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Improving the Performance of a Home Solar Water Heater System Using Porous Materials and Reflectors

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Keywords:
Reflectors; SWH; Thermal Energy Storage; Thermal Load; Thermal Performance; Porous Medium.

Highlights:
- *Overall performance of the SWH system was examined experimentally with using porous media and reflectors in open cycle.*
- *The effect of water mass flow rate on the SWH thermal efficiency was considered.*
- *The value of the overall thermal efficiency of the SWH with using both the PM and reflectors was higher than the value with performing the PM only.*
- *Adding a PM increased the water-carrying pipes' surface temperature in the SWH.*

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Abstract: Solar energy storage is essential in renewable energy systems, considering that solar energy is a periodic energy source that depends on time, so the intensity of solar radiation changes from time to time. Therefore, solar energy systems require storing energy to save it during the night periods or on cloudy days. The current solar heater designs are not feasible and ineffective unless energy storage is utilized (energy retention). The present research addresses improving the home solar water heater (SWH) performance under the atmosphere of Iraq. This study improves the thermal performance of a solar water heater integrated with a thermal storage tank using materials storing heat to achieve the most extended possible period of receding solar radiation. The SWH system performance was experimentally tested in Tikrit-Iraq. Several experiments were performed from 8:30 am to 16:30 hours in February 2022 with a water mass flow rate ($\dot{m}_w$) of (0.016 kg/s) for the circulation system and with a thermal load on the hot water tank ($\dot{m}_{th.L}$) of (0.0066 kg/s) for the two porous medium design cases (with and without solar reflectors). The results manifested that the maximum daily thermal efficiency (η_o) of the SWH system was 36.40% for design case 2 (with porous media and reflectors) at a (0.006 kg/s) thermal load compared to the case 1 (with porous medium and without reflectors) of 32.21%. At the same load, the outcomes elucidated that the overall thermal efficacy of the SWH regime in the convection presence provided the uppermost value utilizing porous media and reflectors. Also, the outcomes of the present investigation were compared with the preceding study, and the comparison outcomes were better than the present design circumstances.

تحسين اداء نظام سخانات المياه المنزلية بالطاقة الشمسية باستخدام المواد المسامية والعاكسات

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الخلاصة

يعد تخزين الطاقة الشمسية أمرا ضروريا في أنظمة الطاقة المتجددة، مع الأخذ بنظر الاعتبار أن الطاقة الشمسية هي مصدر طاقة دوري يعتمد على الزمن، وبالتالي فإن شدة الإشعاع الشمسي تتغير من زمن الى آخر. ولهذا ان أنظمة الطاقة الشمسية تحتاج تخزين الطاقة لحفظها خلال اوقات الليل أو في ايام ملبدة بالغيوم. المشكلة التي تعاني منها تكمن في تصميم السخانات الشمسية، حيث أن التصميم المتوفر حالياً ليس مجدياً وغير فعال إلا إذا تم استغلال تخزين الطاقة (الاحتفاظ بالطاقة). فالمشكلة التي يتناولها البحث كيفية تحسين أداء السخان الشمسي المنزلي في أجواء العراق. يتناول هذا البحث طريقة تحسين الأداء الحراري لسخان الماء الشمسي المدمج مع خزان حراري باستخدام مواد يمكنها تخزين الحرارة لأطول فترة ممكنة في أوقات انحسار الإشعاع الشمسي. تم اختبار أداء نظام سخان المياه الشمسي تجريبياً في العراق - تكريت. أجريت عدة تجارب خلال شهر فبراير ٢٠٢٢ بمعدل تدفق خلال معدل تدفق كتلي رئيسي مقداره (٠,٠١٦ كغم/ثانية) لنظام التدوير، وبحمل حراري على خزان الماء الساخن مقداره (٠,٠٠٦٦ كغم/ثانية) للحالتين ذات التصميم الوسط المسامي (مع وبدون العواكس الشمسية) أجريت الاختبارات التجريبية من الساعة ٨:٣٠ صباحاً حتى الساعة ١٦:٣٠. أظهرت النتائج أن الحد الأقصى للكفاءة الحرارية الكلية (η_o) لنظام SWH كان ٣٦,٤٠٪ لحالة التصميم الثانية (عند دمج الوسائط المسامية والعواكس) عند الحمل الحراري مقداره ٠,٠٠٦ كغم/ثانية مقارنة بالحالة الأولى (وسط مسامي بدون عاكسات) بنسبة ٣٢,٢١٪ عند نفس الحمل. أظهرت النتائج أن الكفاءة الحرارية الكلية لنظام SWH بوجود الحمل الحراري أعطت أعلى قيمة عند استخدام الوسائط المسامية والعاكسات معاً. وتمت مقارنة نتائج الدراسة الحالية مع الأبحاث السابقة، وكانت نتائج المقارنة أفضل في ظل ظروف التصميم الحالية.

الكلمات الدالة: العاكسات، SWH، تخزين الطاقة الحرارية، الحمل الحراري، الأداء الحراري، الوسط المسامي.

