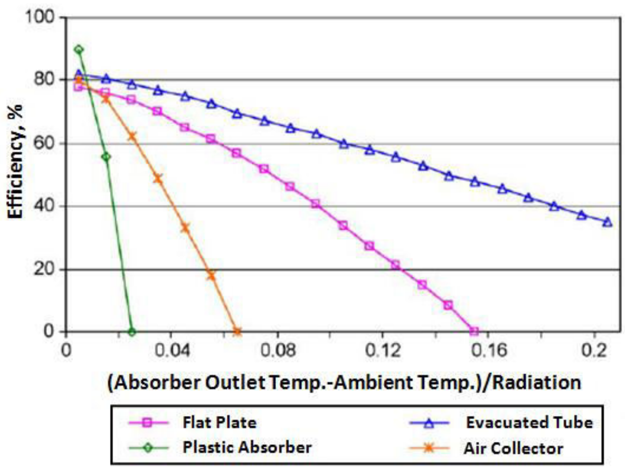

Figure-1. Thermal efficiency curves for four types of solar thermal collectors [15].

A. Flat-plate collectors

Flat-plate collectors are considered to be the more vastly common and used type of collector in solar heating systems applications. Flat-plate collectors are used in applications when high temperature of more than 75 ºC are required. The flat-plate collectors are characterized by their high efficiency compared with other types of collectors [16].

B. Evacuated tube collectors

Evacuated tube collectors differ from other types of collectors due to their vast difference in terms of design and operation. Evacuated tube collectors mainly consist of glass tubes. Any tube contains two layers: an outer layer made of glass and an inner layer which consists of an absorber plate to solar radiations. The tubes are the main configuration for evacuated tube collectors. Evacuated tube collectors are characterized by their ability to reduce convection and thermal conduction losses due to the space between the tubes, which makes them a heat insulator [17].

C. Concentrating collectors

The Parabolic dish collector is very effective due to its design, which uses a reflective parabolic form surface to mirror and focus the solar radiations to a focal point or focal line. consequently, the Parabolic dish collector can achieve very high temperatures due to its ability to diffuse solar radiation in a small area [2].

3. THERMAL ENERGY STORAGE

In spite of the fact that solar energy is very effective in providing energy compared to other renewable energy sources, its major problem lies in the fact that the sun is an intermittent source. As energy depends on the period of solar radiation, thermal energy storage is considered the perfect solution to solve this issue of intermittent solar radiation. Thermal energy storage works by enhancing the conservation of energy and developing the performance of the heating of solar energy [18]. There are two types of thermal energy storage systems. The first one is a latent heat thermal storage system, and the second is a sensible heat thermal storage system. The latent heat thermal storage system can be classified as solid to liquid, liquid to gas, and solid to solid, while the sensible heat thermal energy storage system includes liquid materials or solid materials [19, 20, 21, and 15].

The advantages of the latent heat storage system are its ability to provide high energy storage, work in constant temperature [7], its large capacity per unit volume and unit mass, its efficiency in working for long durations [18], and low energy loss through isothermal methods due to its charging and discharging operations [10]. On the other hand, the sensible heat storage system is used due to its good chemical properties. However, it is not used commercially, due to its inefficient heat transfer rate and high cost [22].

The phase change material is used as a storage medium which increases the capacity of the latent heat storage and makes the system roughly one hundred times more efficient than the sensible heat storage. Moreover, the important factor that distinguishes the latent heat storage from the sensible heat storage is its smaller size yet with the same amount of heating [23]. Therefore, the PCM integrated with the latent storage is the most common in heating solar systems.

3.1 Phase change material storage system

One of the most significant things to emerge from this study is the investigation of the effect of using PCMs in thermal energy storage. Many types of research have shown that when solar energy is stored in the form of latent heat by using PCMs, it gives a good performance. This is due to the fact that the PCMs provide suitable temperature rates during the melting and freezing processes. Consequently, using PCMs is a more effective way to meet the request of energy and balance between request and supply of energy [24].

Many researchers have argued that solar heating systems integrated with a thermal energy storage unit are used for various types of PCMs.

A numerical analysis by Fath [25] was carried out to investigate the performance of a thermosyphon solar air heater with a built-in latent heat storage system using a PCM. The melting temperatures of the PCM were found to be 61°C, 51°C, 43°C and 32°C respectively. The author compared the solar air heater performance with and without a thermal energy storage unit. The results of the numerical analysis indicate that the solar air heater which used a PCM at melting temperatures of 51°C and 43°C had a better performance. The results also show that when the melting temperature of the PCM was 43°C during the night period, the minimum discharge process of the thermal load from the air heater was equal to 0.01 kg/s at a mass air flow rate of 30 m^3/h. Furthermore, the average efficiency of the solar air heater varied between 27% and 63.8% depending on the melting temperature of the PCM.
An experiment was carried out by Krishnananth and Kalidasa [26] to check the performance of the double pass solar air heater integrated with a thermal storage system.

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In this experiment, paraffin wax was used as a thermal storage medium in four configurations. The first configuration was used without a thermal energy storage system, the second configuration used capsules which were placed above the absorber plate, the third used capsules which were placed below the absorber plate, whereas the fourth placed capsules above the back plate. Consequently, the author shows that the efficiency of the air heater with thermal storage was higher than the air heater without a thermal storage system. Moreover, the solar air heater with the second configuration performed better than the other configurations.

In the field of drying agricultural crops, an experimental study was carried out by Esakkimuthu *et al.* [7]. The set-up of the experiment is depicted in Figure-2. The author investigated the use of HS 58, an inorganic salt, as a PCM in solar air collectors to store surplus solar thermal energy. The melting and freezing temperature of the PCM were 58°C and 57°C respectively, while the air mass flow rate used three different values: 200 kg/h, 300 kg/h, and 400 kg/h. The author found that the heat losses correlated with the decrease of the middle temperature of the collector, resulting in a higher efficiency of the collector and an increase in the value of the heat transfer at the mass flow rate of 400 kg/h. The author also found that at the mass flow rate of 200 kg/h, it was capable of providing a near regular rate of heat transfer through charging and discharging processes. Consequently, the low mass flow rate is capable of using the maximum capability of the storage system and equipping heat for a longer period.

Figure-2. Experimental setup of solar air collector suggested by [7].

The design of the air heating solar collector integrated with paraffin wax and an embedded aluminum matrix as a PCM melting temperature of 58°C was used for energy storage in a humidification-dehumidification-desalination cycle. This study was carried out by Summers *et al*. [23] to produce consistent air outlet temperatures throughout the day or night by using a built-in phase change material storage. The ADINA simulation was run at a mass flow rate of 46.8 kg/h and the PCM was placed under the absorber plate directly at six different PCM depths: 4 cm, 6 cm, 8 cm, 10 cm, 12 cm, and 14 cm. It showed that the depth of the PCM 8cm layer performed better than the other cases, as it was enough to produce a consistent output temperature close to the PCM melting temperature with a time and 35% thermal efficiency of the collector. Therefore, the experiment selected an 8cm thick PCM layer to built and test in a set of weather and operating conditions. The experimental set-up for the air heating solar collector is visible in Figure-3.

