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An experimental study of a hemi-spherical solar collector under Egyptian climate

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ABSTRACT

Traditional flat plate collectors have shown, under many investigations, low system operating efficiency, which prompted the idea of designing new solar collectors operating with higher efficiency. Such designs include spherical, hemi-spherical, cylindrical, or rhombic solar collectors. The current study experimentally investigates the performance of a stationary newly designed hemi-spherical solar collector in comparison with a flat plate solar collector with the same surface area and weather conditions. This target has been achieved through designing and manufacturing a hemi-spherical collector, followed by analyzing its performance under normal operating conditions of Egyptian climate. The Hemi-spherical solar collector showed a maximum efficiency of 69% compared to 42% for the flat plate solar collector. Additionally, the hemi-spherical collector resulted in an optical efficiency of 75% compared to 54% for the flat plate collector. Also, the flat plate collector achieved an average efficiency of 31%, compared to an average efficiency of 48.5% for the hemi-spherical collector. The hemi-spherical collector showed a more constant hourly efficiency distribution which makes the spherical solar collector a more reliable source of heating throughout the day, unlike the flat plate collector, where efficiency only peaks during midday, and drops significantly during the early morning and late afternoon.

1. Introduction

Solar technologies offer convenient alternatives for fossil fuels, economically and environmentally, that shall help in solving world fossil fuels shortage problem. Though, the commercialization of solar systems in the international markets is restrained by the efficiency level achieved by existing solar systems. Several improvements have been taken place and hence resulted in further cost reduction, more efficient manufacturing processes and radical reduction in the levelized cost of solar energy during the last decades. Additionally, most of governments have generated their rules to motivate and attract the customers and the private sectors to shift to solar applications.

Solar Collectors are very promising for solar space heating, solar refrigeration, solar desalination, and solar thermal systems. Hence, several energy researches focus on investigating and enhancing the efficiency of solar collector for better energy harvesting and to satisfy part of the energy needs from renewable energy supplies. Many studies and investigations have shown conventional flat plate collectors to be lacking in terms of efficiency, prompting the idea of new solar collectors designs such as spherical, hemispherical,

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Nomenclature

A_c	Surface area of the collector (m^2)
C_P	Heat capacity of the fluid ($J\ kg^{-1}{}^{\circ}C^{-1}$)
F_R	Heat Removal Factor
I_T	Total Radiation (W/m^2)
K	Thermal conductivity (W/m.°C)
m	Mass flow rate (kg/s)
Q_{It}	Total Irradiation received by the collector (W/m^2)
Q_{useful}	Useful Energy Gain (J)
T_{amb}	Ambient Temperature (°C)
T_{in}	Inlet Fluid Temperature into solar collector (°C)
T_{out}	Outlet Fluid Temperature out of solar collector (°C)
U_L	Overall heat loss coefficient of the solar collector (°C)

Greek Symbols

τ	Transmissivity
α	Absorptivity
ε	Emissivity
η	Efficiency of the Flat-Plate Solar Collector

cylindrical, or conical solar collectors.

Several researches have been previously conducted to examine the effect of these different solar collector designs on the conversion efficiency of the implemented solar collector aiming to achieve better system performance [1–6].

