Tanzania Journal of Science 51(1): 77-101, 2025
ISSN 0856-1761, e-ISSN 2507-7961

A Review on Thermal Energy Storage Media and Technology for Flat Plate Solar Collectors: Experimental and Modeling Perspectives

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Received 18 Nov 2024, Revised 22 Feb 2025, Accepted 20 March 25, Published 14 April 2025
https://dx.doi.org/10.4314/tjs.v51i1.7

Abstract

Solar thermal conversion by collectors used in solar water heating systems solar thermal power generation systems undergo thermal losses. Hence there is need for the application of thermal storage media through appropriate technologies. These technologies require the use of various thermal storage media. A study and detailed discussion on thermal storage methods, sensible heat storage systems, sensible heat storage technologies, thermal storage materials and their applications are the aim of this review paper. This is done through analysis of thermal performance of flat plate solar collector, and the effects of the thermal parameters of the solar thermal storage systems as well as the functioning parameters on heat transfer fluids. Both experimental and modeling work on the application of thermal storage media are analyzed and discussed in this paper. Research findings show that thermal storage media improve the efficiency of solar water collectors by reducing thermal losses by these systems. This review is concluded by identifying various heat storage fluids for flat plate solar collectors which can improve their thermal performance for various heating applications.

Key words: Thermal storage; Solar collectors; Efficiency; Modeling

INTRODUCTION

The first flat plate solar water collector used for water heating was invented in 1767 by Saussure (Iksan et al. 2023). A Flat plate solar collector consists of a dark flat plate absorber, transparent glass cover, heat transport fluid, and insulation on the back. The circulating fluid in the absorber tubes may be of two kinds: air-based or liquid-based. Air-based collectors are usually used for heating buildings and drying crops. Liquid-based collectors can be of two types: glazed and unglazed. Liquid- based collectors are usually used for providing domestic water heating and for space heating purposes (Kazimierz 2005, Steinmann 2015, Horace 2018). However, there are thermal losses by the solar water collector that needs to be addressed through the usage of thermal storage media.

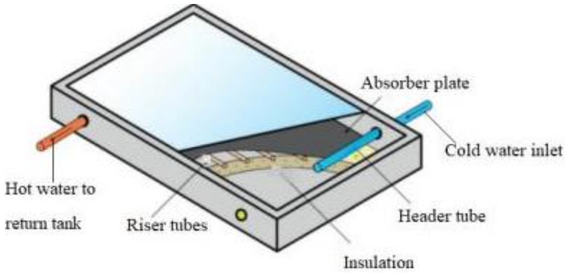

Figure 1: Absorber layer made of metallic tubes, (Adapted from Tripathi and Aijaz 2014).

The incident solar radiation falling on the collector is absorbed by the plate attached to the pipes through which water to be heated flows.

THERMAL PERFORMANCE ANALYSIS OF FLAT PLATE SOLAR COLLECTORS

Flat plate solar water heaters should be glazed with selective materials with low emittance and high transmittance within the solar spectrum, withstanding the ultraviolet rays degradation (Alghoul et al. 2005, Raja et al. *2018*).

The size of a solar water heater required to obtain the desired fluid temperature depends on the radiant flux striking the plate as expressed in Equation (1), (Warui et al. 2017).

$$I = \tau_{cov} A_P I_T \qquad (1)$$

where I_T is the irradiance on the collector, A_p is the exposed area of the plate and τ_{cov} is the transmittance of any transparent cover that may be used to protect the plate from the wind.

The radiant energy incident on the collector is a function of collector area and solar radiation intensity, expressed in the form (Kumar 2017):

$$Q_i = I_T A_C \qquad (2)$$

The instantaneous energy gained by the receiver Q_r is given by (Duffie and Beckham 2006, Struckmann, 2008, Fabio 2013, Kumar 2017):

$$Q_r = (\tau\alpha)_{eff} I_T A_C \qquad (3)$$

where $(\tau\alpha)_{eff}$ is the effective optical fraction of the energy absorbed, I_T is the solar radiation incident on the tilted collector, and A_C is the collector aperture area.

Equation (3) therefore shows the influence of effective transmittance absorbance product on instantaneous heat gained by the receiver.

Solar collectors normally undergo convective and radiative heat losses. Although, the glazing does not allow infrared-thermal energy (long wavelength) to escape. The convective heat Q_{conv} losses due to the temperature difference between the absorber plate and the ambient is given by the following equation (Matuska and Zmrhal 2009):

$$Q_{conv} = UA_r(T_r - T_a) \qquad (4)$$

where A_r is the area of the receiver, U is an overall heat loss coefficient, T_r is the receiver's temperature and T_a is the ambient temperature. Heat is lost by radiation Q_{rad} due to the temperature difference between the collector and the sky dome (Amira *et a.* ,2019, Matuska and Zmrhal 2009):

$$Q_{rad} = \varepsilon_{eff} \sigma A_r({T_r}^4 - {T_a}^4) \qquad (5)$$

The heat loss coefficient combines heat losses from the collector surfaces and the edges. The major loss occurs at the top surface due to optical loss, convection and radiation (Balotaki 2017).

Absorbed solar energy by the fluid can be determined by the heat transfer equation in the form: (Amira et al. 2019, Iksan et al. 2023):

$$Q_{u\_} = A_c F_R[S - U_L(T_r - T_a)] \qquad (6)$$

where Q_u is the heat absorbed by the fluid, A_c is the collector surface area, U_L

is the heat loss coefficient, S is the heat absorbed by the collector.

Equation (6) shows that the heat absorbed by the working fluid is determined by the heat removal factor.

A heat-conducting fluid, usually water, glycol, or air, passes through pipes attached to the absorber plate. As the fluid flows through the pipes, its temperature increases. The amount of energy taken by the working fluid corresponds to a fraction of the useful energy collected after the heat losses. The instantaneous thermal efficiency corresponds to the fraction from the incoming solar radiation that is recovered to be used (Gang et al. 2011, Fabio 2013, Amira et al. *2019*):

$$\eta = \frac{Q_u}{I_T A_C} \quad (7)$$

$$\eta = (\tau\alpha)_{eff} - \frac{UA_r}{I_T A_C}(T_r - T_a) - \frac{\varepsilon_{eff}\sigma}{I_T A_C}({T_r}^4 - {T_a}^4) \quad (8)$$

The efficiency and the useful heat gain can be expressed in terms of heat removal factor in the form:

$$\eta = F_R\{(\tau\alpha)_{eff} - \frac{UA_r}{I_T A_C}(T_{in} - T_a) \quad (9a)$$

$$\eta = F_R\{(\tau\alpha)_{eff} - F_R U_L \frac{(T_{in} - T_a)}{I_T} \quad (9b)$$

$$Q_u = \eta I_T A_C$$

$$Q_U = I_T A_C F_R\{(\tau\alpha)_{eff} - \frac{UA_r}{I_T A_C}(T_{in} - T_a)\} \quad (10)$$

Collector efficiency has also been expressed as Andoh *et al*. 2010):

$$\eta = \frac{Q_u}{I_T A_C(\tau\alpha)} \quad (11)$$

It is important to note thermal energy gain, heat loss, heat removal factor, heat loss coefficient and efficiency of a solar collector greatly depend on the solar radiation intensity and the collector area, as shown in Equations (1) to (11).