Figure-3. Solar air heating collector integrated with paraffin wax [23].

A solar air heater was used as a PCM for a thermal storage unit and consisted of 5% paraffin wax and aluminum powder. This achieves a theory submitted by Mahmud et al. [27]. Composites are used for solar heat storage by encapsulating the composite in cylinders working on the solar absorber. The air mass flow rate was set between 0.05 kg/s to 0.19 kg/s. The theoretical investigation found that the increase in mass flow rate decreased the output air temperature and the mass flow rate effect discharged the time mass flow rate. When the mass flow rate was 0.05 kg/s, it took longer to discharge (around 8 hours), while the mass flow rate of 0.19 kg/s took a short time to discharge (around 3.5 hours). The author also found that the performance of solar air heater increased when adding the aluminum powder to paraffin wax better than using pure paraffin as a PCM. Figure-4 presents the cross-section of the solar air collector with PCM cylinders.

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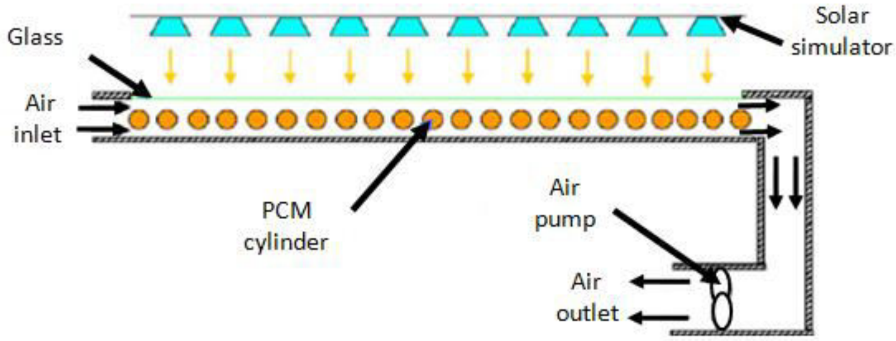

Figure-4. Cross section of the solar air collector with PCM cylinders [27].

An experimental investigation by Alkilani et al. [28] was conducted at the same conditions as the previous study presented by [27]. It assessed the indoor performance of a solar air heater integrated with a paraffin wax-aluminum composite as the PCM. The experiment used various values for the mass flow rates: 0.03 kg/s, 0.05 kg/s, 0.07 kg/s and 0.09 kg/s. The results indicated that the charging time was reduced at the rate of around 70%. In addition, the thermal storage efficiency attained the maximum value 71.9% when the mass flow rate was 0.05 kg/s for pure paraffin wax and 77.18% when the mass flow rate was 0.07 kg/s for the paraffin wax-aluminum composite. Accordingly, this means that adding aluminum to the wax gives better storage efficiency the use of pure wax.

A particular type of thermal storage exchanger has been established as a heat storage device for heating buildings. Various experimental investigations have been conducted by Feng *et al*. [4] to assess the performance of a thermal storage exchanger in two cases for PCM. The first case used capric acid, and the second case used a composite of capric acid and float stones as an energy storage medium. The experimental results showed that the use of float stones with capric acid raised the thermal conductivity of PCM by 250%. Hence, the inner temperature decreased from 51°C to 32.8°C, while the outer temperature increased from - 9°C to 0°C. This change quotient between inner and outer temperatures led to the attainment of more than eight hours of fresh air.

An experimental and numerical investigation was also carried out by Charvat [29] to check the thermal performance of a solar air collector with latent heat storage integrated with a solar absorber plate. The experimental solar collectors are shown in Figure-5. Paraffin was used as a PCM and placed in aluminum containers to assess the storage of solar thermal energy, while the flat plate collector was used to absorb solar radiation. The aluminum containers and the flat plate collector were designed side by side with the same tilt, orientation and dimensions. Through experimental and numerical investigations, the author found that the solar air collector integrated with the latent heat storage led to stability in the outlet air temperature of the collector. Likewise, it obtained the best efficiency of the collector. The results also show that the high efficiency of the collector integrated with PCM can reduce heat loss by less than the average air temperature.

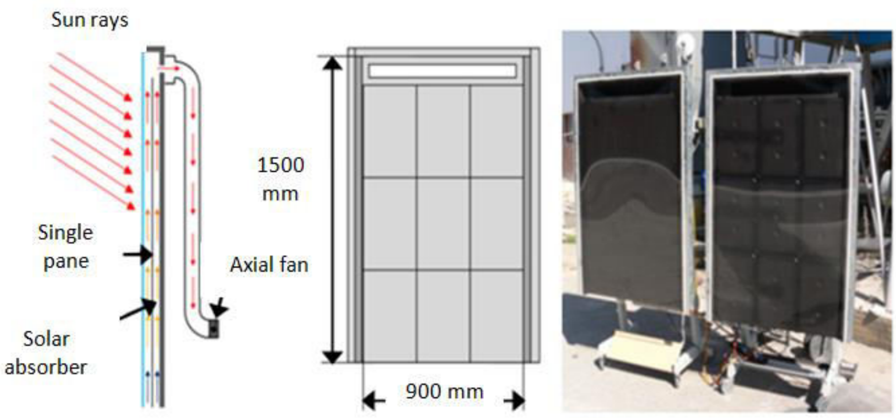

Figure-5. Experimental solar collectors integrated with PCM [29].

An experimental investigation was conducted by Chun and Hussain [30] for the extension of the operational time of a solar water heating system during thermal energy storage. This was verified by an outdoor experiment involving a flat plate solar collector integrated with paraffin wax as a PCM, as shown in Figure-6. The melting and solidification point of the paraffin wax that was used were 60.45°C and 58.84°C respectively. The author compared two cases: with and without PCM. The results of the present study suggest that the system efficiency was 52% when the inclination angle of the surface collector was 10° and the mass flow rate was 0.5kg/min. However, the system efficiency was 51% when the inclination angle of the surface collector was 20° and the mass flow rate was 0.5 kg/min. Furthermore, both inclination angles (10° and 20°) provided about 38°C temperature hot water during daytime. The results also proved that the 10° inclination angle harvested the solar radiation more. Hence, it helped to melt the PCM faster.

Figure-6. Solar water heater system integrated with PCM [30].

