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A Proposed Preheating Technique for Enhancing the Thermal Performance of a Flat-Plate Solar Collector: An Experimental Study

Haitham Farhat Karar [(1)] Ramadan Bassiouny Mohamed [(2)] Mohamed Salah Hassan [(3)]

Mohamed Reda Othman Ali [(4)]

Mechanical& power energy, Faculty of engineering, Minia university, Minia, Egypt [(1)]

mechanical engineer, mechanical& power Energy Engineering,mania city, Mania [(2)]

Mechanical Power Engineering and Energy Department, Faculty of Engineering, Minia University, Minia. 61519, Egypt. [(3)]

Mechanical Power Engineering and Energy, Faculty of Engineering, Minia University [(4)]

Abstract

Due to the worldwide continuous increase in energy demand and cost, great efforts are exerted to seek, develop, and use alternative energy sources. The solar energy is the cleanest renewable source to be used in many applications. One of these applications is the water solar heater. Being simple, cheap, and has low maintenance, the solar heater has been attracting many researchers to study its performance and seek ways for enhancement.

Previous efforts focused on enhancement techniques as absorber surface modification, using phase change material, nano-fluids, thermal coating, and using porous medium around the absorber. As a proposed idea, the present investigation utilizes the stored thermal energy in sandy soil to warm the flowing water before entering the solar heater collector. An experimental, locally manufactured water solar heater was installed in El Wadi El Jadid region (24° 33′ latitude and 27° 13′ longitude).

The results showed an enhancement in the performance of the water solar heater using the thermal energy stored in sand. The daily solar collector efficiency and average outlet water temperature improved by nearly 14.7% and 26%, when sand storage was covered with a plastic transparent sheet and sand was wetted with a certain percentage of waste oil.

Key words: water solar heater – flat-plate collector - solar energy - buried tube – heater performance – sand storage

Highlights:

- A proposed idea of using sand thermal storage with some additives to preheat flowing water before entering the flat-plate collector.
- Aluminum and iron powder with waste oil additives were added to sand to improve its thermal storage capacity.

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- An enhancement in the heater efficiency when sand was used as a preheating compared to traditional solar heater.

- A significant result was obtained when waste oil was added to the sand storage that was covered with a plastic sheet.

1. Introduction

The rapid depletion of fossil fuel and its remarkable effects on the environment forced the efforts to be directed to maximizing the use of renewable energy sources. Renewable energy sources such as solar energy, wind energy, biomass energy, geothermal energy, etc. become essential sources in the field of energy generation, transformation, and saving.

The solar energy has been extensively used in many applications such as: electricity generation through the, photovoltaic, PV cells, using concentrating mirrors to directly boil water, or through heating oil as fluid medium, and the solar chimney principle either for power generation or space ventilation.

Since there is a worldwide great care about energy sources and impact on the environment, renewable technologies are considered as clean sources of energy and its optimal use minimizes environmental impacts. Sun is the source of all energies. The primary forms of solar energy are heat and light. Sunlight and heat are transformed and absorbed by the environment in a multitude of ways [1].

Being simple, cheap, and easy to fabricate and maintain, the flat-plate solar collector is commonly used in heating a fluid as water or air, but it has a lower thermal efficiency and lower outlet temperatures, compared to other heating sources. So, the researchers have been worldwide carrying scientific research in the field of enhancing the thermal efficiency and performance of the solar heater. Farrag and Ayman [2] carried a field study to show the current use situation of solar water heaters in residential blocks of flats build by Egyptian government. They quoted that the sunshine time in Egypt ranges between 9-11 hours with high intensity of direct solar radiation between 2000-3200 kW/m^2. The authors concluded by proposing a road map to maximize the use of solar energy for residential buildings for water heating.

Rajendra and Sharma [3] developed a mathematical model for the thermohydraulic performance of a once-through water solar heater. The model was validated using experimental results. The authors concluded that using heat transfer enhancement techniques, such as twisted tape, can improve the thermal efficiency of the collector by nearly 5.3% to 6.2%. Kanimozhi et al [4] used a porous medium with an agitator to improve the thermal efficiency of the flat-plate collector. Pebble stone was used as a porous medium while an aluminum sheet as an agitator. The authors concluded that using a porous medium and agitator would increase the heat transfer area; hence improve the thermal efficiency to 63.8% compared to 56.6% without porous medium, but with a high pressure drop. Murugavel et al [5] used quartzite rock, red brick pieces, cement concrete pieces, washed stones and iron scraps in the basin of a solar distiller with a minimum water depth. The authors found that the quartzite rock with 19-mm size was found to be the best option. Similarly, glass balls, rubber, and gravel, as a thermal storage material, had been tested by Nafey et al [6] in water solar distiller. The results showed that black rubber (10-mm thick) improves the water productivity by 20% at brine volume 60 L/m^3 and glass cover angle of 15°.