1.INTRODUCTION

Renewable energy is one of the standard measures for evaluating economic growth and living standards due to its reliability. The solar energy is an attractive renewable energy source that can be used in domestic water heating. The water heating consumes approximately 20% of the total energy consumption of an ordinary household [1]. Also, one of the most significant solar energy applications is solar water heaters (SWH), which are used worldwide for numerous purposes, like laundry, showers, and domestic central heating. Also, the Flat Solar Collector (SFC) and the Thermal Storage Tank (TST) are the principal parts of the solar system; the first component arrests the heat from the solar energy and transfers it to an operating fluid inside the collector, while the second component is the Storage Tank (ST) that stores the thermal energy leaving the collector to compensate the thermal load [2]. Several researchers studied how to use different materials, such as porous materials such as stone and gravel, and inexpensive and new design additions, such as solar reflectors, to improve the SWH system in the process of Solar Thermal Storage to maximize the benefits of meeting society's needs. The present research resulted in the stable evolution of SWH's existing technology. Deepak and Adhichelvan [3] improved the thermal efficiency of SWH by employing porous media. The study experimentally measured the water temperature in the case of porous media presence and compared it with a solar heater without the presence of additions or improvements. The temperature of the water produced from the solar water heater with and without the porous media was verified as (32.97 °C) and (30.55 °C). Mandal and Ghosh [4] studied the double-pass solar water heater (DPSWH) performance with an inverter by studying the effect of mass flow rate on the outgoing water temperature. The thermal performance ranged from (0.0022 to 0.0044 kg/sec), where the ultimate thermal efficacy obtained for a flow rate of (0.0044 kg/s) was (50.26%). Eleiwi et al. [5] improved the thermal energy storage performance of a SWH using a porous medium and phase change materials by conducting an experimental evaluation of SWH thermal performance analysis: Without utilizing a porous medium (PM) and a phase change material ((i) PCM), (ii) with the PM and without PCM, and (iii) employing the PM and the PCM outcomes for the system's total thermal efficiency (η_o) with a volume evinced an enhancement of about (2.83%) and (6.35%) in case 3 compared with cases 1 and 2, respectively. In their experimental analysis, Kanimozhi et al. [1] used a porous medium with the catalyst to improve the SWH system's thermal efficiency. They used gravel as a heat-absorbing porous medium in the solar collector, in addition to using strips of flow agitator inside the SFC tubes. It was found that the system's efficiency reached (63.8%) using a porous medium and (56.6%) without it. Atram and Satpute [6] studied the effect of mineral foam as a porous material on the thermal performance of a SWH for increasing heat transfer. Also, the authors compared many experimental results cases. It became clear from the data that the maximum water temperature in the solar heater without additives was (35 °C), and with the porous media was (47.5 °C). Bhowmik and Amin [7] conducted an experimental facility of a solar heater system consisting of a flat metal solar collector using inverters with and without reflectors tested in (Gazipur, Bangladesh). The practical results showed that using a reflector improved the solar collector's performance by increasing the concentration of the solar radiation intensity upon the collector surface. The collector's total efficiency without reflectors was (51%) and with reflectors was about (61%), with an increase of (10%). Mulugata and Tesfay [8] based on the design of the solar panel complex and the influence of integrated reflectors with solar collectors installed upon the sides of the complex (bottom, top, left, and right) and at three angles, i.e., (15°), (30°), and (45°), from the horizontal plane, was analyzed. As for the collector's efficiency, experiments were conducted on the solar collector with and without reflectors. The results illustrated that the maximum temperature of the exit water was about (98 °C) at a total solar radiation intensity of (1200 w/m^2) obtained on a sunny day with the presence of reflectors. The maximum exit water temperature, i.e., the collector without reflectors, was about (70°C) at the same radiation value obtained on a sunny day. Jouybari et al. [9] investigated the effect of porous mineral foam on the FSC performance at different flow rates using the ASHRAE standard to examine the effect of mineral foam. The authors found that the porous material improved the energy absorption coefficient up to 18.5%. Bagaria et al. [10] used pebbles and flat metal chips to increase the SWH heat absorption. The design model elucidated a significant improvement in heating efficiency from 18% to 22% with an increase in working time by 2 hours. Kadhim and Habeeb [2] aimed to study the effect of porous materials on increasing the time of the hot water supply to solar collectors to improve the storage time in the TST as long as possible. Also, the experiments were performed with no porous media and various porous media levels, i.e., 150, 300, and 450 mm. Also, the outcomes portrayed that increasing the porous media level contributed to the hot water supply at a temperature beneficial for home usage (>20 °C) during the day. Sopian et al. [11] investigated the thermal efficiency of a double-pass solar collector (DPSC) with and without porous media by developing a theoretical and experimental model of a DPSC. Comparisons were made between the theoretical and practical results, including the solar collector's outlet temperatures and thermal efficiency for different designs and operating conditions. The results showed that the theoretical simulation and the investigational data are close. The results showed that the porous media in the second channel increased the heat transfer area. The typical thermal efficiency of the double-pass collector with the porous media was 60-70%. Balashanmugam and Balasubramanian [12] conducted an experimental work using a porous media-excited SWH in a new and effective way to improve the system's thermal efficiency by filling the collector surface with gravel and stainless steel chips to capture and retain the heat for a longer period. The researchers found that the collector's efficiency with the agitator and foil was the highest among all other combinations. The present investigation presents an experimental test by building an integrated SWH system with a TST using simple, economical, and available materials in the local markets. This study aims to increase the SWH thermal performance to the best level by adding gravel, as an absorbing surface, into the solar collector and solar reflectors, i.e., to increase the concentration of radiation intensity solar on the collector surface. Also, in light of previous investigations, the combination of the two porous media and the reflectors under the climatic circumstances of Tikrit in Iraq has yet to be studied. Also, the current work aims to enhance the SWH's thermal performance by conducting an experimental study to find out the effect of the thermal load $\dot{m}_{th.L}$ on the SWH's performance and its role in heating water to the best level for domestic use.

2. METHODOLOGY

A SWH with a storage tank, using a porous medium (PM), and reflectors are explained in this section regarding the SWH manufacturing, experimental procedure, measuring devices, and total thermal efficiency.