The evacuated tube solar collector is a successful and good technology that is widely used in the applications of solar heaters. To demonstrate the potential of this approach and its suitability for the application of solar heaters, an experimental investigation was conducted by Mehla and Yadav [17] to explore the evacuated tube solar air collector when compared with the latent heat storage for producing hot air. It used acetamide as a PCM with a melting temperature of 81°C. The author displayed three configurations for the heat exchanger: the ordinary collector, the ordinary collector with the copper coil, and the ordinary collector with circular fin. They investigated two different air flow rates: 0.018 kg/s and 0.035 kg/s. The results of the present study suggest that the maximum temperature that was identified between the heated air and the ambient air was 37°C during daylight hours and 20.2°C during the night hours in the circular fin configuration with an air flow rate of 0.018 kg/s. The present findings also suggest that the efficiency at an air flow rate of 0.018 kg/s was 0.05–0.5 times less than air flow rates of 0.035 kg/s. Accordingly, it considered the circular fin configuration to be better than the other configurations, as it can be used after sunset for the highest thermal storage efficiency.

Experimental investigations were also conducted by Bharath *et al*. [31] to analyze the thermal performance of solar flat plate collectors with and without paraffin wax as a PCM. The paraffin wax was combined with the thermal energy storage unit to determine the performance of the integrated collector storage solar water heater (ICSSWH). The melting point of the paraffin wax was set at 60°C. The author found that the use of paraffin wax in the solar water heater gave high thermal efficiency for a longer period, high thermal storage capacity, and a good performance during the charging and discharging processes. Thus, the use of paraffin wax in the solar water heater is better than a conventional solar water heater. The author also indicated that the aforesaid thermal storage system can be used in many applications, such as water heating and building heating, due to the fact that it is cost-effective.

Mathematical analysis was also carried out by Chen *et al.* [32] for the energy storage process of a solar flat plate collector integrated with an aluminum foam porous structure Paraffin wax was used as a PCM. This study focused on the analysis of the heat transfer between the metal foams and paraffin wax in solid and liquid phases at a two-temperature model. Analysis of the results showed that two cases were used: paraffin wax with aluminum foams and pure paraffin wax. The results reveal that the use of paraffin wax with aluminum foams significantly influenced the heat transfer and melting rate of the paraffin wax. The results also show that the temperature distribution in the paraffin wax with aluminum foams was more uniform than that of pure paraffin, as illustrated in Figure-7. Accordingly, the use of paraffin wax with aluminum foams wasbetter than pure paraffin wax due to its high thermal conductivity.

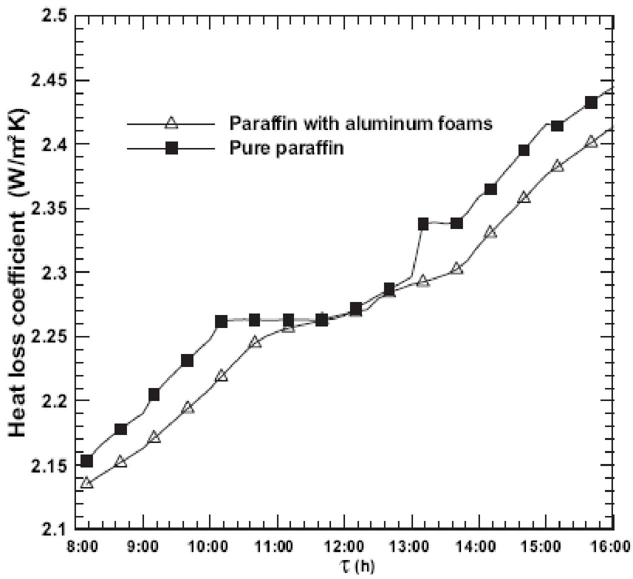

Figure-7. Difference of the heat loss coefficient of thermal collector versus time [32].

An investigation was undertaken by Malan *et al.* [33] for the design of an experimental storage module and

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its use in solar tower technology. An experimental storage module was tested through heat absorption and heat removal cycles. In addition, a numerical analysis was carried out to model the experimental storage module. The author identified the parameters for a specific phase change storage unit in the application of a solar tower with high temperatures. The author found that the numerical simulation indicated that the solar tower technology provides a high-temperature heat source. The author also found that the melting or solidification rates for the PCM need to be exposed to a sufficient heat transfer area. Hence, the author identifies the size and geometry of the solar thermal storage system from this analysis.

In the field of water heating technology for homes in the cities, experimental investigations have been carried out by Koyuncu and Lüle [34] on the domestic type of a 304 stainless steel chromium flat plate solar water collector integrated with paraffin wax as a PCM. The melting temperature point of the paraffin wax was 55°C, the fluid flow was 0,02 kg/s.m^2, the melting latent heat was 50 kcal/kg and the density was900 kg/m^3. The flat plate solar water collector was directly linked to the pressurized city water line unit, as shown in Figure-8. To identify the performance of the solar collector, it was tested during the day and night. The results suggest that the thermal efficiency of the solar collector was 12.5% when the fluid was stored and 62.0% when it flowed. Furthermore, the author stated that the chromium type collector was better than the aluminum and copper type collectors, due to its many advantages, which include the fact that it does not impact on chemical compositions of the water, it keeps a hot water temperature inside the solar collector after sunset, its cheap price, the fact that it does not need maintenance, and it has a high thermal efficiency.

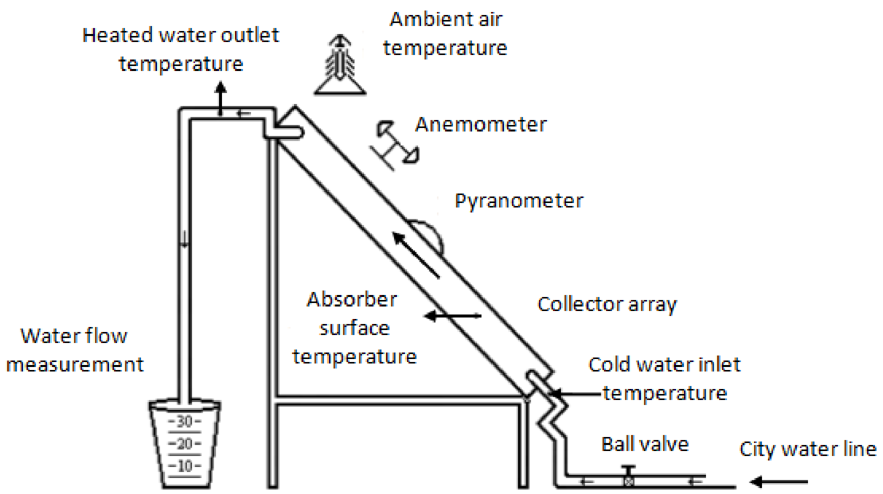

Figure-8. Schematic offering of experimental solar thermal collector [34].

