
Experimental and Theoretical Evaluation of a Flat Plate Solar Collector with Variable Flow Rates and Reflective Mirrors under the Climate Conditions of Kirkuk, Iraq

Soran J. Mohammed¹, Hussein M. Hamad², Mohammad S. Hassan³ Mahmood H. Khaleel⁴

¹Department of Mechanical Power Techniques, Kirkuk Polytechnic College, Northern Technical University, Kirkuk, 36001, Iraq, soran247@ntu.edu.iq,

² Department of physics, College of science, Wasit University, Wasit, Iraq, hhamad@uowasit.edu.iq.
<https://orcid.org/0000-0001-8028-5701>

³Department of Mechanical Power Techniques, Kirkuk Polytechnic College, Northern Technical University, Kirkuk, 36001, Iraq, engineer.abosadan@ntu.edu.iq,

⁴Department of Mechanical Techniques, Kirkuk Polytechnic College, Northern Technical University, Kirkuk, 36001,Iraq, Mahmood.aborettag.husain@ntu.edu.iq,

Abstract: The aim of this study is to evaluate and improve the thermal performance of a flat plate solar collector (FPSC) focusing on the water flow rate and the addition of a reflective mirror under the specific climatic conditions of Kirkuk, Iraq. This study combines theoretical modeling and experimental testing to reduce the gap between simulation and actual operation improvements and the associated real-world constraints of FPSCs. By modeling solar radiation and energy balance equations, practical experiments were conducted using a plate solar collector model designed and implemented in a way that accepts testing several parameters to conduct a detailed thermal analysis of the collector. The results demonstrated that the low-flow condition (0.55 L/min) achieved the highest overall daily efficiency (28%), attributed to favorable thermo-hydraulic balance and reduced optical losses. Although higher flow rates improved instantaneous thermal stability, they reduced the net efficiency due to smaller inlet-outlet temperature differences. The 120° reflective mirrors enhanced morning and evening performance, while the 90° mirrors increased midday heat gain but suffered from angle-dependent losses. Furthermore, the use of single-layer glazing increased convective and radiative heat losses across all cases. Overall, the findings emphasize that temporal continuity of energy gain is more critical than instantaneous efficiency peaks. The novelty of this research is that specific climatic conditions—such as the semi-arid conditions in these study experiments—require tailored solar collector designs. The results indicate that incorporating multi-layered glass and adaptive mirror alignment can further improve system performance in local solar heating applications.

Keywords: Flat Plate Solar Collector (FPSC); Thermal Performance; Reflective Mirrors; Flow Rate Effect; Solar Radiation Modeling; Experimental and Theoretical Analysis; Energy Efficiency.

1 Introduction

Due to the ongoing climate change, it has become necessary to shift to exploring new energies. In addition to the expected rise in oil prices and the scarcity of fossil fuels, our societies have increasingly focused on exploring new energy sources. Solar energy is the lifeblood of the Earth. The energy sources available on Earth have evolved over the years. We prefer geographical and environmental changes and transformations. The fear of the depletion and environmental pollution of traditional energies remains the main reason for the green energy revolution in recent years. Research and industry have contributed to the shift to clean energy sources and environmental conservation. Researchers have recently focused on studying solar energy[1]–[5]. Solar energy is a widely used and renewable energy source. It is one of the most reliable alternative energies, as it is carbon-free, environmentally friendly, and cost-effective, which reduces electricity consumption. It is widely used as the most valuable and economical energy compared to other energies for heating water in domestic and industrial applications. Flat-plate solar collectors (FPSCs) are the most common and widely used due to their simplicity and ease of maintenance compared to other types. Solar collectors are a key component of a solar heating system, converting solar radiation into heat energy that is transferred to the air, water, or liquid

for use in various domestic and industrial applications.

Factors affecting solar collectors include the collector plate, coating material, the distance between the tubes, the length and diameter of the tubes, the amount and angle of incident radiation, the thickness of the side and bottom insulation, and the working fluids in the collector. Solar collectors have been the focus of interest for most researchers around the world in improving their thermal performance [6]–[8]. Among the interests of researchers is the study of nanofluids as an alternative working fluid due to their significant role in improving the performance of the solar collector. Studying the efficiency of flat-panel solar collectors using reflectors and their impact on it was also part of this interest. [14]–[18].

Zhang J. Tao (2015) They studied the effect of the design structure of flat solar collectors and its effect on their efficiency using the simulation method. It was found that reducing the distance of the tubes and increasing the absorption plate increases the efficiency. They also recommended using a suitable insulation thickness and short tube lengths with large diameters [14]. (A. Alvarez 2010) They designed a flat solar collector with corrugated channels instead of the traditional parallel channels to improve efficiency and thermal performance using the finite element modeling (FEM) method. The study showed that the corrugated channels design outperforms the traditional parallel channels collector design, especially during peak solar energy times [15]. (B. Howmika 2017) They conducted a study in Bangladesh on a flat-panel solar collector using an innovative reflective mirror to improve the efficiency of the collector and heat water, achieving a 10% increase in water temperature and solar energy capture, comparison without it [16]. In a study (Saffarian 2020) that used nanofluids ($\text{Al}_2\text{O}_3/\text{H}_2\text{O}$ and $\text{CuO}/\text{H}_2\text{O}$) and different tube configurations to improve the efficiency of flat solar collectors, it was concluded that energy consumption and efficiency were improved using corrugated and spiral tubes compared to U-shaped tubes. [9].