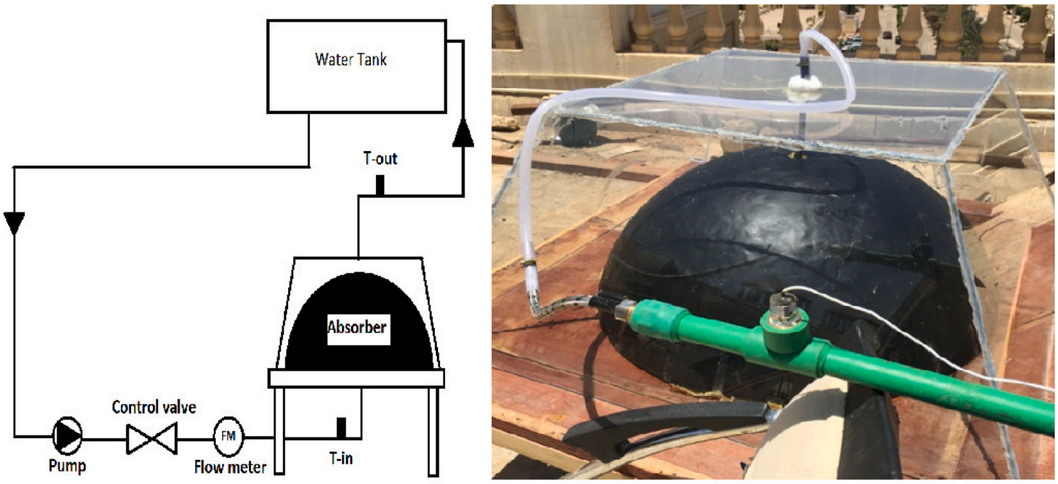
Öztekin et al. [7], conducted a comparative analysis between spherical solar collector and flat solar collector at four different flow rates. The study demonstrated that spherical collector results in higher hourly efficiency over the flat plate collector. Flat plate collector showed a maximum hourly efficiency of 56% while the spherical collector achieved an efficiency of 79%. In the same context, Gaspar and Deac conducted a similar comparison with flat plate solar absorber integrated with tracking system [8]. The results of the study showed a good correlation between surface temperatures and incident solar radiation values, where the spherical solar collector acts like a sun tracking device. At any point during the day half of the sphere is shaded while the other half is exposed to the sun's radiation. Nonetheless, the daily average temperature of the spherical solar collector is shown to be smaller than flat plate solar collector, making it a less efficient solar collecting surface.

Similarly (Ilze et al.), [9–11] examined the performance of a semi-spherical solar collector through measuring the temperature distribution throughout the day. On sunny days, the southern and northern collectors reached a maximum of 100 $^{\circ}C$ and 45$^{\circ}C$ respectively. The semi-spherical design showed to be more durable against the harsh conditions than the flat plate collector and is also able to receive more solar radiation in both morning and evening times. Also (Ilze et al.), [9–11] studied the performance of semi-spherical for water heating, the results showed that semi-spherical collector is comparable to vacuum tube for such applications.

In attempts to develop solar collectors with different geometries and efficiencies, in 2016 Noghrehabadi [12] studied the performance of both square and rhombic solar collector through analyzing the variation in the efficiency and temperatures. Both designs resulted in similar efficiencies at noon. However, the rhombic solar collector resulted in higher efficiencies than the square design during morning and afternoon times as it allows more diffused radiation to be collected. The rhombic solar collector resulted in an efficiency of 56.2% in the morning, and 56.1% in the afternoon. Whereas, the square solar collector has 53.5% efficiency in the morning and 54% in the afternoon. In the same year, they studied the performance of conical collector at different flow rates, it showed that the conical collector can reach a maximum temperature of 77.1$^{\circ}C$ and efficiency of 60% [13]. Later in 2017, Noghrehabadi et al. [14] examined the effect of nanofluids on a square flat plate collector performance, where it has been concluded that using SiO_2/water results in better system efficiency than pure water. For further enhancement in collector's efficiency and solar capacity, Pelece and Shipkovs [15] created a new cylindrical collector design for air and water heating. The study revealed that cylindrical collector receives more energy than flat plate collector during both morning and evening times with a cylindrical collector daily sum of energy of about 1.5 times greater than conventional flat plate for the same amount of received solar energy for equal surface areas.

Additionally, Moravej et al. [16] proposed an improvement for the solar thermal energy conversion by designing a new conical collector. The efficiency of the new conical geometry design is experimentally tested by investigating the temperature changes in the collector. It showed an efficiency of about 53%.