Numerical simulations were carried out by Rudolf *et al.* [35] for two different types of solar air collector: front and back pass. The first type was a solar collector with a light-weight solar absorber made of a simple metal sheet 0.5 mm thick with a thermal conductivity of 40 W/m.K, while the second type was a solar collector with an absorber containing the PCM. The melting temperature point of the PCM was 40°C and the latent heat was 180 kJ/kg. The author provided an in-depth simulation to assess the performance of the air collector model by using TRNSYS as a simulation tool and using the MATLAB to create a model for heat transfer in the PCM. The results of the numerical simulation indicate that the thermal energy storage in the PCM will lead to a reduction in air temperatures at the outlet of the solar collector during the day. The results also show that the heat stored during the day in a PCM when released during the night will lead to a rise in air temperatures.

An experimental and theoretical investigation was proposed by Saman *et al.* [36] to study the thermal performance of a phase change thermal storage unit (TSU). The TSU is used to heat buildings. The TSU consists of many layers in the form of slabs filled with PCM at a melting temperature point of 29°C. The hot air passes through the spaces between the layers filled with PCM to charge the TSU, as shown in Figure-9. In the study, the author focuses on the impact of charging and discharging periods to analyze the transient thermal behavior of the TSU. The author also takes into consideration the impact of sensible heat during the melting or freezing of a PCM when the temperature of a PCM is below or above the temperature melting point. The results reveal that the high inlet air temperature raises the heat transfer rates and reduces the melting period. On the contrary, the low inlet air temperature raises the heat transfer rates and reduces the freezing period. The results also reveal that the high air flow rate raises the heat transfer rate and reduces the melting period, which leads to an increase in the outlet air temperature. However, at freezing the high air flow rate raises the heat transfer rate and reduces the freezing period, which leads to a reduction in the outlet air temperature. Furthermore, the author indicated that there is a good agreement which has been validated through comparing the model employed and the experimental data.

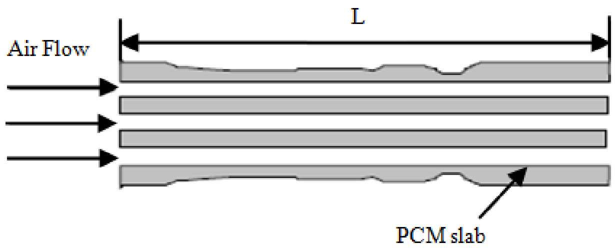

Figure-9. Layout for the thermal storage unit [36].

A numerical simulation was performed by Waqas and Kumar [37] to analyze a solar air heating system integrated with PCM to heat buildings and provide comfort conditions during the winter season. In this work, the author used a combination of salt and paraffin wax as a PCM. The analysis was conducted with differing melting point temperatures of a PCM: 19°C, 21°C, and 23°C. It also used differing mass air flow rates of 10 m^3/h, 15 m^3/h, and 20 m^3/h respectively. The results of the numerical simulation indicate that the best performance of the thermal storage unit was when the melting point temperature of the PCM was equal to the medium comfort temperature of winter months. Therefore, when the melting point temperature of a PCM deviates away from the comfort temperature, it will lead to a retreat in the performance of the thermal storage unit.

An experimental investigation was conducted by Smolec [38] to explore the performance of a solar air heater with a box-type absorber integrated with a heat storage unit. Paraffin wax was selected as a PCM in the heat storage unit. To improve the thermal conductivity of the PCM, the author suggested the use of a thin aluminum strip matrix structure in the paraffin wax. The results of this experimental investigation indicate that the efficiency of the solar air heater without paraffin wax is 40%, while with paraffin wax it is 42%. When a thin aluminum strip matrix structure is used in the paraffin wax, it is 44 %. The results also show that the solar air heater was able to increase the air temperature 5°C higher than the ambient air temperature for more than one hour after sunset.

Numerical simulations were performed by Bouhssine *et al.* [39] to optimize the building integrated solar collector with PCM. The author focused on an enthalpy method through the development of a mathematical model to control the thermal behavior of the solar collector integrated with PCM. In addition, the thermal conductivity for the PCM was optimized through repeat simulations. The results of the numerical simulation indicate that the optimization of the thermal conductivity for the PCM leads to a decrease in the internal air temperature from 40°C to 30°C. However, the outlet air temperature from the collector and the ambient air temperature were equal to 70°C and 15°C respectively. Accordingly, the solar thermal energy storage unit integrated with PCM was established, which provides a comfortable temperature in living spaces during the winter season.

A numerical simulation was presented by Guo [40] to analyze the enthalpy-porosity model. The author identifies the influence of the heat transfer enhancement of nanoparticle enhanced high-temperature phase change materials (ENHTPCM) where alumina (Al_2O_3) nanoparticles are placed in high-temperature phase change material (HTPCM). The results reveal that the thermal energy storage rate of ENHTPCM is better than conventional HTPCM due to an increase in the thermal conductivity and melting rate for the ENHTPCM. Hence, it will lead to an improvement in the efficiency of heat transfer.

3.2 Sensible thermal energy storage system

Sensible heat storage materials are described as a set of materials that do not change the phase when there is varied temperature during the storage process. Accordingly, water can be to store solar thermal energy [20].

The essential ingredient of a solar water heating system is the solar collector that works by absorbing solar radiation and then converting it to heat. After the fluid (water or air) is absorbed and this heat crosses the collector by heat transfer. The heat gained can be used immediately or stored [3].

Several studies investigating performance have been carried out on sensible thermal energy storage systems by using different materials as a storage medium.

An experimental study published by Gupta and Tiwari [41] has primarily concentrated on prophecy room air temperature, storage water temperature, and the impact of thermal energy storage on the mass of water. This experimental study has used a tank to store water with dimensions of 90 mm height and 55mm diameter. The tank was painted black and placed in the center of a greenhouse. The author observed that the mass of water affected significantly the thermal energy storage and room air temperature. The author also found that the mass of storage water increased when decreasing the thermal load, and changed at any month of a year.

A mathematical model was designed by Betrouni *et al.* [42]. The main aim of this model was to heat water by using sensible heat to store thermal energy in the water. Consequently, the author used an insulated storage tank with a capacity of 800 liters. To study the thermal conduct of the insulated storage tank, a mathematical model was developed based on the finite difference with the experimental method. The insulated storage tank was connected with 8 flat plate collectors. Each collector was 1.8 m, and consisted of two glazing surfaces. The research found that the mathematical model was perfectly passable. Accordingly, this simulation can be used in a variety of configurations for flat plate collectors. The best configuration to increase the temperature of the water inside the insulated storage tank was also defined.

Experimental and numerical investigations have been out by Taheri *et al.* [43] for solar water heaters integrated with a water tank to equip hot water in homes.

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This study focused on determining solar thermal performances during the absorption of solar radiation for enhanced heat transfer. Figure-10 illustrates the materials used for theabsorption of solar radiation as a cover glass, black sands and V-shaped galvanized plate all submerged in the water tank. The results reveal that the thermal efficiency was higher than 70% due to the rate of stored energy being more than the rate of consumed energy. The results also show that there are good agreements between the experimental and numerical results.