Sakthivel and Shanmugasundaram [7] used 6-mm size of black granite gravel inside the basin of a solar distiller which improved the daily productivity of fresh water by 20%. Abdel Rahim and Lasheen [8] used glass balls packed layer at the bottom of the basin of a solar desalination system and found a 5% improvement in thermal efficiency.

Yassen, T.A et al [9] studied solar water heater with a corrugated absorber surface. The authors reported that the daily thermal efficiency values of the solar collector were 59%, 65% and 67% in case of using corrugated absorber surface depending on the mass flow rates. Filipovi´c et al [10] suggested using a low-cost polymeric material to reduce the overall cost of the collector. They used wooden box as its base and polycarbonate plate as the absorber. However, they found that the efficiency decreased to 30% than the standard flat-plate solar collector. Fan et al [11] developed a V-corrugated new absorber with multichannel and compared it with sheet and tube flat-plat collector. The result showed that the thermal efficiency reached 69.1%; however, challenges are to compensate for the high pressure drop. Chadge et al [12] experimentally and numerically modified the simple solar water heater with V-trough reflectors and compare the experimental results with simulation using Ansys software. The authors concluded that the efficiencies were 79.5%, 91%, and 84%; while using V-trough reflector at an inclination of 65°, 70°, and 75°; respectively with absorber plate compared to traditional solar water collector during typical days of experimentation.

Müller et al [13] conducted a test using different absorber coatings. The results showed that all coatings featured an absorptance above 90% and thermal emittance in the range of 5% to 90%. So, the absorber coating enhanced the thermal performance and reduced the risk of collector overheating during stagnation period. Lati et al [14] tested the performance of collectors with sand coated absorber plates. It was found that the absorber plate, coated with finer sand particles of 0.063 mm diameter has a better performance with a maximum efficiency of 62.1%.

Zhou et al [15] studied the performance of flat-plate solar collector with transparent insulation material. The authors showed that the used material reduced the heat loss from the top surface to the surrounding. However, they reported that the transmittance of this material should be higher than 80% to insure absorbing more incident solar radiation. Visa et al [16] studied a new developed isosceles trapezoidal flat-plat collector focusing on insulation. The results showed that the improved contact between the tubes and the absorber plate has a significant effect on the experimental conversion efficiency. They reported that the efficiency reached 61.85% of different tested configurations.

Ramadhani Bakri et al [17] experimentally investigated the effect of varying glass cover thickness on the performance of a flat-plate solar collector used for drying fruits. The authors concluded that a 4-mm glass thickness improves the performance of the air solar collector by a 7.6%, compared to other thicknesses. Kalidasan and Srinivas [18] theoretically investigated the effect of the number of glass plate and refractive index on the performance of the solar water heaters. The results showed that using two glass covers with a lower refractive index of 1.1 is the optimum for harvesting useful heat. Prasad et al [19] experimentally investigated the performance of a flat plate collector with a tracking system. The results showed that the tracking system improves the heater efficiency by almost 21% compared to the traditional heater.

Faizal et al [20] tried to estimate the potential to design a smaller solar collector that can produce the same desired output temperature. This is possible by using nanofluid as working fluid. The authors reported that a weight save in the collector was obtained when using copper oxide, CuO, silicon oxide, SiO_2, Titanium oxide, TiO_2, and Aluminum oxide, Al_2O_3, nanofluids. Said et al [21] studied the use of TiO_2–water nanofluid as a working fluid for enhancing the performance of a flat plate solar collector. The results showed an increase in the energy efficiency by 76.6% with high exergy efficiency of 16.9% for 0.1% volume fraction and 0.5 kg/min flow rate. Furthermore, the authors concluded that the pressure drop and accordingly pumping power of TiO_2 nanofluid was very close to the base fluid for the studied volume fractions. Rehena and Alim [22] theoretically investigated the effect of the solar irradiation and diameter of the riser pipe through a flat-plate solar collector with Cu nano-fluid used inside the riser pipe of the solar collector. The results showed that the thermal efficiency enhances from 44% to 50%. Further, the mean outlet temperature of Cu/water nano-fluid increases as irradiation increases and decreases as inner diameter of riser pipe increases. Ashour et al [23] numerically investigated the effect of using zinc oxide (ZnO), and CuO as a nano-fluid with three volume concentration fractions of 0.05, 0.10 and 0.15% nanoparticles varied for various mass flow rates of 0.0125 and 0.025 kg/s for a flat-plate solar water collector, under steady Egyptian weather conditions. A 3D computational fluid dynamics model for the investigated system is developed to predict timely outlet temperature and absorber temperature. The authors concluded that the best achievement was obtained by using H_2O–CuO nanofluid with an average efficiency of 81.64% at a mass flow rate of 0.0125 kg /s and nanoparticles volume concentration of 0.15%. H. M. Teamah and M. Teamah [24] developed a mathematical model for studying the effect of the integration of using a phase-change material, PCM, and nano-composite phase change material in the flat-plate solar water collector. The authors concluded that the carbon-based nanocomposites and metal foams have shown the best enhancement of phase change material thermal conductivity. The optimum position for phase change material integration was reported to be beneath the heat transfer fluid tubes