The usable heat gained by the working fluid can also be expressed as a function of both inlet T_{in} and outlet T_{out} temperatures as (Shariah 1991, Santiago and Jimenez 2002, Duffie and Beckham 2006, Fraisse et al. 2007, Struckmann 2008, Gang et al. 2011, Fabio 2013, Amira et al. 2019):

$$Q_u = \dot{m}c_p(T_{out} - T_{in}) \quad (12)$$

where c_p , and m are the specific heat capacity at constant pressure, and mass flow rate of the working fluid, respectively.

Equation (12) shows that the fluid flow rate in the solar collector affects the usable heat gain.

Heat removal factor F_R, which relates to the actual useful energy gain of a collector surface that is at the fluid inlet temperature (Matuska and Zmrhal 2009, Orlando and Jose 2018), can be expressed in the form (Santiago and Jimenez 2002, Baldini et al. 2009, Daghigh et al. 2011):

$$F_R = \frac{\dot{m}c_p(T_{out} - T_{in})}{I_T A_C\{(\tau\alpha)_{eff} - \frac{UA_r}{I_T A_C}(T_{in} - T_a)\}} \quad (13)$$

The collector heat removal factor can also be expressed in the form (Raghu et al. 2000 Matuska and Zmrhal 2009, Iksan et al. 2023):

$$F_R = \frac{\dot{M}c}{A_a U}[1 - \exp\left(\frac{-A_a U F'}{\dot{M}c}\right)] \quad (14)$$

where, $\dot{M}$ is the total mass flow rate of fluid through the solar collector, in kg/s; c specific thermal capacity of fluid, in J/kgK; and A_a the aperture area of solar collector, in m^2.

Thermal conductivity within the system is given by the expression (Andoh *et al*, 2010).:

$$Q_c = -kA\frac{dT}{dx} \quad (15)$$

where Q_c is the conducted heat, k thermal conductivity, A the cross sectional area of the heat flow and $\frac{dT}{dx}$ the temperature gradient.

Thermal conductivity values in Equation (13) is useful in selecting appropriate absorber and insulation materials for a solar collector.

THERMAL STORAGE METHODS

There are three main thermal energy storage methods in thermal energy storage systems (TES), namely;

- Sensible heat storage
- Latent heat storage
- Thermochemical storage

Several researchers have investigated the flat plate solar collector experimentally and numerically analyzing these methods to enhance performance (Bruno and Noel 2013, Stutz et al. 2016, Sarbu and Sebarchievici 2018).

Sensible Heat Storage

This involves an accumulation of thermal energy, hence changing the temperature of the storage media without changing its phase. The quantity of the sensible thermal energy depends on the specific heat capacity, temperature change and mass of the material. The design of sensible heat storage systems is the simplest of the other types. However, they require large volumes thus retrieval constant temperature of the stored energy is not attainable (Stutz et al. 2016, Sarbu and Sebarchievici 2018). Low-temperature sensible heat storage is normally applied in solar water heating for domestic small-scale and district large scale purposes (Stutz et al. 2016).

In sensible heat storage systems, the storage medium can be either a solid or a liquid material. Liquids used for SHS include water, hydrocarbon oils and molten inorganic salts, and solids such as rocks and refractories (Ataer 2006). The amount of sensible energy stored by the medium is defined by (Fabio 2008, Kumar and Shukla 2015):

$$Q_s = \int_{t_i}^{t_m} mc_p \, dt = mc_p(t_f - t_i) \quad (16)$$

where Q_s , m, c_p, t_i and t_f are stored heat energy, mass, specific heat capacity, initial temperature and final temperature respectively.

In SHS systems the choice of materials is determined by the suitable temperature level for the intended application. For instance, water is used for temperatures below 100 °C and refractory blocks for temperatures close to 1000 °C (Stutz et al. 2016).

Sensible heat storage systems

SHS storage systems can be classified as either passive or active (Hossain et al. 2015, Olives *et* al. 2015, Fabio 2013). This classification depends on the state storage medium circulation within the system.

Passive storage

In this system the storage medium does not circulate within the storage chamber. Thermal energy is transferred by the heat transfer fluid (HTF) from the solar field to the storage medium during the charging phase. The thermal energy is then recovered from the storage medium during the discharge process. This storage mechanism mainly uses heat exchanger or regenerator inside solid materials such as rocks, sand, concrete, ceramics, or recycled materials from wastes to optimize heat transfer (Fernandez et al. 2010, Fabio 2013, Hossain et al. 2015; Olives et al. 2015). This heat exchange technology can also be used in latent heat storage systems to improve both heat transfer and thermal cycling (Stutz et al. 2016).

Active Storage

This storage system is characterized by the circulation of the storage medium within the storage chamber. When the circulating HTF in the solar field is the storage medium, the storage process is referred to as direct storage. However, when one fluid circulates in the solar field and another one is used for thermal energy storage then the technology is referred to as indirect storage (Fabio 2013, Stutz et al. 2016, Warui et al. 2017).

In the active system, the storage system is often composed of two tanks, one for the coldest fraction of the storage media and the other for the warmest fraction. The storage media is a fluid within the range of temperature considered, and is also used as a heat transfer fluid (HTF). It can flow through heat exchangers to transfer heat during the charging and discharging steps.

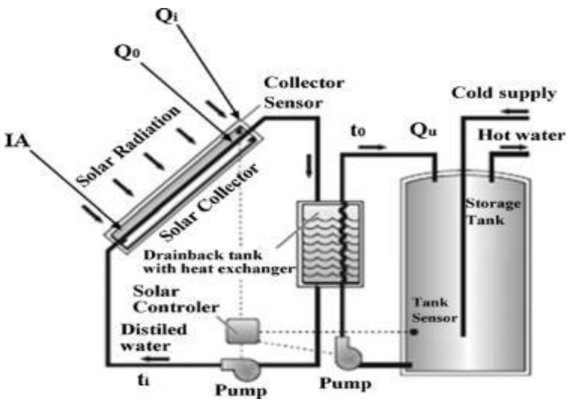

Figure 2: A typical active solar thermal storage, (Adapted from Santiago and Jiménez 2002)

The main disadvantage of passive TES using sensible heat is that the temperature decreases during discharging as the storage material cools down: hence lowering efficiency and control. Another drawback of passive TES (with respect to forced convection applied in active systems) are the low heat transfer rates when solid TES materials are used (usually there is no direct contact between the HTF and the storage material as the heat is transferred via a heat exchanger) (Fabio 2013).

Active Storage in one Tank

This is a single storage tank system fitted with a pump for thermal storage fluid circulation. This active and indirect system has circulation pumps between the storage tank and the solar collector. Some systems also incorporate a second pump to force convection between the primary hot water storage tank and the heat exchanger. Two sensors are used, one in the tank and another in the solar panel to sense temperature differences (Fabio 2013, Warui et al. 2017).

Active Storage with two Tanks

In this system, a hot storage tank allows the exit fluid from the solar field to supply the steam generator during the cold periods. At the steam generator output, the cold fluid is sent to a second cold tank before returning to the solar field.