2.1. SWH Building Specifications

The single open-loop solar collector was built from a rectangular container made of wood, i.e., (137 cm) in length, (86 cm) in width, and (15 cm) in height, linked with thermal storage. An absorbent plate was fitted in this container, which comprised parallel Copper (Cu) tubes that were equally set apart with an inside diameter of 10.5 mm, an outside diameter of 15.1 mm, and a (120 cm) length. Also, the space between every center line of nearby tubes was 10 cm. The system design was selected based on a previous study [13]. Additionally, these tubes are linked to two header tubes at the ends. Furthermore, these tubes were made from brass with a 41 mm outer diameter and 80 cm length, with two open ends for the collector as its inlet and outlet. The headers' open ends were supplied with screws for easy separation. The tubes with the headers were semi-submerged on the surface of commercial pebbles. The pebbles were used as a porous medium to absorb a portion of the total solar energy and release it into the working fluid during the day. Table 1 shows the physical properties of the gravel used in the present study. The porosity and density properties were measured in the College of Chemical Engineering, Tikrit University laboratory. The collector box was covered with a sheet of 4 mm-thick single-wall glass. Two concentric cylindrical tanks were made from galvanized steel sheets, and the water storage in the inner tank had a capacity of 18 liters. The storage tank was furnished with a float for controlling the water quantity, fed from another water supply tank. Also, reflectors (68 cm long and 86 cm wide) were installed on the upper and lower edges of the solar collector, and the design of the corners was selected based on the study [14]. The reflectors' role is to increase the incident solar radiation intensity concentration on the collector surface. The upper reflector was installed with the norm at an angle (θ_1), while the lower reflector was installed with the horizon at an angle (θ_2) with the possibility of controlling the inclination angle based on the period in which the test was conducted. The inclination angle was determined from Eleiwi and Shallal [15], as shown in Fig. 1. Also, the construction details of the present prototype are listed in Table 2 and revealed in Fig. 2.

Table 1 Physical Properties of the PM.

Material	Porosity %	Density g/cm³
Pebbles	31	2628

Table 2 The Technical Specifications of SWH.

Part	Specification
Frame of solar collector	137 × 86 (cm)
Reflectors dimension	68 × 86 (cm)
Number of reflectors	2
The absorber plate	120 × 80 (cm)
No. of tubes	8
Thermal conductivity of the Plate material	386 (W/m. K)
Riser pipes diameter	15.1 (mm)
Diameter of header pipes	41 (mm]
Material of absorber plate	Copper
Thickness of glass sheet	4 (mm)
Angle of collector	(45°)

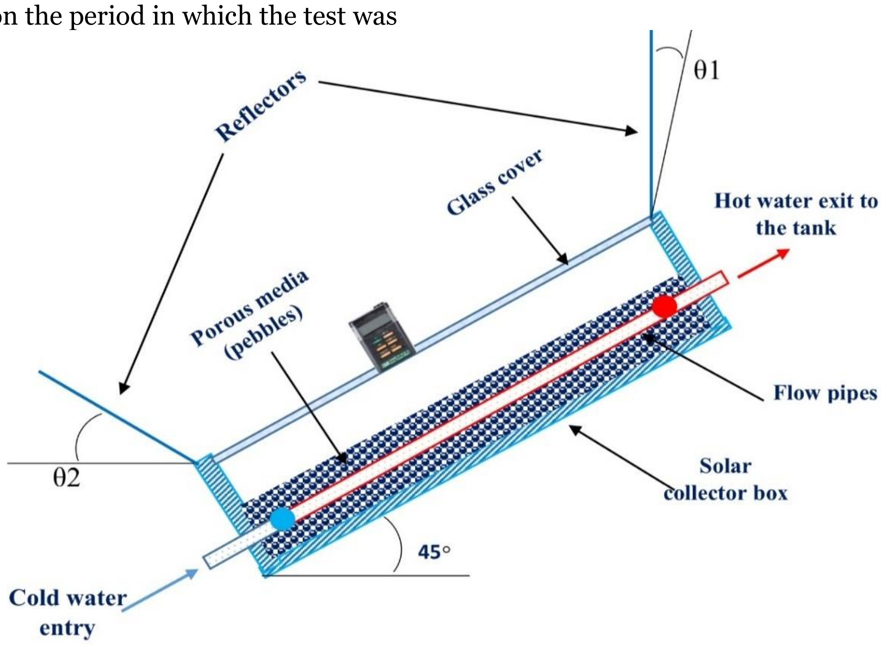


Fig. 1 Schematic for Reflectors Installed on the Solar Collector.

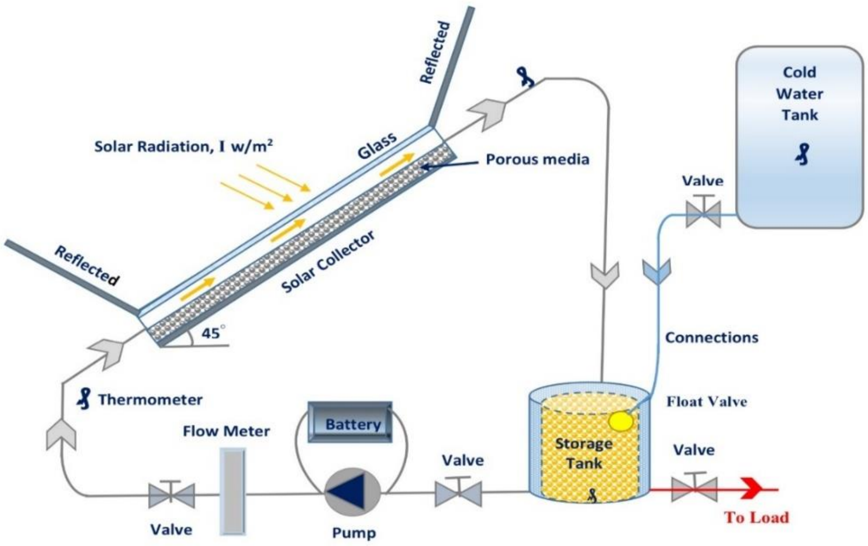


Fig. 2 The Schematic of the Investigated System of Solar Thermal Collector.