Vengadesan and Senthil [25] experimentally investigated the serpentine flow channeled of a flat-plate solar water collector. The results showed that the serpentine flow channeled collector offers higher energy and exergy efficiencies of 78.9% and 6.47%; respectively at a water flow rate of 0.025 kg/s. Al-Manea et al [26] experimentally and numerically studied the effect of the number of riser tubes connected to headers that are covered with a glass sheet if were replaced with a single serpentine-shaped collector tube covered with a plastic sheet. A transient system simulation, TRNSYS, model for the proposed flat-plate solar collector was developed and validated using the experimental data. The results showed that the average difference between the input and outlet temperatures of the proposed solar collector were approximately up to 23 ◦C. The average efficiency of the collector was approximately 58% with an error of almost 1% between the tests and simulations.

Vengadesan and Senthil [27] experimentally studied the effect of bifunctional rectangular cut flow deviator longitudinal flow inserts with a tilt angle of 30° fixed inside the absorber tube with different water flow rates. The results showed that the maximum obtained instantaneous efficiency was 72.93% at 0.025 kg/s, which is 23.6% higher than that of the traditional collector. In addition, a better exergy efficiency of 3.3% was achieved at lower mass flow rate of 0.0083 kg/s.

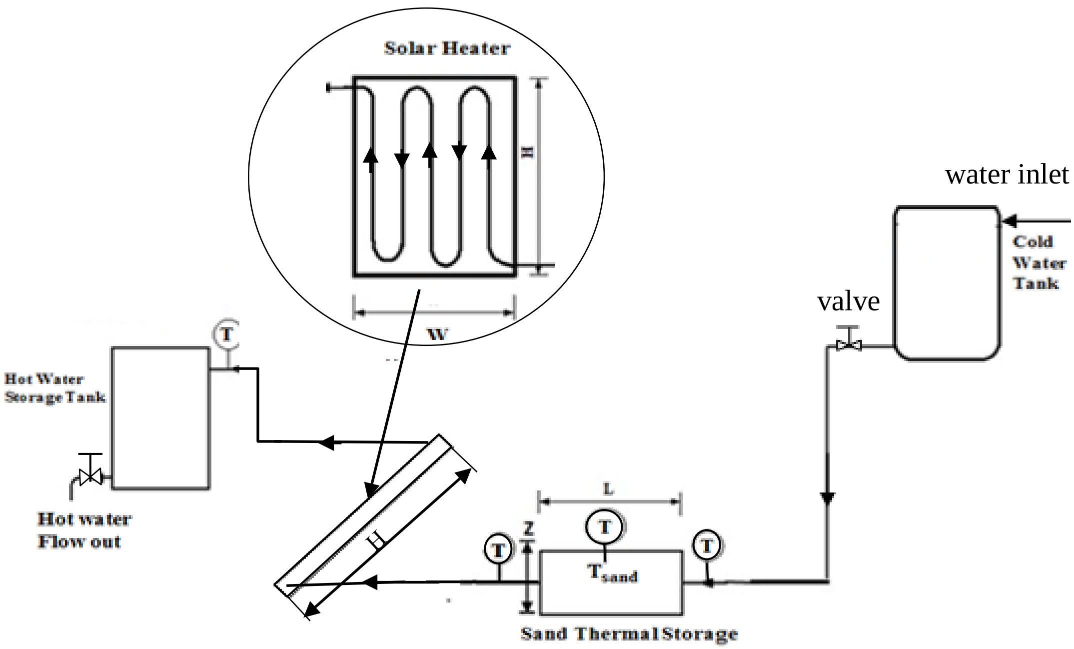
The reviewed previous studies, as surveyed, investigated the improvement of the solar heater through proposing heat transfer enhancement techniques such as using twisted tape, corrugated absorber plate, using porous media with an agitator, using nanofluids, using phase-change material, thermal coating, reflectors such as using glass balls, stones around the absorber. In order to contribute to these efforts, the present study presents a proposed, low-cost technique that utilizes the thermal storage capacity of sand in preheating water before entering the solar collector. The water feeding tube to the heater is buried into sand soil storage at different depths. In addition, a proposed additive is mixed with sand to enhance sand thermal properties, and this accordingly allow transferring some thermal energy from sand to the flowing water before entering the collector, as a preheating technique.

2. Experimental Set-up and Procedure

An experimental, locally manufactured set-up of a water solar heater was installed in El-Wadi El Jadid region in the western desert of Egypt. This region is famous of its abundant solar radiation in addition to sand soil specifications and its thermal storage. Therefore, the study focuses on utilizing the thermal energy stored in sand to warm flowing water before entering the solar collector. As a proposed idea as well, an additive is suggested to be added to the sand aiming at enhancing sand thermal properties, and accordingly thermal capacity.