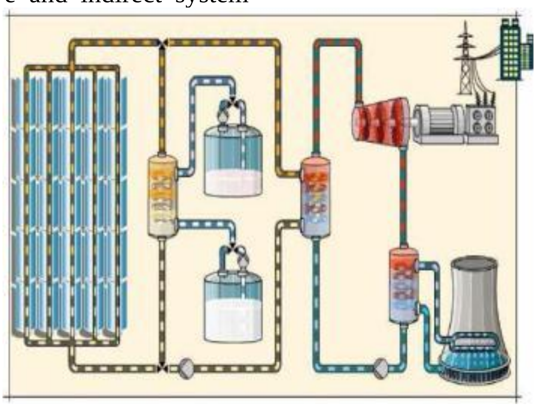

Figure 3: Indirect active storage system with 2 tanks, (Adapted from Herrmann and Nava 2006)

This system uses molten salts as storage fluid, while heat transfer is by steam, a synthetic oil or a different salt than the one used for storage, depending on the desired applications. Using molten salts only for storage, minimizes solidification problems inside the solar field, but requires an additional heat exchanger (Fabio 2013).

Latent Heat Storage

This thermal storage method involves the heat absorbed or released when a material changes from one physical state to another. LHS therefore uses phase change (PMC) materials. The most studied PCM include Glauber's salt, calcium chloride hexahydrate, sodium thiosulfate pentahydrate sodium carbonate decahydrate, and disodium phosphate dodecahydrate (Kaygusuz 1999). The storage capacity Q_s, in J, of the LHS system with a PCM medium, is given by, (Tian and Zhao 2013):

$$Q_s = \int_{T_i}^{T_m} mc_p dT + mf\nabla q + \int_{T_m}^{T_f} mc_p dT \quad (17)$$

$$Q_s = m[c_{ps}(T_m - T_i) + f\Delta q + c_{pl}(T_f - T_m)] \quad (18)$$

where T_m is the melting temperature, in ℃; m is the mass of PCM medium, in kg; c_{ps} is the average specific heat of the solid phase between T_i and T_m in kJ/(kgK); c_{pl} is the average specific heat of the liquid phase between T_m and T_f in J/(kgK); f is the melt fraction; Δq is the latent heat of fusion, in J/kg. For example, Glauber's salt ($Na_2SO_4 \cdot 10H_2O$) has $c_{ps} \approx$ 1950 J/(kg℃), $c_{pl} \approx$ 3550 J/(kg℃), and Δq = 2.43 × 10^5 J/ kg at 34 ℃, (Sarbu and Sebarchievici, 2016).

The main advantage of using LHS over SHS is that more heat can be stored from PMC materials than in sensible storage. Energy densities for latent heat storage are greater than those for sensible heat storage. A phase transition from a solid to a liquid is the most desired since a change to and from a gas requires a lot of additional volume (McLeske 2009).

Thermochemical Storage

TCS uses thermo-chemical materials (TCM), which store and release heat by reversible endothermic/exothermic reaction processes (McLeske 2009, Bruno and Noel, 2013, Sarbu and Sebarchievici 2018). TCS processes are sorption, adsorption, absorption and chemical decomposition. A sorption process involves the fixation or capture of a reactive gas by a condensed medium. When the condensed medium is solid, the process is referred to as adsorption and absorption for a liquid medium. The general chemical equation in thermochemical storage is in the form (Stutz et al. 2016):

$$< S > + mG \leftrightarrow < SmG > + mHr \quad (19)$$

where $< S >$ is the reactive solid, m stoichiometric coefficient, G reactive gas and Hr reaction enthalpy of the reactive gas.

The thermochemical processes of solid/gas reactions have an energy density range of 200- 500 kWh/m^3 operating within a wide temperature range of 80℃ − 1000℃, depending on the reactive pair. Research on such thermochemical systems has been conducted for thermal storage and temperature applications for space heating (Michel et al 2014), and concentrated solar plants (Pardo et al. 2014, Schmidt et.al. 2017). More research has been carried out on characterization, heat control and mass transfer in porous reactive material (Mauran et al. 1993, Zamengo et al. 2014, Boulnois et al. 2015). Pilot plants for significant scales have been investigated (Michel et al. 2014, Pardo et al. 2014, Schmidt et.al. 2017).

A seasonal adsorption TES system, working with the silica-gel/water pair was presented by Hauer in 2007 as shown in Figure 4**.** During the summer, while the system is charging, the heat from the solar collectors is conducted to three adsorbent beds, promoting the desorption stage. In the winter, the low temperatures in the solar collector promote the evaporation of the water in the evaporators/condensers, and the heat of adsorption is released to the building heating system (Hauer 2007).

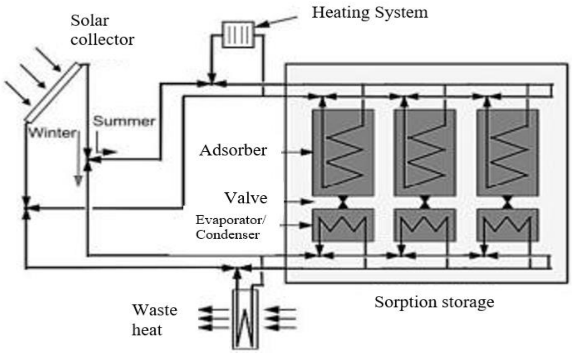

Figure 4: Seasonal adsorption thermal storage system, (Adapted from Hauer 2007).

The use of porous materials can improve heat and mass transfer processes thus resulting in high thermal storage (Kalaiselvam and Parameshwaran 2014).
From the research findings, thermochemical energy storage systems have advantage over sensible and latent heat storage systems since they are best in terms of energy density, durability, reversibility and thermal storage without insulation. The promising thermochemical material pairs are silica gel/water, magnesium sulphate/water, lithium bromide/water and sodium hydroxide/water (Michel et al. 2014, Pardo et al. 2014, Schmidt et al. 2017).

Experimental Work on Thermal Storage by Solar Collectors

There are different types of heat transfer fluids whose usages depend on the geographical location of the water heating system. These fluids are air, water, glycol-water, hydrocarbon oils, refrigerants or phase change fluids, silicon, molten sodium nitrate, or potassium nitrate mixture (Ataer 2006). Sunflower oil has been reported to be a good heat transfer fluid (HTF) as well as heat storage medium for domestic medium temperature applications (Ogonuriola et al. 2008). These heat-transfer fluids carry heat through solar collectors and heat exchangers to the heat storage tanks in solar water heating systems (Basecq et al. 2013).

The first major project on flat plate solar collector using water as a thermal storage fluid was built in Nykvarn, Sweden in 1985, which utilized 7500 m^2 of collector area and a 1500 m^3 water tank for storage. The storage tank temperature was 55℃ C-90℃. The optimal amount of water for storage is about 100 liters per square meter of collector area (McLeske 2009).
Thermal storage fluids (TSF) have been incorporated in flat plate solar collectors through various designs in thermal storage technologies as illustrated in Figure 5.