2.2.Experimental Work and Instruments of Measuring

The SWH was directed toward the south of Tikrit City in Iraq (latitude=34.27˚N and longitude=43.35˚E). Two cases were studied: with porous material without reflectors and with porous material and reflectors. The water mass flow rate was (0.0166 kg/sec) in all experiments. The experiments were conducted from 8:30 to 16:30. The $\dot{m}_{th,L}$ (Appendix A) was measured using a mass flow meter at 12:00 to 16:30. Three thermal load mass flow rates were considered, i.e., 0.0029, 0.0044, and 0.0066 kg/s. Additionally, the solar collector was mounted upon a frame made of steel at a (45°) angle from a horizontal axis. Furthermore, the experiments were conducted on sunny and cloudless days. Before performing the experiments, the glass was washed using distilled water, a battery was pre-charged completely, and a pump was connected to the battery. The measuring devices were turned on. The data was recorded every 30 minutes. The assembly of the solar collector components with heat storage is shown in Fig. 3. Two thermal storage states of the SWH system were tested in the presence of a porous medium and with and without reflectors. Eight thermocouples (TPM-10) were utilized for measuring the temperatures from (-50°C) to (110°C) in various locations, as shown in Fig. 4, with a (±1°C) accuracy. In addition, a solar meter (TES-1333 R) was utilized to measure the solar radiation intensity with an accuracy of (±5%). Furthermore, a digital thermometer type (AS-MHT2) was used to measure the ambient temperature with an accuracy of (±1°C). Moreover, a supplementary pump (AD20P-123°C) was used to circulate water from a tank to the collector at an ultimate rate of (60 L/h). This supplementary pump can be governed via a valve with (4%) accuracy. Its uncertainty analysis was also calculated in Appendix A.

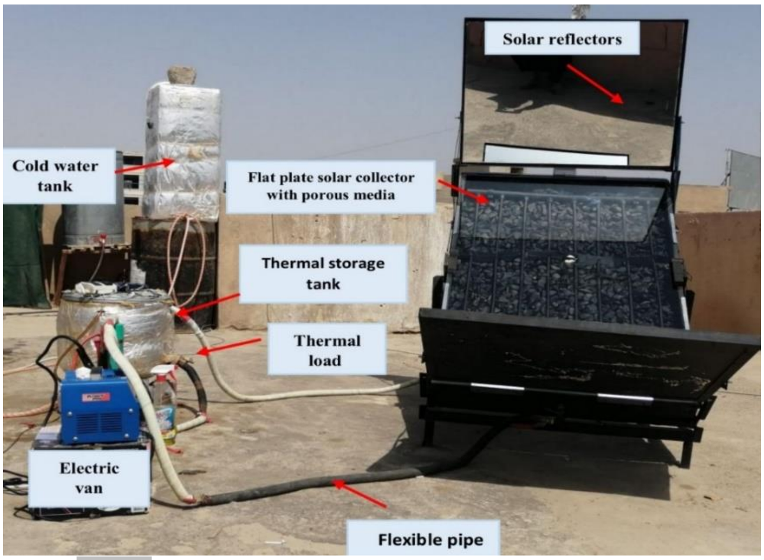


Fig. 3 The Photographic Depiction of the Operating Model of the Flat Plate SWH with a TST.

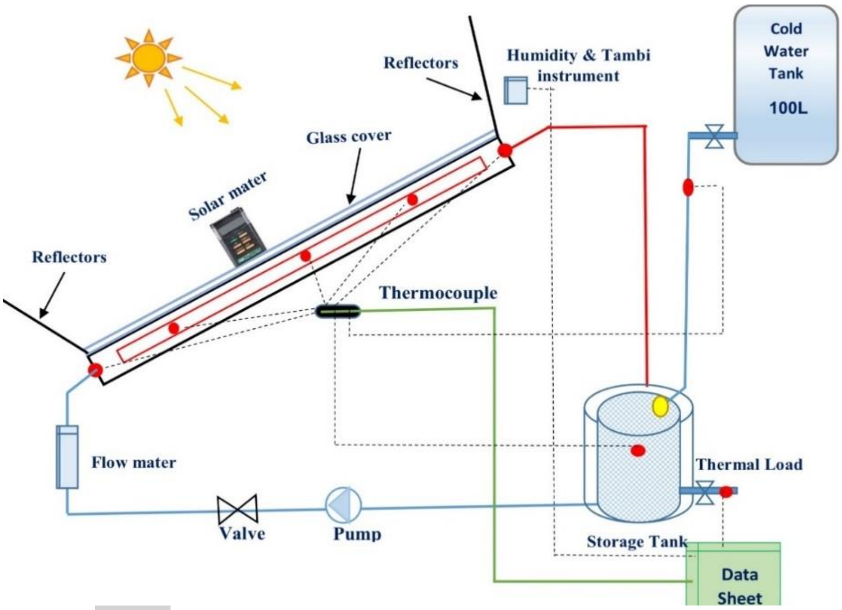


Fig. 4 Thermocouples Locations of the System of SWH.

3.CALCULATIONS

The total thermal efficiency (η_o) was computed for (2) cases, with PM with no reflectors and with PM and reflectors for a solar system. The solar collector efficiency (η_c) was computed as follows [15]:

$$\eta_o = \frac{Q_T}{Q_{in}} \times 100\% = \frac{Q_l + Q_s}{Q_{in}} \times 100\% \quad (1)$$

where Q_{in} represents the collector's overall solar energy and can be computed as follows [16].

$$Q_{in} = \int_0^t I\, A_C\, dt \quad (2)$$

Where I is the solar radiation (W/m²), and A_c is the solar collector aperture area (m²). The tank's energy stored (Q_S) can be written as [17]:

$$Q_S = \dot{m_w}\, C_{p_w}\left(T_{f,tank} - T_{i,tank}\right) \quad (3)$$

where (M_w), ($T_{i,\,tank}$), and ($T_{f,\,tank}$) represent the mass (18 kg), the water's initial temperature in the storage tank measured at (8:30), and the water's final temperature in the storage tank and measured at (16:30), respectively.
The total heat load energy (Q_l) taken from the hot water tank can be calculated as follows [18]:

$$Q_l = \dot{m_w}\, Cp_w \int_0^t (T_{out,l} - T_{in,l})dt \quad (4)$$

Where $\dot{m}_w$, $T_{in,L}$, and $T_{out,L}$ represent the rate of mass flow, the temperature of hot water drawn from the HWT initial load, and the temperature of the hot water drawn from the HWT final load for domestic use, respectively.