Figure 1 shows a schematic diagram of the experimental set-up. It consists of a flat plate collector with an area of 1.22 m (W) x 1.40 m (H) coupled with a sand container of area 0.79 m (L) x 0.35 m (Z) through which the feeding tube is passing at a depth of 20 mm. A cover made of transparent plastic sheet of 3 mm thickness is used to cover the sand container. The collector has thirteen 20-mm diameter iron tubes with a length of 1.22 m. The tubes are laid on a black metal sheet of 1.25 mm thickness that is insulated from the back. The collector is facing south with an inclination angle of 33° to the horizontal. Photos of the experimental set-up are shown in Fig. 2.

The experimental tests were carried out in El-Wadi El Jadid region in the western desert of Egypt (24° 33′ latitude and 27° 13′ longitude). Water flows through the tubes with a rate of 0.005 and 0.006 kg/s. The tubes are placed at 45 mm underneath the glass cover. The back of the collector was insulated using foam to minimize the heat loss to the surroundings. The glass cover edges were sealed with silicon paste to prevent the leakage of hot air from the inner of the collector.



T= Temperature measurement

Figure 1 A Schematic Diagram for the Experimental Set-up.

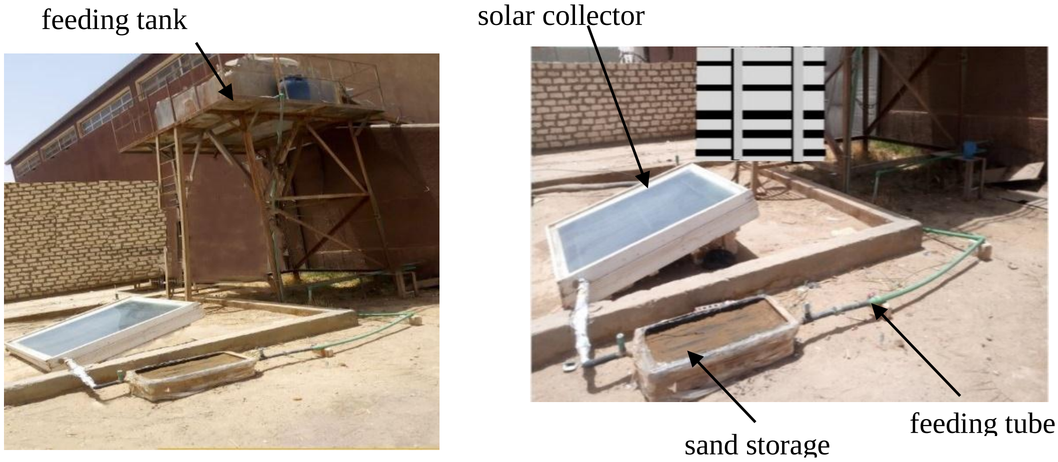


Figure 2 Photos for the Experimental Set-up with Different Components.

Measurements were taken during the winter months, January, February, and April 2021 from sunrise to sunset. Different temperatures were measured using a Mercury-in-glass thermometer (± 0.5^{o}C) and type-K thermocouples (± 0.1^{o}C). The experiments were carried while the dry sand container uncovered and covered with a plastic transparent sheet. Also, other tests have been carried out using a fraction of waste oil added to the covered sand container. The top surface of the sand container is totally exposed to sun radiation. The surface of the sand plays an important role in allowing incident radiation to be largely absorbed. Table 1 summarizes the cases, subcases, and the description of experimentally studied conditions. In all cases, the water temperature at the inlet and outlet of sand container and solar collector was timely measured. Along with that the hourly solar intensity was measured over the day, then the daily average was estimated.

Table 1 Different studied cases of water solar heater system

Case	**Proposed Idea**	**Subcase**	**Description**
I	----	*A*	Traditional, local-manufactured, flat-plate solar water heater
II	Preheating using dry sand storage	*B*	Sand container is uncovered
		C	Sand container is covered with a plastic sheet
III	Modified sand properties using Waste oil	*D*	Adding 1 kg of waste oil to sand container covered with a plastic sheet

It is very necessary to estimate the error in the measured parameters to judge the accuracy of the quantitative assessment of the system. Therefore, the uncertainty is a method used to estimate the possible values of the error envelop of the reported results of a measurement.