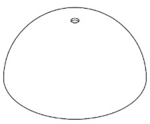
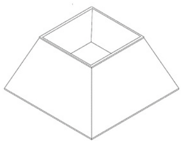
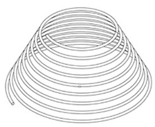
In 2018, Wang et al. [17] proposed a perfect absorber design that uses a periodic array of Bi2Te3 (bismuth telluride) pyramidal nanostructures on a substrate. A numerical study was conducted to investigate the solar radiation absorption and determine the geometric parameters ranges which are suitable for the submerging of the proposed structure in water. Results have shown that the proposed structure was able to achieve absorptance higher than 99.9% within the wavelength range of 300–2400 nm, which could enable for effective solar harvesting in photothermal conversion processes in water. The next year in Dhanbad, India, Perwez & Kumar [18] conducted an experimental investigation to determine the thermal performance of a spherical dimple plate solar air heater compared to a flat plate solar air heater using air of mass flow rates ranging from 0.009 kg/s to 0.028 kg/s. Results show that the



(A) (B)

Fig. 1. (A) Schematic drawing for the forced circulating water absorber system. (B) System Set-Up.

Table 1
System specifications.

Component	Absorber	Glazing	Tubes	Insulation
Material	Copper Sheet Metal	Window Glass	Copper	Glass Wool
Area (m^2)	1.9	1	L = 15 m, D = 12.7 mm	2
Thickness (mm)	1	4	0.7	20
Mechanical Properties	$\varepsilon_a = 0.3$ $k = 61\ W/m.^\circ C$ $C_p = 480\ J/kg.^\circ C$ $\alpha = 0.9$	$\varepsilon_g = 0.88$, $\tau = 0.88$, $k = 1.12\ W/m.^\circ C$ $C_p = 670\ J/kg.^\circ C$		$k = 0.04\ W/m.^\circ C$
Drawings				

spherical dimple plate solar air heater had heat transfer rates 1.51 to 1.64 times higher than that of the flat plate solar air heater. Maximum outlet temperature increase of 4.6 °C greater than the flat plate solar air heater was found for the spherical dimple plate solar air heater at an air mass flow rate of 0.009 kg/s. Also, instantaneous thermal efficiency for spherical dimple plate solar air heater is shown to be about 23.45%–35.50% greater than the flat plate solar air heater.

In 2021, Moravej et al. [20] experimentally evaluated a fixed three-dimensional hemispherical solar collector in accordance with ASHRAE standards. Spiral tubes were used to transport fluid from the inlet to the outlet without the use of a riser. Under different environmental conditions, pure water, and Ag-water with different flow rates (0.1–0.6 GPM) and nanoparticle concentrations (0.1, 0.2 and 0.3%) were tested. Results have shown an average increase in efficiency of around 11% when switching from water to Ag-water nanofluid, with the maximum efficiency of 61.1% occurring at 0.3% nanoparticle concentration and 0.6 GPM flow rate.

In the current study, a hemi-spherical solar collector is designed and manufactured to analyze its performance experimentally in comparison with a flat plate solar collector with the same surface area and under the same weather conditions. The main advantage of this proposed system is enabling solar collectors to receive maximum solar radiation by passively tracking the sun, which will increase absorbed solar energy and system efficiency, while eliminating high cost sun tracking mechanisms. This is due to the hemispherical shape, in which all orientations have the same effect of tracking the sun.

2. System design and manufacturing

Forced circulation solar water heating system is designed with a pump that circulates water from the tank through a 15 m length of copper tube connected to the hemispherical absorber. The solar energy is absorbed and then transferred to the working fluid, leading to temperature rise in the working fluid temperature. Then the heated working fluid is derived back to the storage tank, forming a closed system. The storage tank is placed above the collector, with the pump, control valve and an YF-S201 flow meter with an accuracy of