4.RESULTS AND DISCUSSION

Two cases were tested: (1) With PM and without reflectors, and (2) with PM and reflectors on (16/2/2022) and (19/2/2022) for each case at (0.0166 kg/sec). Also, the forecast outcomes, like (η_o), (Q_{tank}), (I), (T_{tank}), and stored outlet water temperature ($T_{w,\,out}$) were considered.

4.1.Environmental Data Variations

The results of the climatic variables for the two cases are illustrated in Fig. 5, which reveals the solar radiation (I), the relative humidity (**Φ**), and the wind speed (V_w) from 8:30 to 16:30. Figs. 5 (a) and (b) portray the distribution of climatic variables with the test time for the design case using gravel (as a porous medium) without reflectors and for the design case in the presence of the porous medium and the reflectors for the days 16/2/2022 and 19/2/2022, where the uppermost values of (I) were 1042 W/m² and 1267 W/m², correspondingly. Additionally, the figures reveal that (**Φ**) was conducted for a similar time of test and depicts an inversely proportionate relation with (I), contrasting to the speed of wind variable through the hours of daylight. Furthermore, Figs. 5 (a) and (b) display the effect of the solar radiation intensity on the system temperatures. The temperature increased with the solar radiation absorbed from the flow tube surface in the solar collector at a similar mass flow rate with different design conditions.

4.2.Effect of Porous Media and Reflectors on the Water Storage Temperature

Figure 6 shows the change in the water storage tank temperature with the test time for cases 1 and 2 in the presence of the three thermal loads. From Fig. 6 (a), the maximum tank water temperature value was 47°C at 12:30 for a thermal load of 0.006 kg/s. For case 2, as shown in Fig. 6 (b), the water tank temperature reached its maximum value of 52°C at 12:00 for the same thermal load of 0.006 kg/s. From Fig. 6 (b) of the thermal load, the stability of the reservoir water at a high temperature can be noted due to the inclusion of the stored thermal energy by the double effect of the design additions (solar reflectors and porous medium), which enhanced the amount of solar radiation intensity on one hand, and the release of thermal energy from the porous medium to the water-carrying pipes in the solar collector on the other hand. The reservoir water temperature decreased during the convection period due to the decrease in the thermal energy stored in the thermal reservoir and the reduction in the solar radiation intensity for the period extending from the beginning of the load to the end of the test.

4.3. SWH System Performance

Table 3 presents the change in the input energy balance and the SWH system's output energy with the thermal efficiencies of the thermal load (0.006 kg/s) for cases 1 and 2 on the same test days. The input energy is the amount of energy from the solar radiation, and the output energy represents the energy stored from the water in the tank (case 1 and case 2). Also, the resulting energy represents the combination of the load and water-stored energies. The input energy for case 1 was 22.75 MJ, and the highest output energy was 7.32 MJ. For case 2, the input energy value was 23.34 MJ, and the highest output energy was 8.49 MJ. In both cases, the output energy at the third final load was higher than the total energy output at the first and second loads. The energy output (8.49 MJ) of case 2 was higher than the output energy (72.3 MJ) of case 1 because the energy released to the water through the porous medium (PM) and the reflectors, which is larger than the energy released through only the PM (case 1). By the energy values (input and output energies) of the investigated design cases conducted to improve the system's thermal storage, Fig. 7 demonstrates the total thermal efficiencies of the SWH system for the cases studied (1 and 2) with the thermal load. The system's overall thermal efficiency was 32.21% for case 1 at the thermal load (0.006 kg/s), while the overall thermal efficiency for case 2 was 36.40% for the same thermal load. It was noted that the highest thermal efficiency was in case 2 with the presence of reflectors and the porous medium because the reflectors increased the falling solar radiation's intensity on the solar collector's absorbing surface, while the porous medium released the thermal energy stored in it to the water-carrying pipes. Using the porous medium and reflectors reflected positively on increasing the overall thermal efficiency. The presence of the thermal load with an increase in the amount of thermal energy of convection added to the energy stored in the water tank was also noticed, which means that the solar system strongly supports itself for the heating process.

Table 3 Daily Total Energies and Efficiencies for Cases 1 and 2.

Cases	$\dot{m}_{th.L}$ (kg/s)	Q_{in} (MJ)	Q_O (MJ)	η_O %
Case 1	0.0063	22.75	7.32	32.21
Case 2	0.0063	23.34	8.49	36.40