The result R is a given function can be represented as [28]:

$$R = f(x_1, x_2, \ldots\ldots\ldots, x_n) \tag{1}$$

Let w_R be the uncertainty in the result and w_1, w_2, w_3......., w_n be the uncertainties in the independent variables, x_i. The uncertainty in R can be written as [28]:

$$w_R = \left[\left(\frac{\partial R}{\partial x_1} w_1\right)^2 + \left(\frac{\partial R}{\partial x_2} w_2\right)^2 + \cdots + \left(\frac{\partial R}{\partial x_n} w_n\right)^2\right]^{1/2} \tag{2}$$

A standard K-type thermocouple was used to measure the water temperature. The junction of the thermocouple is almost 1 mm in diameter. This thermocouple has an accuracy of 0.1 ºC, with a percentage of error about 0.25%. A calibration process of the K-type thermocouple versus a mercury-in-glass thermometer reported a deviation of about 2%. A solar power meter was used to measure the solar intensity. This meter has a range up to 1999 W/m^2 and a resolution of 1 W/m^2 with an accuracy (± 10 W/m^2).

The instantaneous solar intensity, $I(t)$, falls on the collector surface. According to the surface featured, part of the incident solar rays is transmitted through the glass surface based on glass transmittivity, τ. This part is absorbed by the absorber plate according to its absorptivity, α, as:

$$S = \alpha\ \tau I(t) \tag{3}$$

Of this amount, the useful part, Q_w, is carried by the flowing water, and is estimated as [20]:

$$Q_w = \dot{m}_w C_w (T_{w,o} - T_{w,i}) \tag{4}$$

The collector efficiency is defined as [20]:

$$\eta_c = \frac{Q_{w,total}}{Qs,total} = \frac{\dot{m}_w C_w (T_{w,o} - T_{w,i})}{I A_c} \tag{5}$$

In case of using sand storage, as a preheating medium, there should be a water heat gain before entering the solar collector. Therefore, the inlet water temperature to the solar collector is the outlet water temperature coming out the sand storage.

3. Results and Discussion

In order to achieve the aim of the study, measurements have been carried out under different operating conditions. The measured parameters are the key to evaluate the system thermal performance. The motive driving parameter for the heater to fulfill its function is the solar intensity. Therefore, the intensity is daily measured over time. The temperature flowing water, sand, and ambient were measured, in addition to water flow rate were measured as well.

Figure 3 shows the daily solar intensity variation over three months: January, March, and August. The figure indicates the hourly increase of solar intensity from sunrise till noon time, and then it nearly decreases similarly till the sunset. As shown in the figure, almost an average intensity of 800 W/m^2 was recorded in the region of experiments.

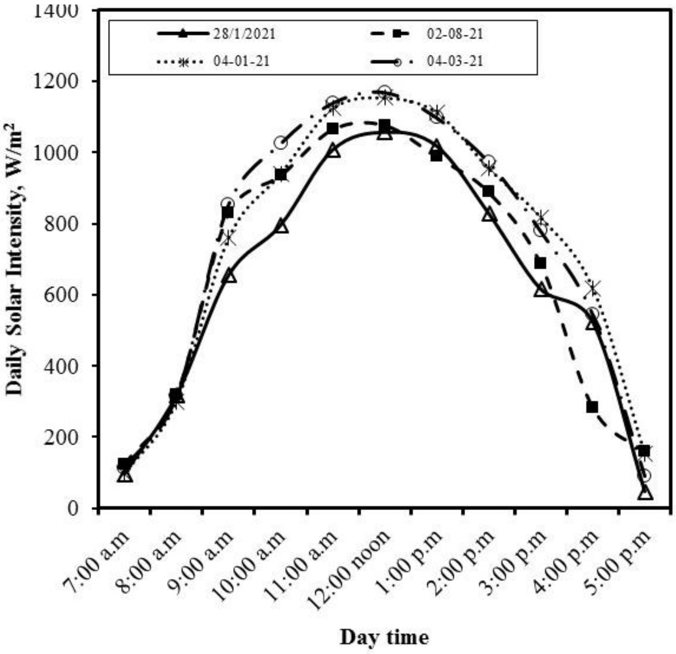


Figure 3 Solar radiation intensity at days of experiments.

In order to decide the optimum depth in sand at which the water tube is buried, a temperature distribution of the sand should be known. Figure 4 illustrates the average monthly sand temperature at five different depths. The measurements were taken all over the year. All measurements showed that the sand has its higher temperature at a depth of 20 mm from the upper surface, and then it decreases as the depth increases. This can be attributed to the accumulated absorbed heat in the layer near the upper surface, then the diffuses towards the depth increase.