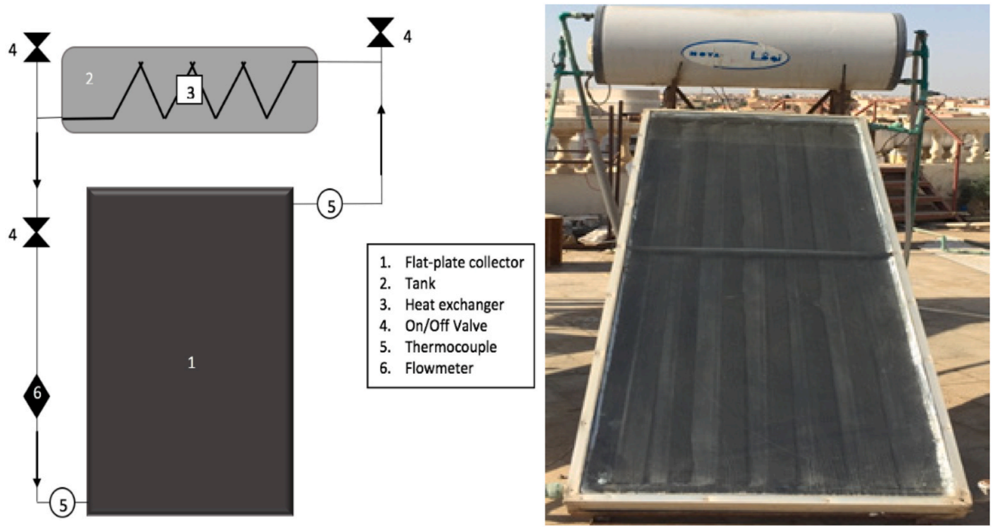


Fig. 2. The flat plate solar collector system.

Table 2
Specifications of the flat-plate solar collector used.

Collector	Absorber	Glass Cover
Area	2 m^2	2 m^2
Working fluid (Capacity)	Water (3L)	–
No of tubes	7	–
Transmissivity	–	80%
Thickness	–	4 mm
Material	Red copper	Commercial Glass
Emissivity	12%	–
Absorptivity	96%	–

0.05 L/min, are connected before the collector. Two PTN digital thermocouples, with ±0.3 °C accuracy and −40°–150° reading range, are used for temperature measurement at the inlet and outlet of the collector as shown in Fig. 1 (A). An OMEGA type FMA 1000 series sensor is used to measure both ambient temperature and wind speed. The collector is enclosed in a glass cover as shown in Fig. 1 (B). The specifications of the main components are shown in Table 1.

Copper tubes are welded into inner surface of the spherical collector in a helical shape. This process is performed such that complete contact between the tubes and the absorber is achieved perfectly for maximum heat transfer rate. Subsequently, absorber outer surface is sprayed with black coating to enhance its absorptivity. The inner surface of the hemispherical collector is then insulated with glass wool to preserve the heat gained by the tubes. After the insulation process, the absorber is placed on the support table along with the glass cover. A control valve is placed after the pump to control the mass flow rate moving through the collector. The flat plate solar collector used for the comparison is shown in Fig. 2. The specifications of the collector are presented in Table 2.

3. Experimental procedure

Several experiments have been carried out on the manufactured hemi-spherical solar collector at a constant mass flow rate of 0.7 L/min for a period of three days from the 31 of May to June 2, 2020. During the experiments, ambient temperature (T_{amb}), inlet water temperature (T_{in}), outlet water temperature (T_{out}), average Incident Solar Radiation Intensity, average absorber Temperature, average glass temperature and wind speed were measured using the appropriate measuring devices. Incident solar radiation approaching the semi-spherical collector is obtained by measuring the radiation reaching each side of the glass cover, with 10 W/m^2 uncertainty, whereas solar radiation approaching the flat plate solar collector is measured at 45° facing south. A PYR-1307 pyranometer was used to measure the incident solar radiation reaching the collector and a GM700 infrared thermometer was used to measure the surface temperature of the absorber and glass cover.