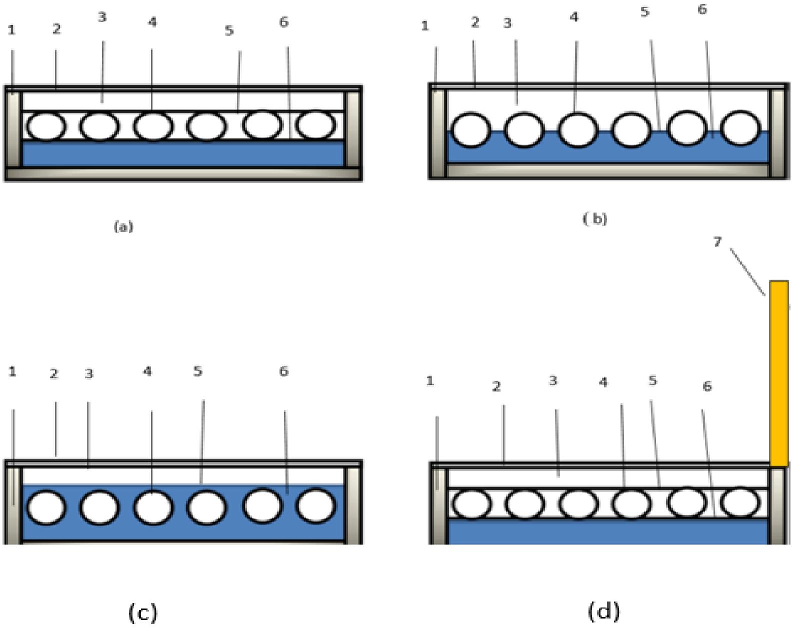

Figure 6: Schematic representation of a flat plate solar collector with TSF in thermal storage technologies, (Adapted from Faud and Kerswani, 1973) (a)below tubes, (b)half perimeters of the tubes, (c)immersed tubes, (d)with reflector, (1) insulation, (2) glass cover, (3) air space, (4) tubes, (5) absorber plate, (6) TSF, (7) reflector.

A comparative study was done in 2013 on the thermal performance of a DHW system with PCM and those of a conventional DHW system. In this study, the solar collector that acts as the PCM thermal storage medium consists of six 80mm diameter copper pipes that are connected in series and are integrated with a back container of paraffin wax. The performance of the integrated thermal storage collector or device is compared with that of the conventional device in terms of parameters such as the temperature difference across the collector, instantaneous efficiency, heat removal, and overall heat loss coefficient. The results indicated that the temperature difference in the storage collector is 66% higher than that in the conventional one. Furthermore, the instantaneous efficiency of the storage collector was 41.7% to 55.1% higher than that in the conventional one (Khalifa et al 2013).

A further experimental investigation was done on the storage collector device under different weather conditions, including a clear day in January (average solar radiation of 698Wm^{-2} and ambient temperature of 11.59 °C, February (average solar radiation of 701Wm^{-2} and ambient temperature of 24.84 °C), and semi-cloudy days in March (average solar radiation of 747Wm^{-2} and ambient temperature of 24.5 °C). The study findings suggested that energy was released from the storage-collector system at approximately 14:30h in January, 16:00h in February, and 17:00h in March. The efficiency of the storage collector was higher on semi-cloudy days than on clear days because the PCM temperature is higher than that of the absorber plate (Khalifa and Jabbar 2013).

Enhancement of heat transfer has been done by using high porous aluminum foam incorporated with paraffin. At night, a serpentine pipe was embedded in the PCM to release the solar energy stored during the day. A further numerical study was conducted on the temperature distributions in the integrated PCM solar collector with and without aluminum foam. The results indicated that heat transfer can be improved significantly through aluminum foams filled with paraffin (Chen et al 2010).

An experimental investigation has been done on the use of sodium carbonate dicarbohydrate ($Na_2CO_2.10H_2O$) as PCM in solar collector. The efficiency of this collector was compared with that of the conventional system without PCM. To predict collector performance, several computational models were adopted based on experimental data, including artificial neural networks (ANN), adaptive-network-based fuzzy inference system (ANFIS), and support vector machines (SVM). The findings indicated that the thermal storage collector is more effective than the conventional systems. Moreover, the SVM model predicted system performance more accurately than ANFIS and ANN (Varol et al. 2010).

Paraffin which is a PCM has been studied in a storage system. This system was incorporated behind the absorber of a flat plate solar collector with two rectangular cavities. To investigate the thermal performance of an integrated storage collector of latent solar energy, a four-day experiment was conducted in Tunisia. The influence of collector inclination was examined through numerical modelling, as was the heat flux on the liquid fraction and the solid–liquid interface of PCM. The results suggested that during the experimental period, the average value of energy efficiency in this collector was approximately 27%, which is less than that in commercial solar water heaters. However, the PCM improves solar collector performance at night (Boudila et al 2013).

Paraffin can be directly incorporated into the lower surface of the absorption plate of the flat plate solar collector to store thermal energy. To increase the heat transfer area, the surface was extended from the absorption plate to the PCM reservoir. In addition, they experimentally investigated the effect of PCM on the solar water heater with a rectangular cavity, as well as the effects of different mass flow rates and collector tilt angles on solar collector performance. Results indicated that the storage-collector unit efficiency was 52.72% and the hot water temperature for daytime demand was 38.1℃ with 0.5kg/min flow rate and 101 to 201 inclination angle. Hence, such technology can be easily incorporated into the conventional solar collector without requiring any major or expensive modification (Lin et al 2012).

Outdoor experiments investigated the effect of water flow rate and the influences of solar energy on the melting and solidification of PCM. The energy was released from the PCM through a copper pipe located equidistantly from the PCM container walls to maintain equal PCM thickness around this pipe. The results indicated that the generated useful heat increased with the increase in the flow rate of water mass (Mettawee and Assassa 2006).

A study on the integration of PCM into the solar collector of the DHW system was conducted in 2007. The system consists of two rectangular cavities. The top and bottom cavities are filled with PCM and water, respectively, as presented in Figure 6. The collector is covered with transparent insulation materials.

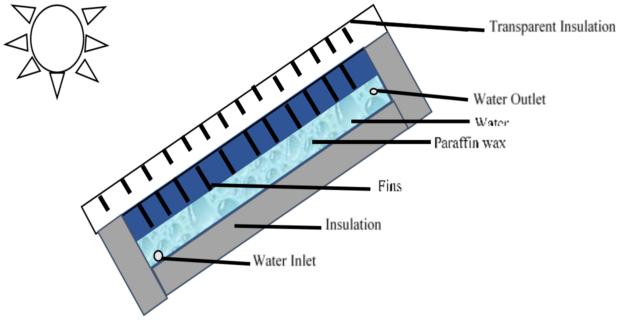

Figure 6: Integrated collector storage solar water heater with fins inside the wax, (Reddy 2007)

To improve the thermal performance of the storage collector, the researchers also investigated the effect of the fins configuration attached to PCM given different pitches as a technique of heat transfer enhancement. The findings suggested that the thermal performance of nine fins was ideal based on the other configuration without fins (Reddy 2007).