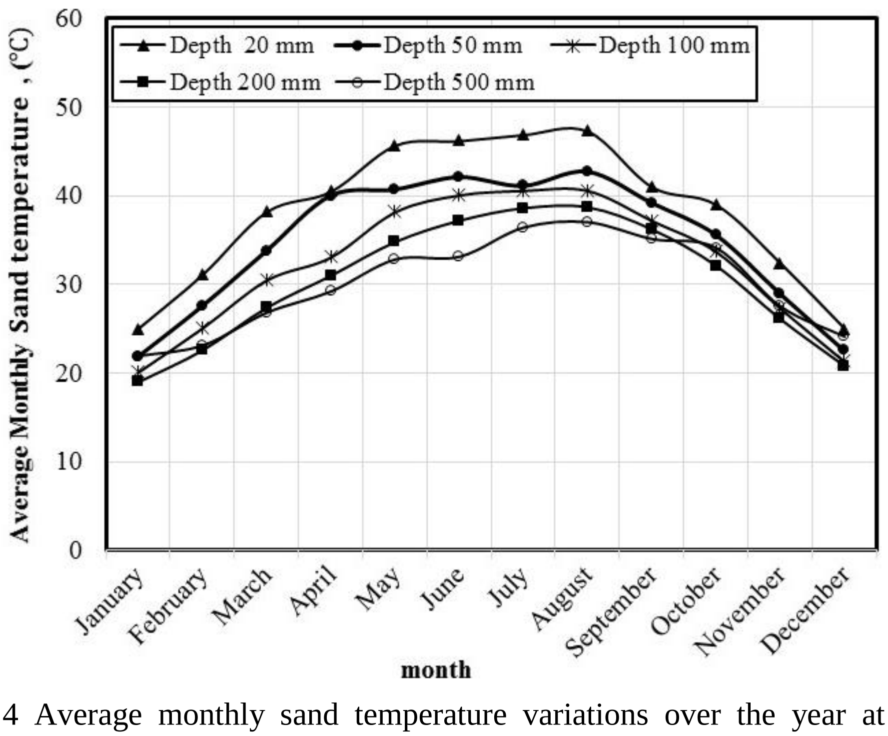
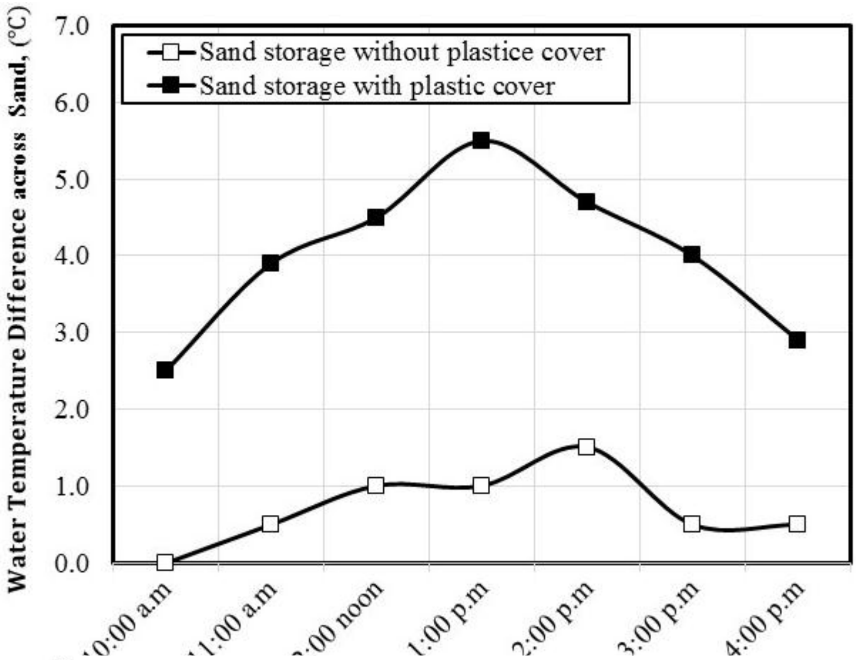


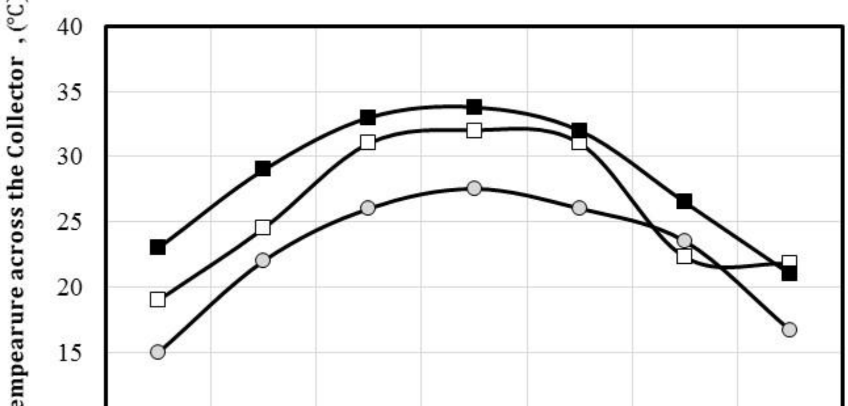
Figure 4 Average monthly sand temperature variations over the year at different depths.