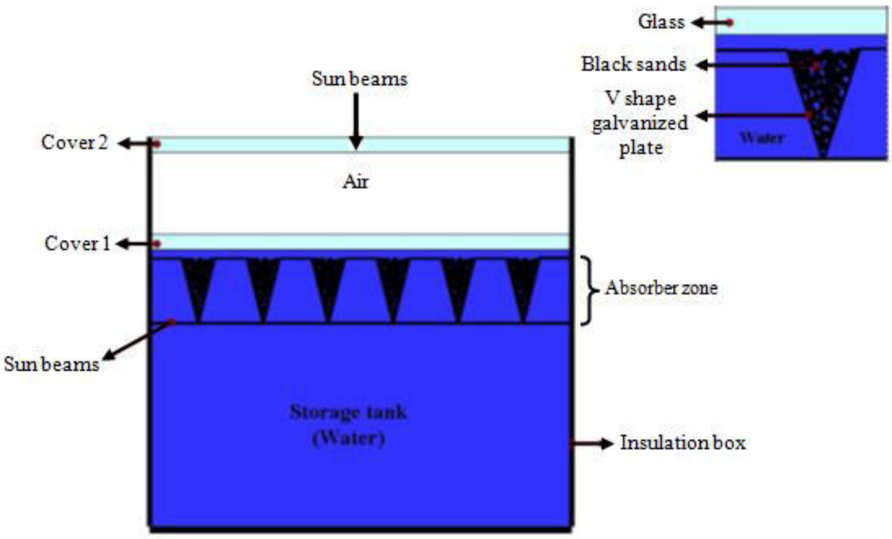

Figure-10. Experimental model for solar water heaters integrated with a water tank [43].

A mathematical model was created by Temperatures and Bonanno [44] to store thermal energy as sensible heat in the diathermic liquid at median temperatures. The aim of the work was to investigate the effect of different design parameters on the thermal discharge of the accumulator by conducting a parametric analysis of the model to diagnose the thermal losses of the storage tank. The author studied the accumulator discharge function at various forms during a period of 170 hours in order to determine the effect of the thermal insulation for an accumulator. Furthermore; the author concluded that the storage tank could achieve an increase in volume up to 9 m^3 during the lengthy process and a steep decline of the partial discharge. After this value, the effects of saturation appeared. The author also found that a thermal conductivity below 1 MKS unit gave a good performance when the thickness of the insulation was less than 0.5 m.

An experimental energy and exergy analysis was carried out by Kalaiarasi *et al.* [45] on solar air heaters at two various configurations: with and without sensible heat storage, as are illustrated in Figures 11 A and B. The absorber plate consists of copper tapes and copper tubes filled with a high-quality synthetic oil (Therminol-55) inside. The author compared the performance of two various configurations in the same experimental conditions, including location, time and quantity of solar radiation received. Moreover, the experiments were executed at two various mass flow rates of 0.018 kg/s and 0.026 kg/s. The author found that the best efficiency obtained was 49.4 %-59.2 % in energy and 18.25 %-37.53 % in exergy for solar air heaters with sensible heat storage when the mass flow rates were 0.026 kg/s. Therefore, the performance of solar air heaters with sensible heat storage was better than the conventional solar air heater without storage.

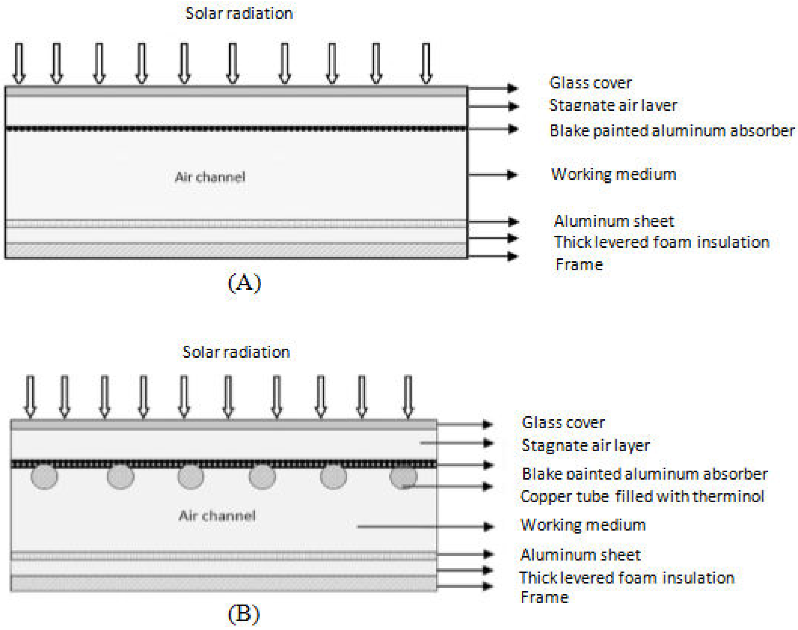

Figure-11. Solar air collector; (A) without sensible heat storage system, (B) with sensible heat storage system [45].

A numerical investigation was carried out by Ferone et al. [46] to study the effect of sensible thermal energy storage systems using a solid medium to improve the performance of high buildings. A storage system was used to test lightweight concrete. To study the behavior of the storage system, the author used afinite element method. The numerical simulation focused primarily on thermal properties at high temperature, the geometry of the storage element and the storage cycle adopted. The results of this numerical simulation indicate that the selected materials contributed to a decrease in material weight and an increase in the specific heat capacity. The results also show that the thermal properties greatly affect the performances of the storage elements. Hence, the thermal storage was evaluated and the thermal properties required to improve the storage system were identified.

3.3 Hybrid thermal storage system

The hybrid storage system combines latent and sensible heat thermal energy storage systems. The hybrid thermal storage system has an effective impact on the storage of thermal solar energy. It provides the optimum solution to overcome the problem of intermittent solar energy. It has many advantages, including a great heat storage capability in a unit volume and isothermal conduct through the charge and discharge processes [10]. Therefore, recently, many scientists have used hybrid storage systems.

An experimental investigation by Reddy *et al.* [10] was carried out using both latent and sensible thermal energy storage systems. The author used various values for mass flow rates: 2 lit/min, 4 lit/min, and 6 lit/min, and used two types of PCM (paraffin wax and stearic acid). The PCM was encapsulated in spherical capsules at several sizes in diameter: 68 mm, 58 mm, and 38 mm. The experimental investigations focused on charge and discharge processes. The results indicate that the different values of mass flow rates of heat transfer fluid do not greatly affect the charging process, due to the fact that the period of the charging process is a long period of roughly four hours. However, in a discharging process, there was not a significant difference in the amount of thermal energy recovered from various values in the mass flow rates of heat transfer fluid. For example, in the discharging process at a mass flow rate of 6 lit/min, the average temperature rose and the amount of thermal recovered dropped, while at a mass flow rate of 2 lit/min, the average temperature dropped and the amount of thermal recovered rose. The author found that the spherical capsule with a diameter of 38 mm gave the best performance compared to other diameter spherical capsules. The author also found that paraffin wax gave a better performance than stearic acid as a PCM during the charge and discharge processes.