An experimental investigation on the variation effects of HTF mass flow rate and collector tilt angle on the thermal performance of the storage-collector system was done in 2012. To enhance this thermal performance, the researchers welded 37 fins under the absorber plate of the solar collector with PCM. The results showed that the hot water outlet reached its maximum temperature when the tilt angle was 10° at 4 kg/min (Lin et al 2012).

The effect of PCM on the operation of a solar DHW system has been studied using a 3D numerical model. The storage-collector is composed of a cylindrical storage tank and a compound parabolic concentrating reflector. PCM is wrapped directly around the receiver tube, as displayed in Figure 7. The researchers investigated two types of PCM (RT-42 graphite, myristic acid) and three layers of PCM. The findings showed that in the daytime, PCM thermal energy with myristic acid is more effectively stored in the collector than in the sensible storage unit, whereas the PCM storage unit is more effective at night for both PCMs.

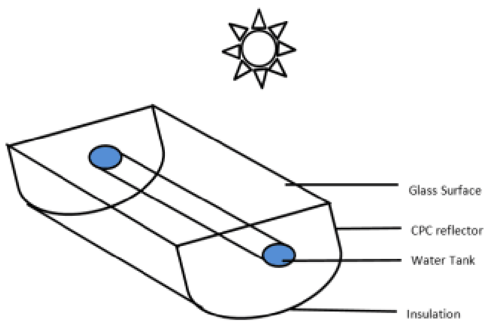

Figure 7: Cross-sectional schematic of the compound parabolic concentrating collector integrated with PCM, (Chaabane *et al* 2014).

Thermal storage has been studied by inserting paraffin wax into a new cylindrical evacuated solar collector system. This method continuously supplies hot water under different weather conditions, such as low incidences of solar radiation. The researchers experimentally analyzed the performance levels of five cases, including the solar collector without PCM as a reference case. They also analyzed four cases given different proportions of PCM (23.43%, 57.6 by volume paraffin, and 25.28%, 100% by volume water as a thermal storage medium). The findings indicated that water stored and subsequently released thermal energy more effectively. Thus, maximum overall thermal efficiency was obtained when the evacuated solar collector tubes were partially filled with water (Riffa *et al* 2006).

Evaluating the performance of the DHW system with PCM has been studied by inserting a PCM into a flat plate solar collector to replace the collector absorber. The researchers applied four types of PCMs (sodium acetate trihydrate, RT65 paraffin, stearic acid, and penta glycerin) to optimize PCM integration in the solar collector. Furthermore, they analyzed and synthesized the different physical properties of the PCMs, including thermal conductivity, absorptivity, storage capacity, and PCM lifetime. The results suggested that the characteristics of three of the four composites were suitable for integration into the solar collector, with the exception of sodium acetate trihydrate (Haillot et al. 2011).

Numerical analysis has been done on the incorporation of PCM into the solar collector to enhance the performance of DHW systems based on the selection and synthesis of the PCMs (Haillot et al. 2012). To improve the thermal performance of the DHW system, the researchers selected compressed and expanded natural graphite and RT65 composites. Moreover, they validated the numerical model experimentally. The results indicated that system efficiency increased under the meteorological conditions in summer but decreased in winter (Lin et al 2012).

A mathematical model was developed to study the effect of PCM-slurry on a flat plate solar collector's performance and to compare this performance with that of the conventional solar collector. The findings showed that the enhancement of solar collector performance was dependent on the boundary conditions and climates. Furthermore, the improvement in instantaneous efficiency ranged from 5% to 10%, and the efficiency of the PCM-slurry solar collector was 20% to 40% higher than that of the conventional water-based solar collector (Serale et al 2014).

The effect of PCM concentration on thermal storage has been studied by filling the rectangular solar water heater with a mixture of water and various concentrations of PCM slurries (10%, 15%, 20%, 25%, and 30%). A simulation model was then utilized to predict the solar collection efficiency of the solar heater storage collector integrated with water-PCM slurries and water systems. The findings indicated that the water-filled solar water heater collected heat slightly more effectively than the system of water-PCM slurry to generate a PCM storage system (Eames and Griffiths 2006).

A study on integrating a solar collector with salt hydrate has been done. The stationary HTF (oil) applied was lower in density than the liquid PCM that floated over a layer of immiscible PCM. To charge the PCM through solar radiation, the researchers coated a metal plate in selectable HTF absorbing film. The radiation passed through the plate to the oil and the PCM. A removable reflector enhanced solar energy absorption during the charging process for release through a finned heat exchanger as shown in **Figure 8**. This reflector also acted as a cover to reduce thermal loss during discharge (Chaabane et al 2014).

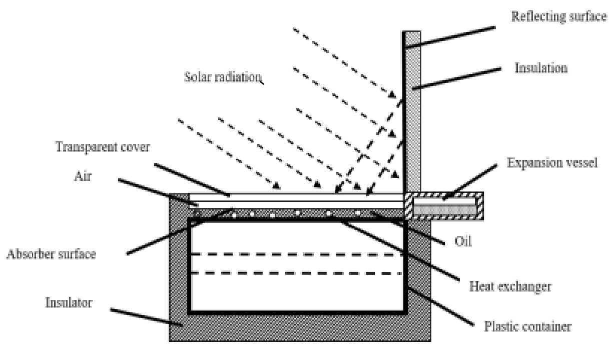

Figure 8: Schematic diagram of the integrated solar collector storage system based on a phase-change material, (Chaabane et al 2014).

Results reported that the transition phase change temperature is in the range of 15–35℃ and the thickness of the PCM layer in the range (20–100mm, which is suitable for heating greenhouses.

More research on thermal storage by PCM involved introducing a solar collector with a PCM-filled storage tank, which was placed underneath the collector. The PCM was charged using a specific HTF (Mobilterm 605), which conveyed heat from the solar collector to the PCM. The heat was released by a serpentine copper pipe and passed through the PCM by water circulation as shown in Figure 9. The authors experimentally analyzed system energy and exergy during charging. In this study, average net energy and exergy efficiencies are 45% and 2.2%, respectively.

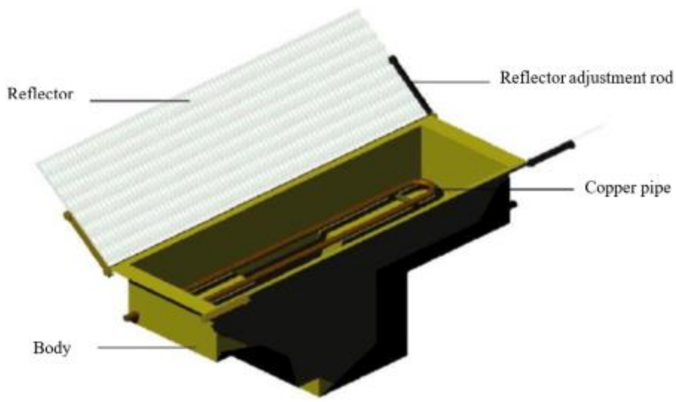

Figure 9: Solar collector with a PCM-filled storage tank**,** (Adapted from Koca *et al* 2008).

A lot of experimental and modeling research work has been done on flat plate solar collectors as will be seen in the subsections of this chapter. The distinction between experimental and modeling work is not perfect, because some researchers did both and presented their results in the same paper. For this reason, there will be mention of experimental work in the modeling subsection and modeling work in the experimental subsection.