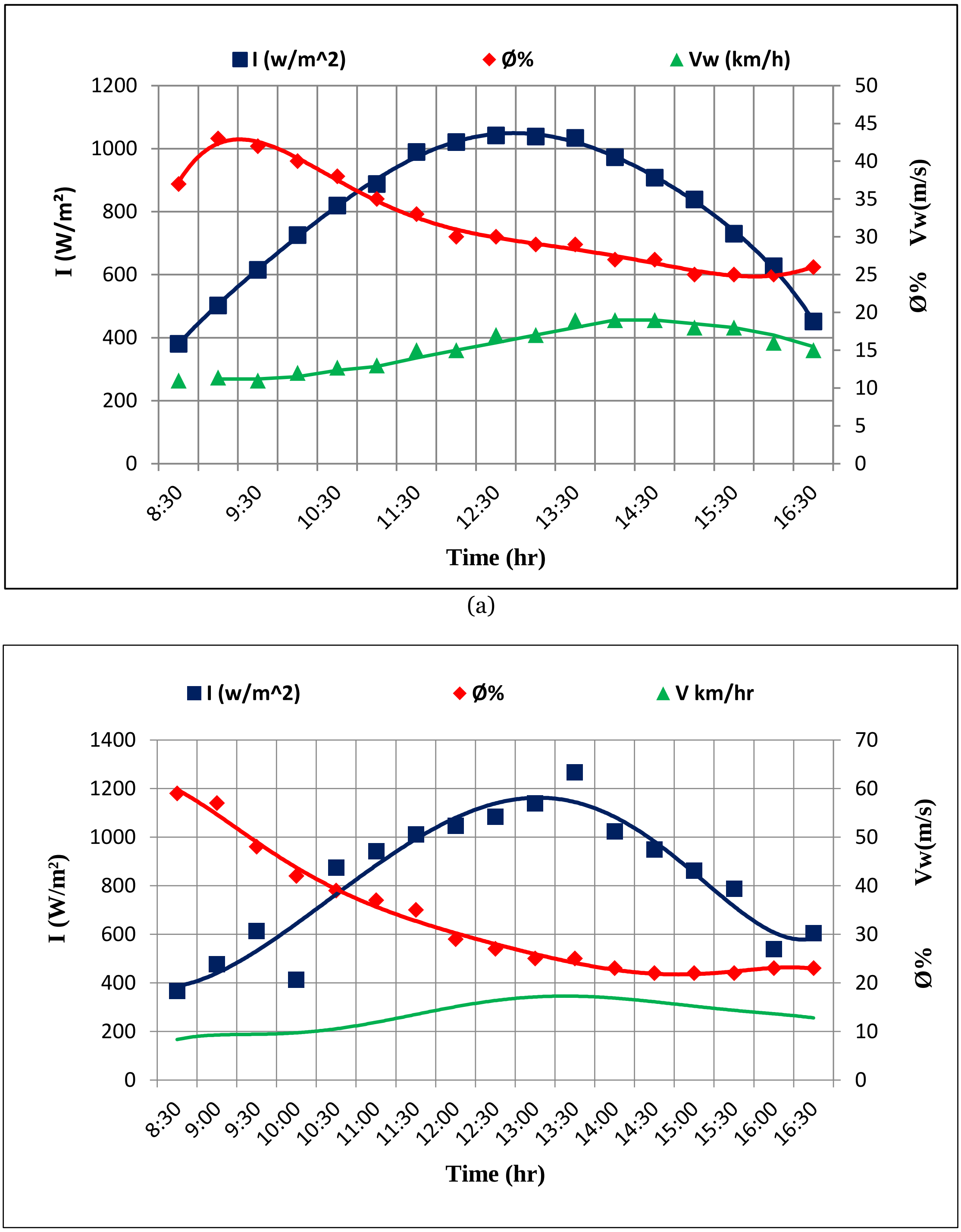
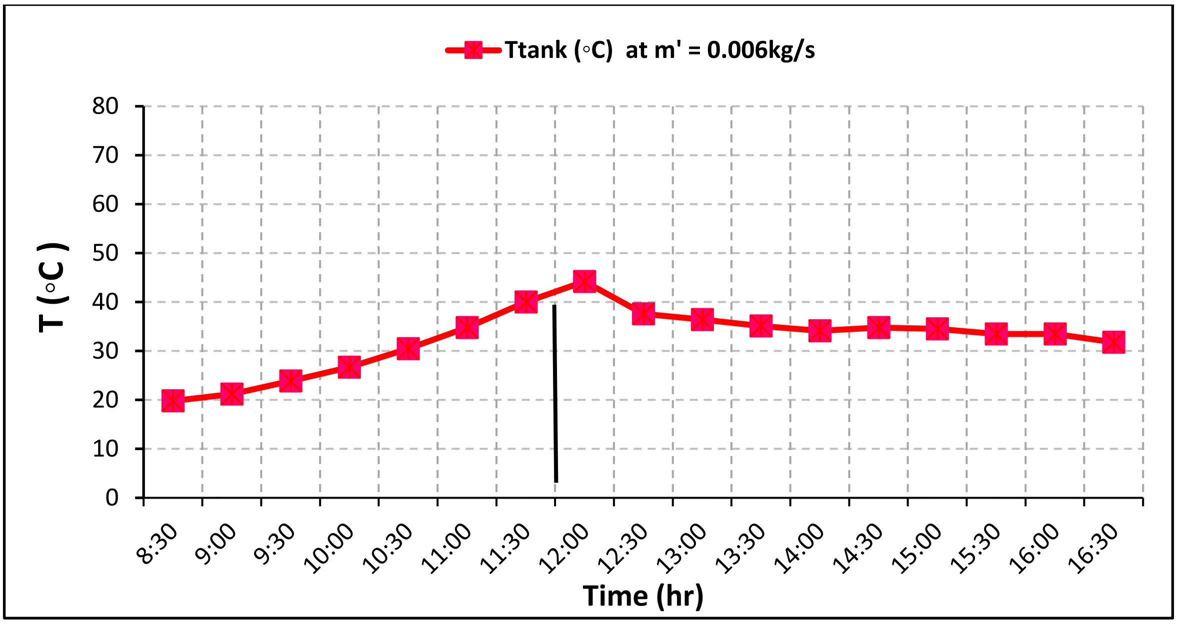
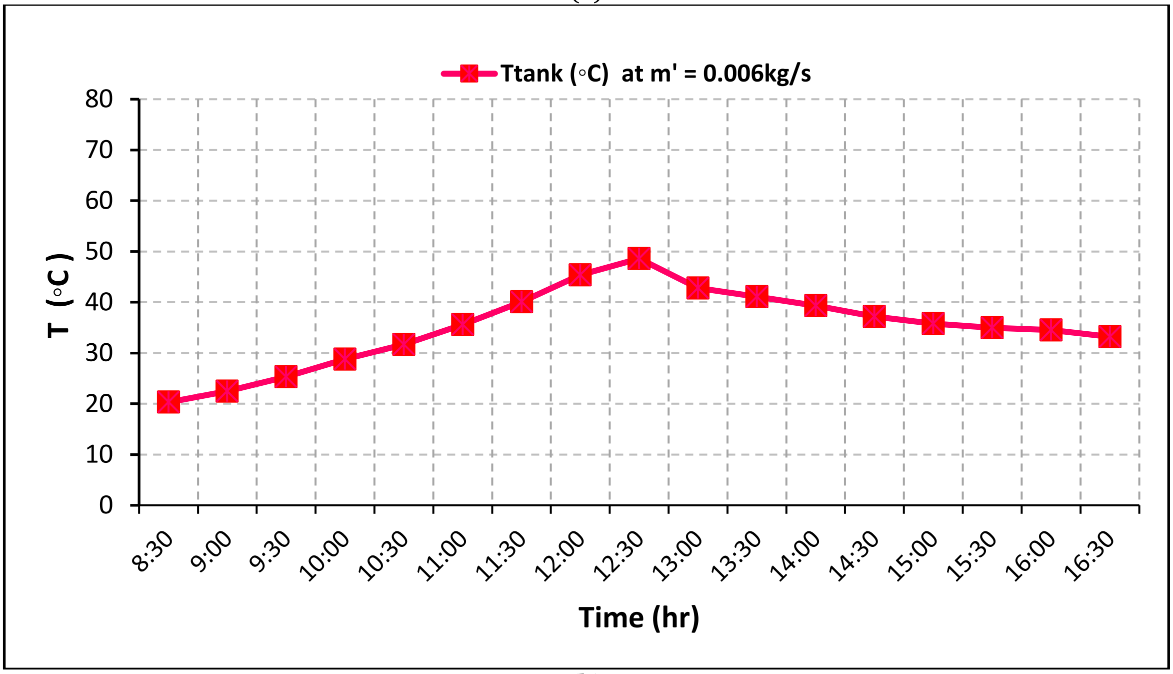