Simultaneously with each experiment on the hemi-spherical collector, experiments were conducted on a flat plate thermosiphon solar collector under the same conditions and same surface area as the hemi-spherical collector. To analyze the performance of each solar collector, collector thermal efficiency, the ratio between the useful energy output of solar collector and the rate of solar radiation striking the collector, is interpreted at different conditions using the following formula:

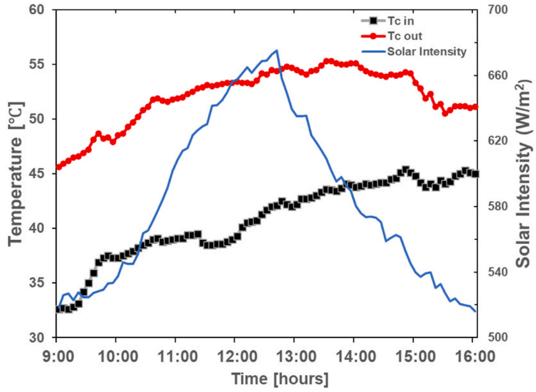


Fig. 3. Temperature distribution in hemi-spherical collector.

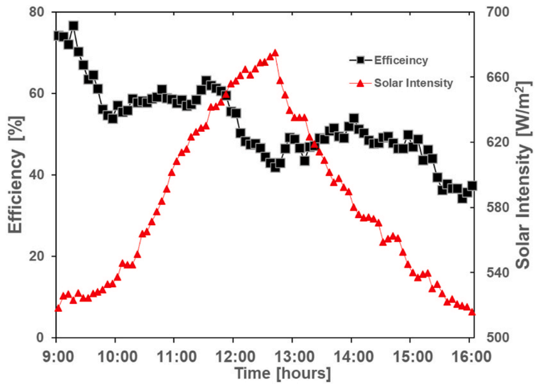


Fig. 4. Solar intensity and efficiency of hemi-spherical collector over time.

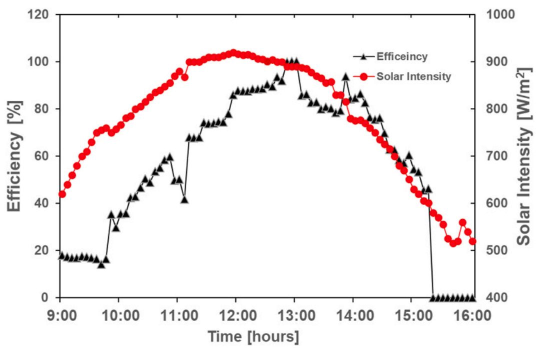


Fig. 5. Solar intensity and efficiency of flat plate collector over time.

$$\eta = \frac{q_{useful}}{q_{I_T}} = \frac{\dot{m}\, C_{p,w}(T_{out} - T_{in})}{A_c I_T} = F_R\left[(\tau\alpha) - U_L\frac{(T_{in} - T_{amb})}{I_T}\right] \tag{1}$$

where I_T is the change in Incident solar radiation W/m^2, U_L is the overall heat loss coefficient W/m^{2}K, τ is the transmissivity of the glass cover, α is the absorptivity of the absorber and F_R is the heat removal factor, $\dot{m}$ is the mass flow rate of water kg/s, $c_{p,w}$ is the specific heat capacity of water J kg$^{-1\circ}$C^{-1}, A_c is the area of the solar collector m^2, and T_{in} and T_{out} are the water inlet and outlet temperatures °C respectively.

4. Results and discussion

The amount of incident solar radiation approaching the semi-spherical collector is obtained by measuring the radiation reaching

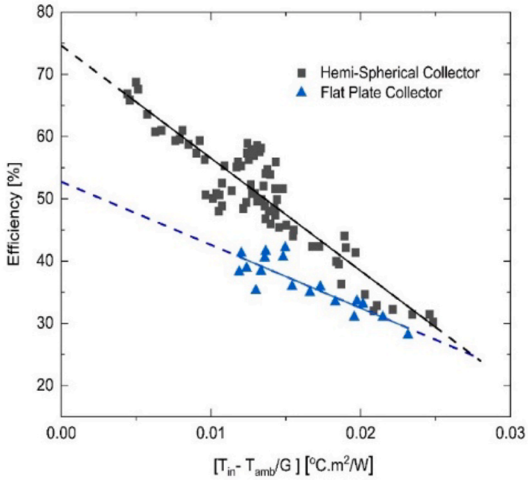


Fig. 6. Comparison between flat plate and hemi-spherical.

each side of the glass cover using a pyranometer of type PYR 1307 with 10 W/m^2 uncertainty. Though for the flat plate solar collector, the radiation is measured at 45° facing south and interpreting system efficiency. Afterwards, temperature distribution and efficiency graphs are plotted for each collector in addition to compare the performance of both systems with each other using performance curves.