Research on experimental evaluation of space heating in Ankara, Turkey was carried out by Tasdemiroglu in 1991. This experimental analysis consisted of a system with two flat plate collectors connected in series, liquid-to-liquid heat exchangers, a storage tank, a liquid-to-air heat exchanger, two pumps for circulation, and a number of valves. Various temperatures were recorded using thermocouples and a digital multi meter. These included fluctuations in the temperatures at intersections of the major system components, room temperatures, and ambient temperatures. Also measured was the total solar radiation incident on the collectors. Data were collected for seven months, from October 1988 to April 1989, and the thermal performance was evaluated, giving 36% and 45% daily efficiencies for direct and indirect modes, respectively (Tasdemiroglu 1991).

An experimental study was conducted on the thermal performance of a solar flat plate water heater (Model TE 39) in Bauchi weather conditions (lat. 10.50° N, long. 10.00° E). The experimental setup is shown in Figure 10.

Figure 10: Experimental setup for Performance Evaluation of Flat Plate Solar Collector (Model TE 39, (Adapted from Abubakar and Egbo 2014)

Fluid was circulated through the imbedded copper tubes in the flat plate collector and inlet and outlet temperatures of the fluid were noted at intervals of five minutes. The experimental-time was between 11:00-13:00 hours daily for a period of 28 days. The result shows that the outlet water temperatures were dependent on the weather condition (solar radiation intensity, cloud cover) with an outlet water temperature of and 70.5% optimum efficiency of the collector obtained at 12:05pm. A comparative efficiency of the flat plate collector obtained in the morning and that of the afternoon shows that efficiency of the flat plate collector is comparatively higher in the morning compared to that obtainable in the afternoon. However, the use of this flat plate solar collector will be viable for domestic heating applications under Bauchi prevailing weather conditions (Egbo 2014).

An experimental setup was developed in 2015 in the city of Shtip to take measurements on flat plate solar panels that have a tracking system. The aim of the study was to investigate the effect of a sun tracking system performance. There was a set of two flat plate solar collectors in which one was fixed and the other was tilted towards the south at 30 degrees with a dual-axis rotation system. The results of that experiment showed a significant increase in the daily energy captured by the moving collector as compared to a stationery collector. The collector with the two-axis tracking system had significantly improved performance, with an increase in collected energy of over 20% in the months of March and April for the afternoon hours. It was also noted that the computational fluid dynamics (CFD) model developed produced better comparisons to experimental data in the system with the fixed collector (Chekerovska and Filkoski 2015).

An experimental study on flat plate solar collectors was also done in 1977 by designing a house at the Technical University of Denmark for heating in the winter season by using solar energy as its main source. The house had insulated walls, and the total energy required for space heating was 2300 kWh per year. The heating system used a flat plate collector that supplied hot water for the whole year. The flat plate collector was 42 m^2 and was attached to an insulated water storage tank of 30 m^3. The absorbed radiation in the solar collector and energy that was accumulated in the storage tank were calculated using a computer model. The wind velocity, ambient temperature, and solar radiation for that particular year were taken as input data from a source to calculate this parameter on an hourly basis. To avoid freezing of the panels in cold weather and cloudy conditions, the water was drained from the collector. The house had a calculated total heat balance such that 7300kWh of energy was collected in the year; 30% of the energy was used for space heating, 30% was used for water heating, and the remaining was lost heat from the accumulator tank (Esbensen and Korsgaard 1977).

A study on solar water heater performance was conducted where a flat plate solar panel, fabricated with a fixed orientation was coupled to a heat exchanger kept inside a water storage drum. The collector was operated at a low temperature and had an operating range from ambient temperature up to 100℃. The study used acetone as the alternative working fluid, which circulated in a closed loop. This system's heat exchanger was used to transfer heat between the water and acetone. The solar intensity had few changes as the time progressed from morning to evening: 550 W/m^2 in the morning at 8:30 am, 850 W/m2 from noon to 1:30 pm, and 640 W/m^2 at 6:00 pm in the evening. The absorber plate temperature was constant in the beginning hours but later increased to 90℃ for two hours and then decreased to 72℃ in the afternoon. The acetone was found to be at the highest temperature between 1:00 pm and 2:00pm. The water temperature also had a significant change, from 30℃ to 62℃ . The overall efficiency of the system was 45% when water was the working fluid in the collector. In the future, alternative fluids that have low boiling points with high latent heat of evaporation such as acetone, methanol, or ethanol could be used as the working fluid for solar collectors (Manickavasagan 2005).

Research has been conducted on the design and materials used in the construction of a thermal solar panel. A cross-corrugated absorber plate was tested experimentally and also studied mathematically. This solar thermal panel has two plates; the top plate is shaped like a wave and the bottom plate is of the same shape. The bottom plate was placed perpendicular to the airflow direction to increase the heat transfer rate. The thermal performance was measured for these plates. they concluded that selective coatings and glass covers would not be useful (Lin et al 2006).

More work on a solar system that included the combination of a solar panel with a tracking system had been done. This system is located in a region with predominately cloudy sky conditions. This tracking option provided better energy capture and efficiency than the non-tracking solar panel. In another experimental procedure, the panels were fixed in three different positions (Ayoub 2012). In this study, Zhong *et al*, in 2011, calculated the optimum performance and theoretically investigated the system using a mathematical model developed by Ayoub (Shariff et al. 2014).

Experimental investigation has been done on hybrid collectors which converted part of the incident sun energy into electricity and recovered the remaining energy as heat. This hybrid system produced higher efficiencies than simple thermal panels or PV panels. There were two solar panels manufactured: PVT-A, which employed a single crystallized silicon solar cell on top of an optimized flat plate heat exchanger, and PVT-B, for which the absorber assembly had square copper channels covered with Cd-Te (Dupeyrat et al 2011).

A research paper on 'Thermal Performance of Two-Phase Thermo-syphon Flat-Plate Solar Collectors Using Nano-fluid' was presented in 2013. In this research, a solar heat pipe collector was designed and fabricated to study its performance in outdoor test conditions. The thermal performance of the wickless heat pipe solar collector was investigated for pure water and nano-fluid with varied ranges of CNT nano-fluid concentration (0.15%, 0.45%, 0.60%, and 1% by volume) and various tilt angles (20°, 32°,40°, 50° and 60°. CNT nano-particles with diameters 10–12 nm and 0.1–10 lm length were used in this experimental investigation. The optimal value of CNT nano-fluid concentration for better performance was obtained from the investigation. The following conclusions were therefore made from their research:

(1) Solar heat pipe collector that uses CNT nano-fluid as working fluid is found to be more efficient compared to the heat pipe that uses pure water.

(2) The efficiency of the solar heat pipe collector is found to increase with the increase in the concentration level of CNT nanoparticles in water, the performance decreases when the CNT concentration exceeds 0.60%. Maximum instantaneous efficiency was found to be 73% for 0.60% volume concentration of nanofluid.