Since the necessity for hot water usually is in the months of winter, the water temperature variation with or without using the sand storage across the flat-plate collector is presented in Fig. 5 a and b during days of January. Figure 5a shows the experimental results in Case II of burring the tube into sand storage with and without a sheet of plastic cover, subcases B and C, Table (1). The figure illustrates the increase of water temperature difference as water passes through the sand storage, $\Delta T_{w,s}$ over a day and it reaches its peak value at 1:00 pm, which is almost corresponding to higher solar intensity at similar hours. It seems that having a plastic sheet cover enhances the water preheating due to reducing the losses to the surrounding, and accordingly increasing the useful energy going into the sand and buried tube it contains.

On the other side, Fig. 5b shows the water temperature difference across the flat-plate collector for the two subcases compared to the traditional solar heater. It is noticed the variation in temperature difference enhanced in case of using the sand storage whether is covered or uncovered with a plastic transparent sheet. This can be attributed to the more trapped solar radiation, similar to green-house effect. A little enhancement was noticed in the average daily collector efficiency by almost 44.11 % and 46.02 % at (subcase B and C sequentially), compared to 43.78 % for a traditional solar collector, (case I).

As a proposed idea to enhance the sand thermal storage energy, a disposable oil was added to wet the sand storage to take advantage of that. This aims to wet the sand soil and study its effect on solar radiation absorbtance. This is Case III with subcases D waste oil with sand.

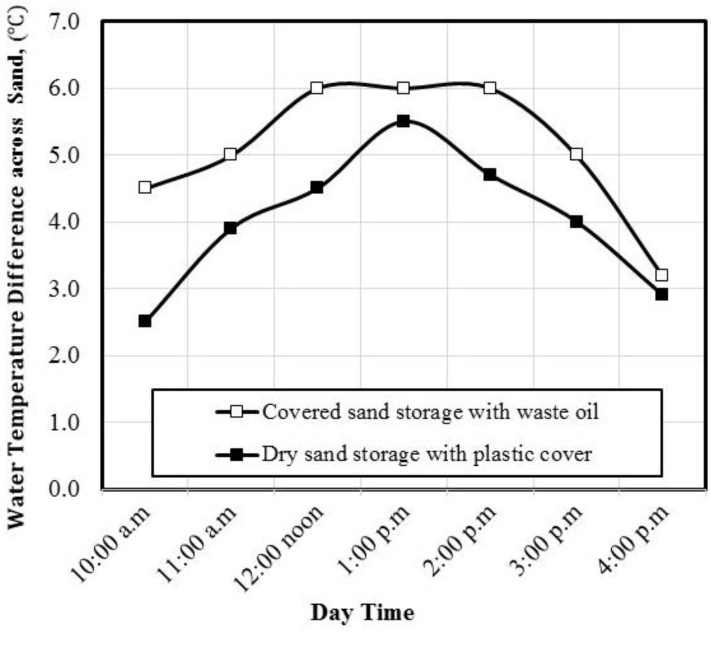




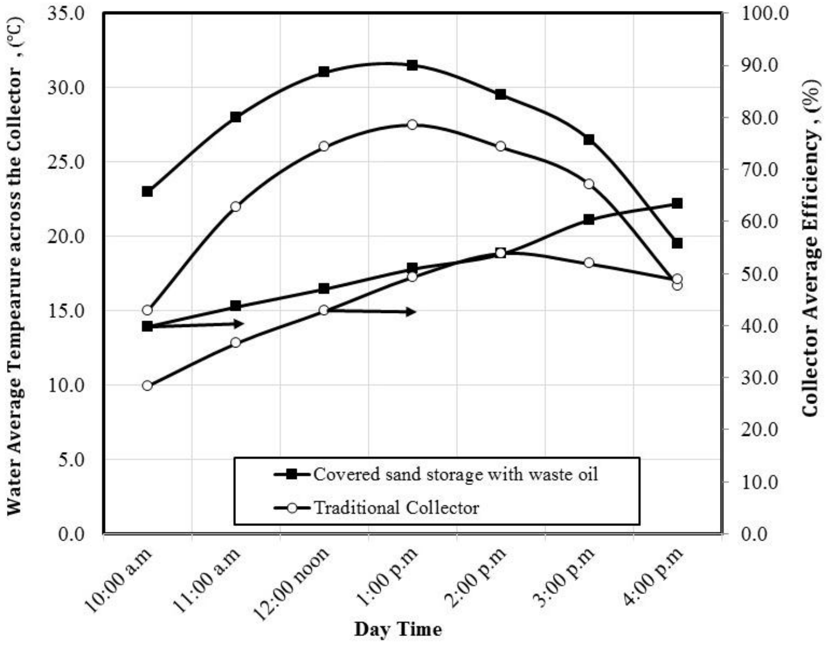
(b)

Figure 5 Water Temperature difference across (a) Sand storage (b) Solar collector.