The performance of the hemi-spherical solar collector is presented in Fig. 3, where the inlet temperature, outlet temperature, along with the average incident solar radiation are plotted during the day. As shown in the figure, the hemi-spherical solar collector resulted in a maximum temperature difference, [T_{out} -T_{in}], of 14°C at an intensity range from 523 to 528 $W/m^2$from 9:10 to 9:20 a.m. where as it resulted in minimum temperature difference of 6 °Cat an intensity level ranging from 516 to 524 W/m^2 during the period from 3:40 to 4:00 p.m.

Figs. 4 and 5 show the efficiency of both systems, hemi-spherical and flat plate solar collectors, throughout the day from 9:00 a.m. to 4:00 p.m. Although the flat plate solar collector shows higher maximum hourly efficiency, hemi-spherical solar collector shows a more consistent efficiency plot, whereas the efficiency of the flat plate solar collector drops to almost zero after 3:15 p.m. This is due to the decrease in the water temperature difference in the solar collector, which stops fluid circulation by the thermosiphon mechanism. This is due to the orientation of the sun not reaching the collector. Nevertheless, this problem is eliminated in the hemispherical collector as it acts like a sun tracking collector. The hemi-spherical solar collector reached a maximum efficiency of 76.3% in the early morning at 9:00 a.m. while a minimum efficiency of 34.3% at 3:50 p.m. As for the flat plate solar collector it reached a maximum efficiency about to 100% at noon. Nonetheless, its efficiency declined up to less than 2% at 3:25 PM.

To compare the performance of hemi-spherical collector with respect to the flat plate collector, the efficiencies of both collectors were interpreted and analyzed. Fig. 6 shows the performance curves of both the flat and hemi-spherical solar collectors. The Hemi-spherical solar collector shows a higher maximum efficiency of 69% whereas the flat plate solar collector only reaches a maximum of 42%, showing an increase of 27%. The average efficiency of the flat plate collector is 31%, compared to an average efficiency of 48.5% for the hemi-spherical collector. Additionally, the hemi-spherical collector resulted in a greater optical efficiency, $F_R\tau\alpha$, of 75% compared to 54% for the flat plate collector. These results are supported by a previous comparative analysis study by Öztekin et al. [7] between spherical solar collector and flat solar collector at four different flow rates, where flat plate collector showed a maximum hourly efficiency of 56% while the spherical collector achieved an efficiency of 79%, showing an increase of 23%, which is consistent with results from current study, taking into consideration difference in environmental conditions, absorber size and flow rates in each case.

5. Conclusions

The current study focuses on enhancing the efficiency of solar collectors through designing, manufacturing, and investigating the performance of hemi-spherical solar collector under normal operating conditions of Egyptian climate. Additionally, it compares the performance of newly designed hemi-spherical solar collector with existing flat plate collector. The analysis has been performed during summer period from 31 May to Jun 2, 2020 at constant mass flow rate of 0.7 L/min. The results of the analysis showed that the spherical collector has an efficiency greater than the flat plate solar collector. The Hemi-spherical solar collector achieved a maximum efficiency of 69% whereas the flat plate solar collector reached a maximum efficiency of 42%. Also, the flat plate collector achieved an average efficiency of 31%, compared to an average efficiency of 48.5% for the hemi-spherical collector. Furthermore, the hemi-spherical collector resulted in larger optical efficiency, 75%, compared to 54% for the flat plate collector. In conclusion, the hemi-spherical collector shows a more constant hourly efficiency distribution. This makes the spherical solar collector a more reliable source of heating throughout the day, unlike the flat plate collector, where efficiency only peaks during the midday, and drops significantly during the early morning and late afternoon.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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