(3) The efficiency of the heat pipe collectors for both water and nanofluids increases with the tilt angle and decreases when the tilt angle exceeds 50° (Sandesh et al. 2013)

Developments in heat pump-based solar collector technology exhibit a promising design to utilize solar energy as a reliable heating source for water heating applications in solar adverse regions. They observed that the choice of heat pump for solar water heating depends on factors such as the nature of their refrigerants. Due to the environmental concerns, refrigerants with high global warming potential have come under scrutiny and several have already been phased out. Driven in part by these concerns, new refrigerants are being sought out and ‘‘old’’ refrigerants such as carbon dioxide, ammonia and propane are being investigated. Apart from the choice of working fluid, there has been a major research focus in improving the performance of various components of the SWH system (Ruchi et al 2013).

Figure 11: Indirect flat plate collector solar cooker with TES, (Adapted from Schwarzer and DaSilva 2003)

A study has been conducted using receivable heat flux by the collector, circulating mass flow rate, driving pressure, total pressure drop, heat transfer coefficient in risers and collector efficiency are defined as system parameters. For this aim, a model of two-phase thermosiphon solar water heater that is acceptable for various inclinations is presented and variations of riser diameter and inclination are considered and water is chosen as working fluid. The results show that a higher inclination angle is required for higher latitude location to obtain maximum solar heat flux. The longer two-phase heat transfer characteristics can be obtained at smaller inclination angles and mass flow rate for all riser tube sizes. Therefore, it is observed that the optimum inclination angles and diameters for solar heat flux, circulating mass flow rate and heat transfer coefficient in a two-phase thermosiphon system do not coincide. From this work, better understanding and useful information are provided for constructing two-phase thermosiphon solar heaters (Nay and Songjing 2013).

A flat plate collector natural convection solar cooker with short-term coconut oil TES has been designed and studied. A double-glazed flat-plate collector covered with a selective surface was used as the power source for the solar cooker achieving temperatures of approximately 150°C. Coconut oil was used as the heat transfer fluid and at the highest part of the thermo-syphon loop there was an oil bath in which two cooking pots were immersed to facilitate good heat transfer between the working fluid and the cooking pot (Mawire 2019).

A flat plate collector indirect solar cooker using a vegetable oil as the heat transfer fluid and an oil/pebble bed TES system which also uses the thermo-syphon principle. The oil was heated up in the collector with reflectors and moved by a natural flow mechanism to the cooking unit. Manually controlled valves guided the oil flow-rate either to the pots or to the storage tank (Schwarzer, and DaSilva 2003).

Solar cookers based on conventional flat-plate solar collectors suffer from the drawback of the performance deteriorating due to the reversed cycles during the night and cloudy periods of the day. The further disadvantages are that they are expensive to construct and the non-removable pots make cleaning and dishing of food difficult (Mawire 2019).

Modeling Work on Solar Collectors

A study on numerical techniques that accounted for the thermal behavior of a solar collector was done in 1991. The multidimensional and transient heat transfer properties that describe the solar collector were all taken considered. Different aspects of the systems, such as dimensions and arrangement of the components, a combination of inlet velocity and inlet temperature of the fluid, and different outdoor conditions were studied by this numerical simulation. This analysis is for an air collector that has rectangular ducts. The heat transfer caused by the free convection between the air gap zones was calculated using empirical relationships, and the solar irradiance was taken to be hourly constant.

The dynamic modeling of a flat plate collector plays a significant role in evaluating the performance of a flat plate collector. The flat plate collector was introduced to time-varying meteorological data. The dynamic modeling gave a better result as compared to steady state models. The dynamic model presented here used differential equations, which were solved using the Runge-Kutta and Taylor Series expansion method. The fluid temperature, plate temperature and cover temperature were represented using three different equations. Later, this model was compared with experimental results obtained using a liquid-cooled flat-plate solar collector having a corrugated transparent fibre-glass cover. The results obtained from the dynamic model closely matched the experimental flat plate collector results. The temperature varied ±3℃ for the experimental collector compared to the predicted model. The model was coupled with a1 kW ammonia-water absorption refrigeration system having 30% ammonia by weight and an inlet fluid temperature of 30℃. This dynamic modeling produced better results compared to measured experimental data for the above system (Oliva et al. 1991).

Research on the optimization of design parameters for a thermosiphon SWH was conducted for Amman and Aqaba cities in Jordan through the use of the TRNSYS simulation program. The results indicate that the solar fraction of the system can be improved by 10–25% when each studied parameter is chosen properly (Zueva and Magiera 2001). It was also found that the solar fraction of a system installed in Aqaba (hot climate) is less sensitive to some parameters than the solar fraction of a similar system installed in Amman with mild climatic conditions (Shariah and Shalabi 1991).

A mathematical model for a solar collector coupled with a heat exchanger has been developed. In this model, the researchers developed an analytical solution for the heat flow through the collector surface, which is under Cauchy boundary conditions with respect to internal heat sources, which represented the incident solar energy (Zueva and Magiera 2001).

A flat plate solar panel model, for the transient state had been developed. The study included a one-dimensional mathematical model, which simulates the transient processes occurring in panels. The model developed in MATLAB simulates the complete system, which comprises the collector and storage tank. Experiments were carried out for several days to verify the results produced by the model. The results were satisfactory, which showed a significant change in transient fluid temperature at the outlet of the collector. These transient temperatures were measured and computed from a MATLAB program that had an acceptable convergence factor when calculating the overall efficiency and heat loss factor for the complete system (Saleh 2005).

Modeling work on the performance of solar water heating systems for a building was done for exergy analysis and evaluation of the performance of a solar water heating system. The system consisted of a flat plate collector, a heat exchanger, and a pump for circulation. This study included the evaluation of varying water inlet temperatures to the solar collector on the efficiencies of the system components and their effect on other thermodynamic parameters. This particular analysis was checked by using the experimental data taken in Izmir Province, Turkey. The energy efficiency values were found to be 2.02% to 3.37%, respectively. These results were obtained while carrying out eight test runs from around 1:10 pm to 3:35 pm for the overall system (Gunerhan and Hepbasli 2007).

A study was done on an integrated solar system that included a flat plate collector mounted on the roof of a house and had a storage unit composed of a phase change material (PCM). The collector and PCM storage unit were connected in a loop. This work focused on using solar energy collection and storage to provide space heating to residential units, and a house in Blacksburg, Virginia was used as the site. The weather conditions at this location were suitable for this system, which supplied 88% of the heating and hot water needs over the course of ABAQUS software version 6.3 was used for modeling the flat plate solar panels. The simulation results were calculated for a year on an hourly basis. The focus of the analysis was the outlet temperature of fluid from the collector and the storage tank. The research also showed different parameters such as energy collected and energy consumed by the panel and energy and hot water consumption in the home. The collector could provide heated water all the time or it could supply 33% of the space heating needed in January, 58% in December, 86% in November, 88% in February, and 100% in the rest of the months. The total energy the system could supply was 88% of the home's space and water heating requirements over the course of a year (Hassan and Beliveau 2008).

The analysis of a flat plate solar collector has been formulated by a mathematical model describing the thermal performance of a collector in a computational manner using "Hottel-Whillier-Bliss equation" (Fabio, 2008). This is an agreement with other researchers. The results obtained compared well with other research findings. The collector efficiency η was plotted against (Ti–Ta)/I as indicated in Figure 12.