Fig. 5 The Solar Radiation (I), Relative Humidity ($\boldsymbol{\Phi}$), and Wind Speed (Vw) with the Time Upon (a) 16/2/2022 and (b) 19/2/2022.



(a)



(b)

Fig. 6 Distribution of the Water Storage Tank Temperatures for Cases 1 and 2.

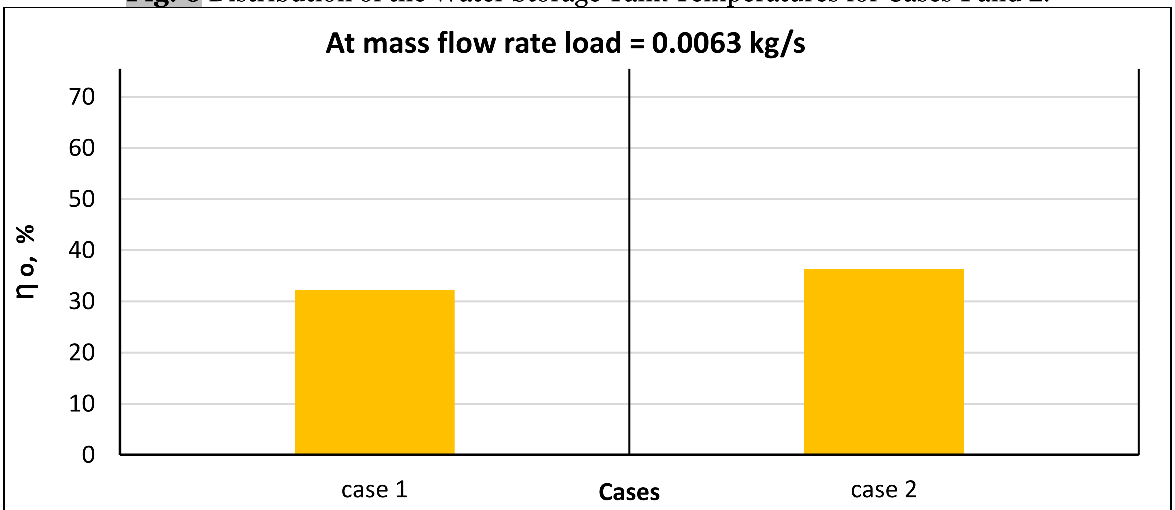


Fig. 7 The SWH Total Thermal Efficiencies for Cases 1 and 2.

4.4.Comparison Of the Present Study with the Preceding Investigations

Table 4 displays a comparison between the present investigation and the previous investigations in computing the overall thermal efficiency (η_o) of a SWH system with a porous medium (PM) and reflectors. The values of η_o in the preceding investigations of [10, [13] were about 21.91% and 57.4% at ($\dot{m}_w$=0.027 kg/s), respectively. While the present work of case 2 included design additions, reflectors, and porous medium, the solar system's overall efficiency was 36.40% at a flow rate of 0.0016 kg/s and a heat load of 0.0066 kg/s. This efficiency value is close to the previous research, knowing that three solar collectors were used in the previous investigation, and a water tank and a larger heat load were used. In addition, the ambient temperature was higher than in the present research. Also, the porous medium (PM) and reflectors increased the water storage tank's output energy compared to the preceding investigations that merely utilized agitators in the collector.

Table 4 The Comparison of the Overall Thermal Efficiency of the Related SWH Systems.