The performance of solar water heating systems was studied by Al-Hinti *et al.* [18] using both latent and sensible heat thermal energy storage. The thermal storage unit included water and paraffin wax as a PCM. Paraffin wax was placed in small cylindrical aluminum containers at two levels inside the isolated water storage tank, as shown in Figure-12. The experiments were carried out in two cases: with and without a PCM and help of an electrical heater. According to the investigation by author, it proved that when using latent and sensible heat thermal energy storage together, the water temperature will be maintained above 45°C under all operational and climatic conditions. Moreover, the author found that when using the combined sensible and latent thermal energy storage, the stored hot water temperature was 30°C higher than the ambient temperature during the experiment consumption of 24 hours. The PCM compensated the temperature of

VOL. 12, NO. 21, NOVEMBER 2017 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

water lost due to consumption after sunset. Hence, this leads to an increase in the operation time of the system during the night hours.

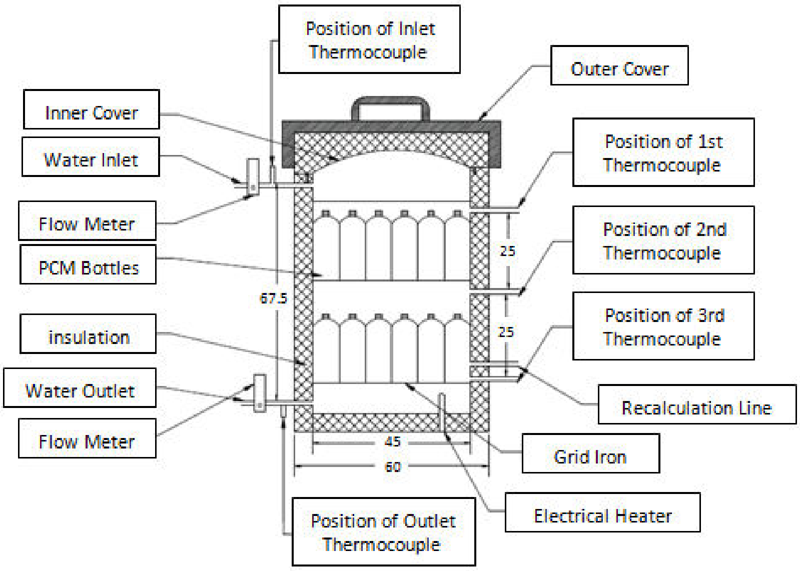

Figure-12. Cross-sectional of the isolated water storage tank integrated with PCM [18].

Experimental investigations were carried out on the combination of latent and sensible thermal energy storage Nallusamy *et al*. [47]. The thermal energy storage unit consisted of paraffin stuffed in spherical capsules as a PCM. The spherical capsules were placed in an insulated cylindrical storage tank, visible in Figure-13. The water was used to transfer heat from the constant temperature at the solar collector into the thermal energy storage tank where the water acted as a sensible heat storage material. The influences of the inlet fluid temperature and theflow rate of heat transfer fluid on the performance of the thermal energy storage unit were tested during charging in constant and variable inlet fluid temperatures. Stored heat recovery occured during the discharging process by both uninterrupted and batch-wise processes. The author also demonstrated that the mass flow rate has a little influence on the rate of charging when the case of constant inlet heat transfers fluid temperature. However, the mass flow rate had a large influence on the heat remove rate from the collector when the case of the storage unit was integrated with the solar flat plate collector. The author also found that the rate of heat transfer increased when the inlet temperature of the heat transfer fluid increased. Furthermore, the author concluded that the common storage system performed better than the conventional sensible heat storage system, due to a direct mixing of the heat transfer fluid with the hot water in the storage tank.

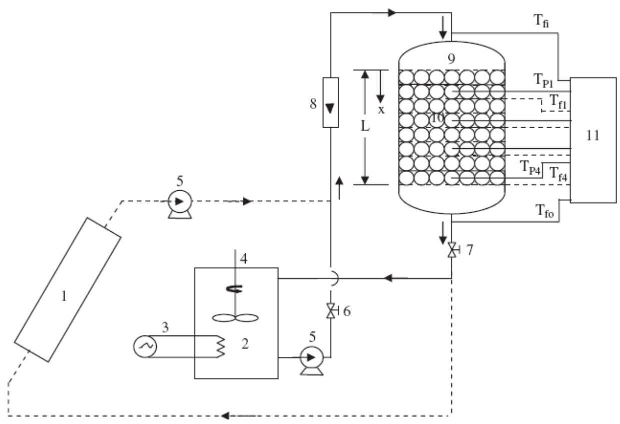

Figure-13. Schematic of the experimental solar water heater integrated with PCM capsules [47].

Experimental investigations were carried out by Pandiyarajan *et al*. [48] on a diesel engine to measure the amount and quality of energy extracted from it and stored. The energy was stored using both latent and sensible heat storage systems. Castor oil was used as sensible heat storage and paraffin wax as latent heat storage. Figure 14 illustrates the system of a thermal storage tank. The author studied the performance of the energy and exergy analysis of the diesel engine with PCM. The results show that determining the real losses of thermal energy devices like a diesel engine could develop the device in a systematic approach. The author recommended using different PCMs to store energy, to increase the competencies of energy and exergy from the highest temperature to the lowest temperature.

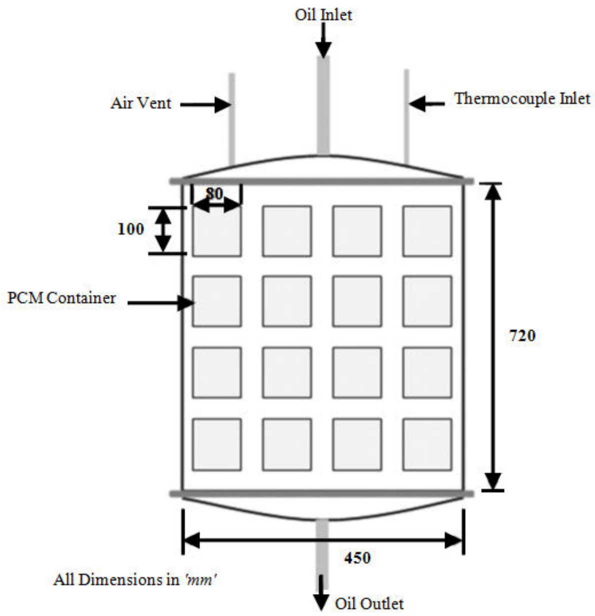

Figure-14. Thermal storage tank with PCM container [48].