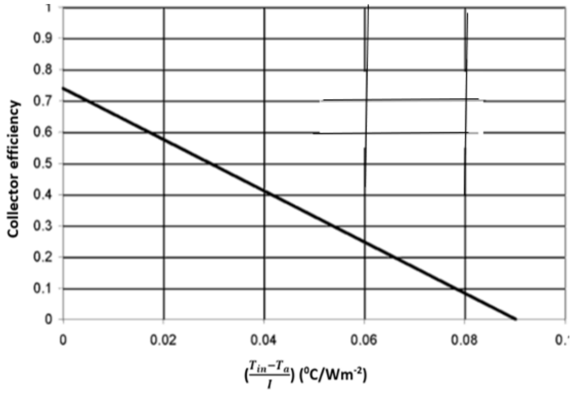

Figure 12: Performance of a typical flat-plate thermal collector (ambient temperature 25°C), (Fabio 2008)

The slope of this line (- F_R U_L) represents the rate of heat loss from the collector. For example, collectors with cover sheets will have less of a slope than those without cover sheets (Fabio 2008)

A study on hot water solar oven for low temperature thermal processes has been conducted using the setup shown in Figure 13.

Figure 13: Experimental hot water solar oven set up, (Adapted from Bello and Odey 2009)

The collector was characterized according to the concrete plates methodology. The energy balance was modeled using the Hottel-Whiller-Bliss generalized performance equations.

The system takes the form of a rectangular-shaped design incorporating the solar collector and storage tank into a single unit as shown in Figure 14.

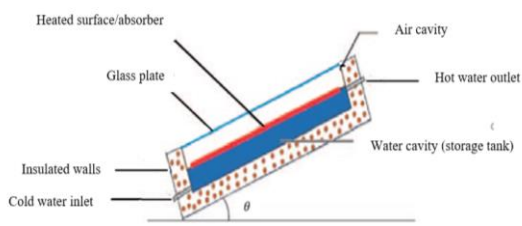

Figure 14: Cross-sectional representation of the SWH, (Bello and Odey 2009)

This was one of the effective ways of solar thermal conversions. However thermal loss reduction measures need to be addressed, hence a need to develop a simple low-cost Integrated Collector Storage Solar Water Heater (ICS-SWH) through simulation in Scottish weather conditions (Bello and Odey 2009)

A detailed one-dimensional, numerical model of a solar flat plate collector was created showing both heat and flow characteristics. This particular model is an extension of the model already developed (Duffie and Beckman, 1991). This was verified by an experiment performed on two different collectors at steady-state conditions (Cadafalch 2009).

Heat pipes coupled with solar collectors to enhance heat transfer rates have been investigated. A new theoretical method was developed for analyzing the thermal performance of a heat pipe flat plate solar collector coupled with a cross-flow heat exchanger. The results obtained from the analysis were compared well with other studies (Xaio *et al* 2012).

Computations and experiments on a prototype model were conducted in Tunis, Tunisia in 2013 to understand the Tunisian air heating needs. The setup of the prototype apparatus consisted of a flat plate collector, hot water tank, and an active layer for floor heating that is integrated inside a single room. The various modes of heat transfer were considered using a simulation program written in TRNSYS. The experimental tests were carried out in local weather conditions for two months, March and April 2013. Experimental results were compared to the computational results, and the accuracy of the simulation program was determined. They also conducted a study using this same program, to optimize design parameters for the prototype house, which included the collector area, mass flow rate, storage tank volume, and thickness of the active layer. The analysis showed that the solar collector with an area of 6m^2, a mass flow rate of $100 kg$/m, and a storage tank of 450 litres achieved maximum performance (Mehdaoui et al. 2014).

A study on the performance of flat plate collectors for the city of Gabes, Tunisia was carried out in 2014. and determined their performance. The collector supplied hot water to the required source. The researchers conducted simulations to determine the dynamic behaviour of the collector and studied the outlet water temperature and the overall heat loss coefficient and other parameters. Their result shows that as working fluid flows through the tubes, the number of tubes used in the collector affects flow rate and heat transfer rate. The simulation results also show that the outlet temperature reaches a peak and then decreases. The mass flow rate of 0.008 kg/s is constant, which indicates that the number of tubes directly affects the velocity of the fluid. The overall heat loss coefficient plotted as function of time shown in Figure 15 depicts the overall heat loss coefficient as a maximum at noon and decreasing from that point. The highest value in the summer and winter seasons is 3.38 W/m^{2}K at a mass flow rate of 0.005 kg/s (Hamed et al. 2014).

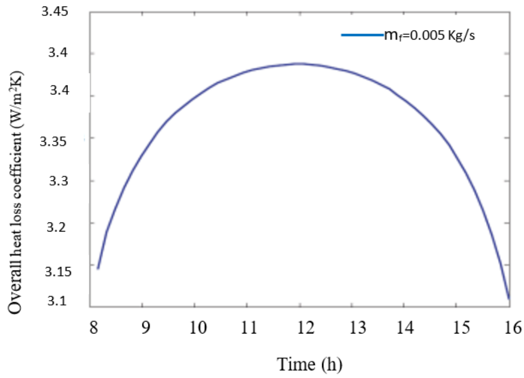

Figure 15: Collector overall heat loss coefficient verses time, (Adapted from Hamed et al 2014)

Research based on Computational Fluid Dynamics (CFD) tool had been used to simulate the condition for different types of absorber plates having different shapes and configurations to obtain better efficiency than ordinary solar collectors. The 3D model of the solar flat plate collector was modeled by UGS NX and then exported in STEP format and then imported in ANSYS Workbench and then the meshing was created in ANSYS ICEM. The results were obtained by using ANSYS FLUENT software (Kumavat 2016).

CONCLUSION

This review paper has been focused on thermal storage methods and systems in flat plate solar collectors. Applications of sensible heat storage and latent heat storage technologies in flat plate solar water heating systems have been extensively discussed. Thermal performance analysis of the solar collector is based on net heat flow, instantaneous energy gain by the receiver, energy balance in the collector, efficiency of the collector, heat removal factor, usable heat gained by the working fluid and the overall heat loss coefficient. From the discussion on both experimental and modelling work on use of thermal storage fluids in flat plate solar collectors, the following conclusion can be made:

- sensible heat storage media that can be used in solar collectors can be solids or fluids. Solids may include rocks, sand, concrete, and ceramics, while fluids such as water and sunflower oil can as well be used. Latent heat storage, which uses phase change materials (PCM) such as Glauber's salt, calcium chloride hexahydrate, sodium thiosulfate pentahydrate sodium carbonate decahydrate, disodium phosphate, esters, fatty acids, alcohols, and glycols can be used in flat solar collectors.
- Application of thermal energy storage technologies through use of thermal storage media can improve thermal performance and overall efficiency of solar thermal energy conversion systems such as flat plate solar collector for water and air space heating.

RECOMMENDATIONS

- Intensive research on thermal storage medium parameters such as heat removal factor, heat loss coefficient, and overall medium effect on the system efficiency should be investigated.
- Future studies should also be focused on hybrid thermal storage systems incorporating nanoparticles and PCM materials to enhance efficiency.

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