Figure 6a explains the temperature difference between outlet and inlet water temperature through sand storage, $\Delta T_{w,s}$, over a day; while Fig. 6b explains the temperature difference across the flat-plate solar collector, $\Delta T_{w,c}$. As shown in Fig. 6 (a and b), an enhancement in the performance of the solar collector when coupled with sand storage, as a water preheating technique before entering the flat-plate collector. Almost, allowing the feeding tube to pass throguh a dry sand storage covered with a plastic sheet enhances the water temperature differenc by 20.6%; while this enhancement becomes nearly 26.4% when a volume percent of waste oil was added to the sand storage. Having a plastic sheet to cover the dry sand storage reduces the heat loss to the surrounding, and accordingly increases the heat gained by the flowing water. Adding waste oil to the sand can increase the thermal capacity of the pure sand. This can be attributed to having sensible and latent heat stored in both sand and oil.



(a)



(b)

Figure 6 Water average temperature difference across a) sand storage, b) solar collector and colleector efficiency when adding waste oil to sand.

Since the water temperature increases, this means that the useful heat absorbed in sand and carried by flowing water increases. This is an indicator of efficiency increase. Comparing to the traditional solar heater, using sand coupled with the flat-plate collector enhances the heater performance.

Table (2) summarized the overall enhancement in the solar heater efficiency for the proposed idea of using the heater coupled with in-sand buried tube. The idea depends on using sand thermal storage by enhancing its thermal conductivity. This enhancement increased the outlet water temperature from the collector due to utilizing energy stored in the sand, if compared to the traditional solar collector. The table indicates the more heat captured and utilized to heat water occurred in case III when dry sand was wetted by waste oil. The table indicates that almost using sand wetted with waste oil enhanced both the average water temperature across the heater and collector efficiency by almost 26% and 14.7%; respectively, compared to the traditional collector.

Table (2) Overall average daily water temperature difference and collector efficiency.

Case	**Subcase**	$\Delta T_{w,avg}$	$\eta_{C,avg}$
		°C	%
I	**A** (Traditional collector)	**22.39**	**43.78**
II	**B** (Dry sand, without cover)	**25.94**	**44.11**
	C (Dry sand, with cover)	**27.0**	**46.02**
III	**D** (Covered sand with oil)	**28.3**	**50.21**

Follows is an overall comparison for the performance enhancement of the proposed technique compared to other modification techniques. Table (3) summarizes the performance enhancement obtained for the low-cost, locally manufacured solar collector compared to other modification techniques. Certainly, the performace enhancement is worthy for a low-cost manufactured solar collector.

4. Conclusions

The present study introduces a proposed idea to improve the performance of a simple, easy to maintain, locally manufactured water solar heater. The proposed idea is to let the water feeding tube pass through sand soil at a certain depth before entering the solar collector. The results concluded that an enhancement in the solar heater average daily efficiency was noticed for the proposed idea. Quantitatively, some concluded points were drawn as:

- Almost a 15% enhancement in the collector efficiency using sand storage with waste oil is noticed, compared to the traditional flat-plate solar collector. On the other side, the collector efficiency reached 46% in case of using dry sand storage covered with plastic sheet compared to 43% for the traditional solar heater.
- An enhancement in the water average temperature difference and collector efficiency by 26% and 14.7%; respectively when waste oil was added to the sand covered with a plastic sheet.

As a recommendation to think about using nanoparticles of high conductive, economic material to enhance the sand thermal properties to be used as a thermal storage.

Table (3) Overall comparison of present proposed technique to some other modification techniques listed in the literature.

Authors	Efficiency of traditional collector	Modification technique	Max. Efficiency
Kanimozhi et al [4]	43.71%	Using Pebble stone as a porous medium while aluminum sheet as an agitator.	49.27 %
Ramadhani et al [17]	32.9%	Varying glass cover thickness on the performance of a flat-plate solar collector	35.4%
Vengadesan and Senthil [25]	61.93%	Serpentine flow channeled with mass flow rate 0.025 kg/s	78.9%
Al-Manea et al [26]	48%	Replacing the number of riser tubes connected to headers with the single serpentine-shaped	58 %
Vengadesan and Senthil [27]	59%	bifunctional rectangular cut flow deviator longitudinal flow inserts with a tilt angle of 30° fixed inside the absorber tube	72.93 %
Present study, Low-cost, Locally, Manufactured solar collector	43.78%	Solar collector coupled with sand thermal storage (Adding 1 kg of waste oil to sand container covered with a plastic sheet)	50. 2 %

Nomenclature

A area, m^2
C Specific heat, $J\cdot kg^{-1}\cdot K^{-1}$
H collector height, m
I solar intensity, W/m^2
L sand storage length, m
$\dot{m}$ water flow rate, kg/s
Q Thermal energy, J
S absorbed solar radiation on the collector, W/m^2
T Temperature, (K or °C)
W collector width, m
Z sand storage width, m

Greek symbols

ε emissivity
η daily efficiency of the collector, %
τ glass transmittivity
α absorptivity
ρ water density, (kg/m^3)

Subscripts

avg average
c collector
i inlet
o outlet
w water

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