An experimental investigation was conducted by Bhale *et al.* [49] to determine the effect of using latent and sensible thermal energy storage systems together to the performance evaluation of a concentrating solar collector. It focused on the charging efficiency and overall efficiency of the system performance. A heat exchanger was designed, which contained stearic acid as a PCM and the surface of area of the concentrating solar collector was 16m^2. The results show that charging efficiency increased in the morning until it reaches a peak at noon and decreases after that. It was also found that the highest value of the charging efficiency was 48.5% at noon without the PCM and 60.19% in afternoon with the PCM. As for the overall efficiency, it was up to the highest value of 27.47% at noon without the PCM and 31.88% in the afternoon. Furthermore, in the tank, the highest temperature reached when the system was without a PCM was 130°C. Finally, it was found that when combining latent and sensible thermal storage systems, the total time interval to reach 65°C in the same conditions was 150 minutes more than the sensible storage system.

An experimental and theoretical investigation by Nallusamy and Velraj [50] was conducted to explore the thermal performance in the solar water heating system integrated with combining latent and sensible heat energy storage The experimental study investigated the use of paraffin as a PCM, which was filled in high-density polyethylene spherical capsules integrated with a solar flat plate collector. The water was used as a sensible heat storage material to transfer thermal energy from the solar flat plate collector to the storage tank. The model achieved the real conditions of the solar flat plate collector by using varying values for the fluid inlet temperature and varying values of mass flow rates. The results of the numerical simulation and experiment indicate that the mass flow rate greatly influences the heat extraction rate from the collector and the rate of charging of the thermal energy storage tank. Accordingly, the results show that there is a large convergence between the numerical results and experimental results.

A numerical investigation was conducted by Ismail and Stuginsky [51] to compare four models used in latent and sensible thermal energy storage systems. The models were the continuous solid phase model, Schumann's model, the single-phase model and the model with a thermal gradient inside the particles. These four models were compared in terms of the impact of particles' size, void fraction, particles material, the difference in flow rates, changes in temperature of fluid entering and thermal losses in the wall. The focus was on calculating the time consumed for each model to solve a test problem. According to an investigation by the author, it was found that the model with a thermal gradient inside the particles consumed more than twenty times the computing required by Schumann's model. The results also show that an increase in particle size also has a significant impact on the model with a thermal gradient inside the particles. The difference in flow rates have very little impact on the results ofall models, but the changes in temperature of the fluid entering it have a significant impact on the results of all models. Furthermore, the void fraction directly impacts on the heat ability of the storage system in all models.

A numerical analysis of the energy and exergy was carried out by Caliskan et al. [52] to explore the model integrated with thermochemical and sensible thermal energy storage systems This was done to demonstrate the potential of this approach and its suitability for building heating applications. Three different temperatures were verified: 8, 9°C and 10°C. The system basically consisted of a floor heating system, system-A, and system-B. The floor heating system contained a floor heating unit, a pump and an energy receiver unit, system-A encompassed a solar collector, a thermochemical, a pump, a heat exchanger and a hot well of aquifer thermal energy storage, while system-B included a heat pump and a cold well of aquifer thermal energy storage. The schematic system of the proposed is shown in Figure-15. The results of the numerical analysis indicate that the maximum exergy efficiency is obtained for the hot well of aquifer thermal energy storage at 88.78% at 8°C temperature, while the minimum for the charging process of thermochemical thermal energy storage was 21.69%. The results also show that the highest exergy efficiency obtained was 98.08% at a temperature of 8°C when the operating system was in all components. Furthermore, the results of the study found that the aquifer thermal energy storage system was more efficient than the thermochemical thermal energy storage system.

VOL. 12, NO. 21, NOVEMBER 2017 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

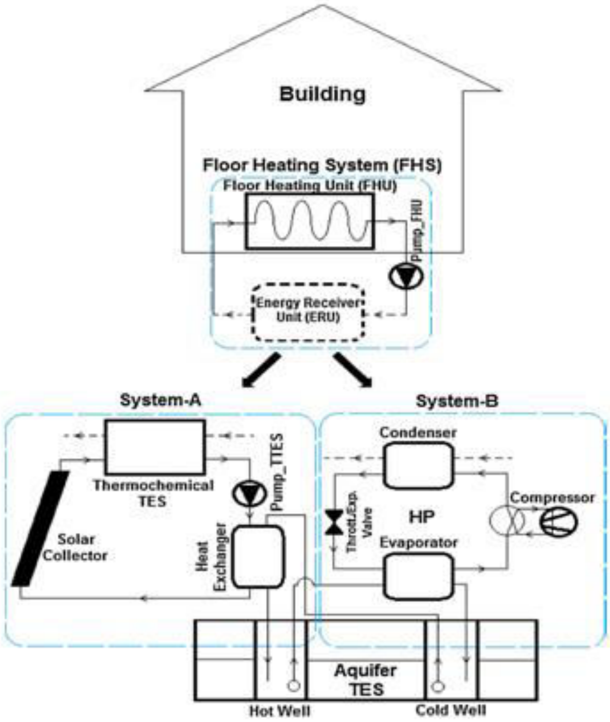

Figure-15. Layout of the suggested system by [52].

A numerical investigation was carried out by Zhou *et al.* [53] to study a hybrid heating system combined with thermal storage using shape-stabilized and phase change material (SSPCM) plates. The simulation was executed on a solar house, which contained SSPCM plates placed in the inside linings of walls and the ceiling. The simulation was used to verify a enthalpy model during the winter. The numerical tests were conducted through late night and early morning to keep the air temperature over 18°C inside the house. The results of the numerical simulation indicate that the use of SSPCM plates provides 47% of normal energy and 12% of overall energy consumption during the winter. The author also found that the use of a hybrid heating system, such as SSPCM plates, improved the level of thermal comfort inside the house.

An experimental investigation was conducted by Sharshir *et al.* [54] to modify the conventional solar still for producing fresh water. The experimental tests were implemented outdoors. The modifications for the conventional solar still include using PCM, film cooling and flake graphite nanoparticles (FGN). The experimental set-up can be seen in Figure-16. The results reveal that the presence of the three previous modifications will enhance the production of fresh water by more than 73.8% compared with the conventional solar still. The author also studied the effect of water depth on productivity. It was found that productivity increased by 13% when the water depth decreased from 2cm to 0.5cm.