Study Type	Operating Time	$\bar{I}$ W/m²	$\bar{T}_a$° (°C)	Ac (m²)	$\dot{m}_w$ (kg/s)	Tank Volume (L)	$m_{th.L}$ (kg/s)	N_g	η_o (%)	Addition	Reference
Experimental	10:40 am to 10:00 pm	653.65	32	0.72	Free flow	-	-	1	21.91	PM and agitator	Bagaria et al. [10]
Experimental	8:00 am to 5:00 pm	516.80	35	0.96 The area of each compound is one of three complexes	0.027	58	0.0055	1	57.4	Twisted tapes inside the water transport pipes	Mohammed [13]
Experimental/ heating water with thermal load	8:30 to 16:30	843.78	27.5	1.1782	0.0166	20	0.006	1	36.40	PM with Reflectors	Present study

5.CONCLUSIONS

This work experimentally studied an SWH with a porous medium (PM) and reflectors. Also, the overall thermal efficiency of the SWH was computed, and the results were compared with previous investigations. The significant main conclusions can be drawn as follows:

(1) The ultimate thermal storage water temperature via utilizing a porous medium (PM) and reflectors (case 2) was higher by (5°C) than the case without them as in case 1. The highest tank water temperature was (52°C) at 12:00 for the thermal load of 0.006 kg/s.

(2) The SWH's overall thermal efficiency in case 2 was higher by 4.19% than in case 1.

(3) The solar system's thermal efficiency increased with the open cycle thermal load.

(4) Adding a porous medium increased the water-carrying pipes' surface temperature in the solar collector.

(5) Adding reflectors increased the incident solar radiation intensity on the surface of the solar collector, increasing the heat energy transferred to the water.

(6) The highest efficiency of the solar regime for the heating system of water in the open cycle was in the presence of porous media and reflectors, which was 36.40% at the convection of 0.006 kg/s.

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NOMENCLATURE

A_C	Solar collector's aperture area, m²
C_{p_w}	Specific heat of water, J/kg.°C
I	The solar radiation, W/m²
$\bar{I}$	The average of solar radiation, W/m²
M_w	The mass of water in storage tank, kg
$\dot{m}_{th,L}$	Rate of the mass flow of thermal load, kg/s
$\dot{m}_w$	Rate of the mass flow of water, kg/s
N_g	Glassing covers' no.
Q_{in}	Input heat to SWH, J
Q_S	Stored heat of water in storage tank, J
Q_T	The total stored energy for the load and the water, J
Q_L	Thermal energy of the thermal load, MJ
T_a	Ambient temperature, °C
$T_{f,\,tank}$	The final temperature of the water in storage tank, °C
$T_{i,\,tank}$	The initial temperature of the water in storage tank, °C
T_{tank}	The temperature of water storage tank, °C
$T_{w,\,in}$	The inlet temperature of the water, °C
$T_{w,\,out}$	The outlet temperature of the water, °C
$T_{in,l}$	Temperature of the hot water drawn from the HWT initial load,˚C
$T_{out,l}$	Temperature of the hot water drawn from the HWT initial load,˚C
$T_{c.w\,in}$	Temperature of the cold water supplied to the HWT,˚C
t	The time, s
υ	The speed of wind, km/h
Greek Letters	
η_c	Solar collector's overall thermal efficacy (%)
η_o	Test unit's overall thermal efficacy (%)
ϕ	The relative humidity
Abbreviations	
PM	Porous medium
Refl.	Reflectors
SWH	Solar water heater
HWT	Hot water tank
TES	Thermal energy storage

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APPENDIX A

A.1.Experimental Uncertainty Analysis

The percentage of errors is categorized into three groups: The calibration, the collection of data, and the reduction of data. It includes the manufacturing specification errors, such as skew, linearity, hysteresis, redundancy, and accuracy. The independent parameters, like relative humidity and temperature, have been computed employing equations, including the bias error (B). The RSS method was used to determine the limit of precision (P) [19-20] as follows:

The bias error (B) can be calculated from:

$$B = \pm\sqrt{(0.5 * Resolution)^2 + (Accuracy)^2} \quad (5)$$

The mean value scale is predicted by:

$$(\bar{X}) = \frac{1}{n}\sum_{i=1}^{n} X_i \quad (6)$$

The standard deviations ($\bar{\sigma}_x$) of the sample distribution are:

$$\bar{\sigma}_x = \frac{\sigma_x}{\sqrt{n}} \quad (7)$$

The whole limits of precision error are written as follows:

$$P_x = t(N-1), 95\% * \bar{\sigma}_x \quad (8)$$

For obtaining a 95% uncertainty confidence (U_χ),

$$U_x = \pm[B^2 + {P_x}^2]^{1/2} \quad (9)$$

The relative uncertainty in percentage can be calculated as:

$$\frac{U_x}{X}\% = \pm\left(\frac{U_x}{X}\right) \times 100 \quad (10)$$

Table A1 lists the uncertainty of the measured parameters.

Table A1 The Measured Parameters' Uncertainty.

	B	$\bar{X}$	σ_x	$\bar{\sigma}_x$	P_x	U_x	$\frac{U_x}{X}\%$
I (W/m²)	±07 0.	1030.8	40.9425	20.47128	65.1396	65.1396	±6.3193
Ø %	±0.05	36.5	1.29099	0.645497	2.05397	2.0545	±5.6289
T_a(°C)	±1.001	21	0.60553	0.302765	0.96339	1.3892	±6.6156
$T_{w, in}$ (°C)	±1.001	47	0.76157	0.380788	1.21166	1.57166	±3.3439
$T_{w, out}$ (°C)	±1.001	50.6	0.496655	0.248327	0.79017	1.2752	±2.5203
T_{tank} (°C)	±1.001	49.35	0.519615	0.259807	0.82670	1.2982	±2.6306
T_{PCM} (°C)	±1.001	19.6	0.4546	0.22773	0.72463686	1.235758706	±6.30489