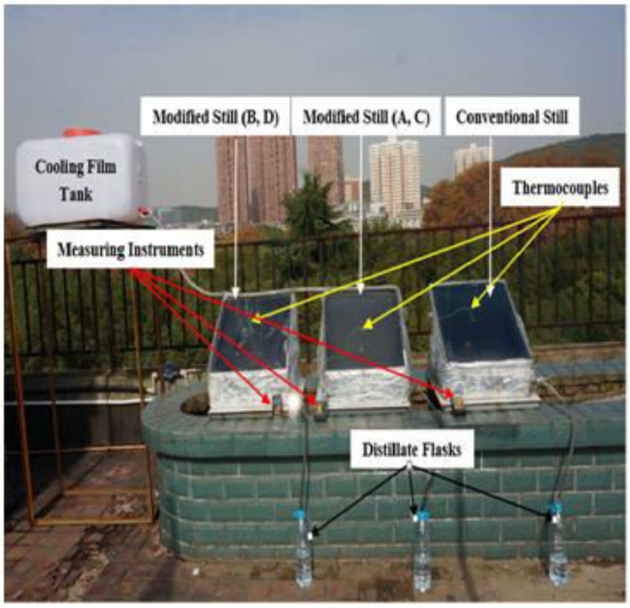

Figure-16. Experimental set-up to modify the conventional solar still [54].

4. DISCUSSIONS

This paper reviews the literature concerning the usefulness of using thermal energy storage unit with a solar heating system. Several contributions have been reviewed by the thermal energy storage unit based on three methods: the latent thermal storage system using PCMs, the sensible thermal storage system, and the hybrid thermal storage system.

This article has presented an exhaustive review of these contributions in terms of the thermal efficiency, the thermal losses, the thermal conductivity of the material used for storage, and output temperature. As illustrated in Tables 1, 2, and 3.

From this study, it is concluded that there is a consensus in among scientists in the recent researches on the use of solar heating system integrated with latent thermal storage unit. For a best thermal performance of a solar heating system and to reduce the thermal losses, volume and system cost. Hence, a PCMs is required with high latent heat and with the great surface area for heat transfer.

Paraffin wax as a PCM is good for thermal energy storage in the latent thermal storage system. When it has a melting temperature range of 58-60°C and high latent of 210 kJ/kg. low thermal conductivity for the paraffin wax adversely affects storage efficiency. Therefore, many researchers have sought to enhance the thermal conductivity by adding different materials to paraffin wax for the improve storage efficiency.

Mahmud *et al.* in [27] and Alkilani *et al.* in [28] are added aluminum powder by 5% to paraffin wax, the results show that thermal storage efficiency for the pure paraffin wax attained the maximum value 71.9% and 77.18% for the paraffin wax-aluminum composite. Charvat in [4] is added float stones to paraffin wax, the results show increased the thermal conductivity of PCM

VOL. 12, NO. 21, NOVEMBER 2017 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

by 250%. Chen *et al*. in [32] are used to the aluminum foams filled with paraffin wax, the results show that temperature distribution in the paraffin wax with aluminum foams was more uniform than that of pure paraffin. Waqas and Kumar in [37] are used to a mixture of salt and paraffin wax, the results indicate that the added salt to paraffin give the best performance of the thermal storage unit, due to the melting point temperature of the PCM was equal the medium comfort temperature of winter months. Smolec in [38] is used to the thin aluminum strip matrix structure in the paraffin wax, the results show to increase the air temperature 5°C higher than the ambient air temperature for more than one hour after sunset. Guo in [40] is placed the alumina nanoparticles (Al_2o_3) in paraffin wax, the results reveal increase the thermal energy storage rate of, due to an increase the thermal conductivity and melting rate.

The results presented by contributions above suggest that the addition of float stones to paraffin wax is a better than other materials, due to increased thermal conductivity at a high rate and thus improve storage efficiency.

As for the solar energy collectors, confirmed the study of literature that the evacuated tube collectors. It has high ability to reduce convection and thermal conduction losses compared to flat-plate collectors. Therefore, an evacuated tube solar air collector widely used in many applications, especially in the regions having good sunshine.

Table-1. Literature review summary for the latent thermal storage system using PCMs in terms of thermal efficiency, thermal losses, thermal conductivity of PCM, and output temperature.

Authors	**Thermal efficiency**	**Thermal losses**	**Thermal conductivity of** (PCMs)	**Output temperature**
Fath	high	low	accepted	good
Krishnananth and Kalidasa	very good	very low	low	accepted
Esakkimuthu et al.	high	very low	degraded	very good
Summers et al.	accepted	low	degraded	good
Mahmud et al.	high	low very	high	good
Alkilani et al.	very high	low very	high	good
Feng et al.	very high	low very	high very	good
Charvat	high	low	accepted	good
Chun and Hussain	accepted	low	accepted	good
Mehla and Yadav	high	low	accepted	very good
Bharath et al.	very high	very low	accepted	good
Chen et al.	high	very low	high	good
Malan et al.	high	low	accepted	good
Koyuncu and Lüle	high	very low	accepted	very good
Rudolf et al.	high	very low	accepted	good
Saman et al.	high	low	accepted	good
Waqas and Kumar	very high	very low	accepted	very good
Smolec	high	low	accepted	good
Bouhssine et al.	high	low	high	very good
Guo	high	low	high	good

Table-2. Literature review summary for the sensible thermal storage system in terms of thermal efficiency, thermal losses, thermal conductivity of materials, and output temperature.

Authors	Thermal efficiency	Thermal losses	Thermal conductivity of materials	Output temperature
Gupta and Tiwari	high	low	accepted	good
Betrouni et al.	high	low	accepted	good
Taheri et al.	high	low	accepted	very good
Temperatures and Bonanno	high	high	accepted	good
Kalaiarasi et al.	high	low	accepted	good
Ferone et al.	very high	low	high	good

Table-3. Literature review summary for the hybrid thermal storage system in terms of thermal efficiency, thermal losses, thermal conductivity of materials, and output temperature.

Authors	Thermal efficiency	Thermal losses	Thermal conductivity of materials	Output temperature
Reddy et al.	high	low	high	very good
Al-Hinti et al.	high	low	accepted	good
Nallusamy et al.	high	low	high	good
Pandiyarajan et al.	very high	low	degraded	good
Bhale et al.	accepted	low	degraded	good
Nallusamy and Velraj	high	low	degraded	good
Ismail and Stuginsky	high	low	high	good
Caliskan et al.	very high	low	degraded	very good
Zhou et al.	accepted	low	degraded	good
Sharshir et al.	high	low	high	very good

5. CONCLUSIONS

The conclusions drawn from the present reviews indicate that the latent heat storage using PCMs is better than the sensible heat storage, due to the higher thermal energy storage density and ability to provide suitable temperature rates during melting and freezing processes for the PCMs. Accordingly, the PCMs effective manner at meeting the request of energy and balancing between request and supply of energy.

It was also shown that the use of paraffin wax as a PCM gives a better performance compared to other PCMs. Furthermore, that adding some materials to the wax increases thermal conductivity and gives a better storage efficiency than use of pure wax.

As for the hybrid thermal storage system has an effective impact on the storage of thermal solar energy. It has many advantages, including a great heat storage capability in a unit volume and isothermal conduct through the charge and discharge processes.

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