In a study by Evangelos Bellos (2023) to estimate the relationship between the operating temperature and the ambient temperature of a flat plate solar collector at different mass flow rates using instantaneous stress analysis and parametric analysis, an optimum efficiency of 13.3% for the operational thermal energy (TEE) was obtained [17]. S. Seadodian (2017) They studied the effect of porous metal on the performance of a flat-plate solar collector at various flow rates, using numerical and experimental analysis. The study demonstrated that the porous medium contributes to an increase in collector efficiency of up to 18.5% [18]. A study by F. J. Diez et al. (2019) used ambient temperatures and collector fluid (water) temperatures with different flow rates using artificial neural networks (ANNs). The study showed that it is simple, accurate, and can be used on any solar collector [19]. Researchers at the University of Denmark (DTU) (Ziqiqn Chen 2012) compared flat-plate solar collectors containing ETFL wafers with those without. They found that collectors with wafers were up to 10% more efficient than collectors without them at multiple flow rates [20]. A study by Yu. K. Rashidov (2022) has shown that low flow and high temperature gradients improve water heating in flat-plate solar collectors, increasing their efficiency in systems of heat supply and helping distribute fluid across the collector [21].

Many studies and researchers have focused on studying the engineering design of flat-plate solar collectors to improve thermal performance and efficiency in terms of tube composition, length, diameter, insulation materials, and length used. These collectors still need continuous improvement, as others previous studies have focused on thermal insulation, nanofluids used, different tube compositions, and absorbent coating. Among the improvements that have also occurred in flat-plate solar collectors is the addition of a reflective mirror and its different tilt angles. In this study, the focus was on the use of a reflective mirror using a theoretical and experimental evaluation of a flat-plate solar collector in Kirkuk, Iraq, to study the effect of variables such as the fluid flow rate and the reflective mirror tilt angle (90 and 120) to improve the efficiency and thermal performance of the collector. The novelty of this work lies in its integrated approach that correlates *temporal energy gains continuity* with *optical and hydraulic interactions*, which, to the best of our knowledge, has not been previously reported for FPSCs operating in dry or semi-arid environments. The ultimate goal is to establish design recommendations that enhance long-term collector performance while maintaining low operational complexity and cost.

2 Mathematical calculations

2.1 Heat load calculation

The amount of heat expended in air conditioning systems is determined by their capacity, which depends on the thermal energy transferred to and from the conditioned space and the season during which the system is used. If it is winter in heating systems, the energy leaking from inside the building to outside is determined, and through it the capacity of the heating device is determined, and it is usually calculated

according to the following equation[22]:

$$Q_{glass} = UA_g(T_{room} - T_a)..... (1)$$

Where A_g represents the surface area, T_{room} is the design temperature of the room, T_a is the ambient temperature, and U denotes the overall heat transfer coefficient, which can be calculated as follows:

$$U = \frac{1}{R_{total}}..... (2)$$

Where:

R_{total} is the total thermal resistance of the material, calculated from the following equation:

$$R_{total} = \frac{1}{h_i} + \frac{x}{K_m} + \frac{1}{h_o}..... (3)$$

Where h_i and h_o are the convective heat transfer coefficients of the inner and outer wall surfaces, . The amount of heat supplied from the storage tank to the air conditioner depends on the amount of heat required for it, which changes with time. The following equation gives the heat transfer rate (Q) supplied by the heat exchanger to the air conditioner[22].

$$Q_{Hu} = m_H C_p (T_{Hi} - T_{Ho})..... (4)$$

Where 'm' represents the total mass flow rate through the heat exchanger, c_p represents the heat capacity of the working fluid, and T_{Hi} and T_{Ho} are the temperatures of the water leaving and entering the heat exchanger, respectively.

2.2 Thermal performance of FPSC

The first experimental analysis of the performance of an FPSC was presented in 1942 by the scientist Hotel Wortz in 1942 and later developed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), which included a standard for evaluating the performance of an FPSC. When sunlight falls on the solar collector, the simplest way to calculate its thermal performance its flow rate. The simplest way to determine the performance of the collector is to first calculate the useful heat gain (Q) from the FPSC as follows:

$$Q_{cu} = m_c C_p (T_{ci} - T_{co}) \dots \dots \dots (5)$$

Where m_c specifies the fuel mass flow rate in the collector, and T and T are the temperatures at the inlet and outlet of the collector. On the other hand, the optical gain effects of the collector and the heat seal also represent the effective usable energy that can be obtained for a business by reducing the UL ratio and the mixed solar radiation S .

2.3 Calculating solar radiation on an inclined surface following the sun.

This document provides a simplified scientific explanation for calculating the solar radiation incident on a surface tilted at an angle of 30° to the horizon and following the sun's motion. An atmospheric clarity factor of 0.75 was adopted.

2.4 Work coordinates in Kirkuk city—Kirkuk Technical Institute

To record the solar radiation data falling on the solar panel collector, we follow the theoretical calculation method (using equations) and the data of the Kirkuk solar city, including the Kirkuk Technical Institute, shown in the table1 below:

Table1: Meteorological data and coordinates for the city of Kirkuk

Property	Symbol	Units	Value
Latitude	Φ	Degree	35.47
Inclination	B	Degree	30
Atmospheric clarity index	clearness index	-	0.75
Solar constant	Gsc	W/m ²	1367

2.5 Mathematical steps

1. Calculate the solar inclination angle (δ):

$$2.5.1 \quad \delta = 23.45^\circ \times \sin \left[\frac{360}{365} \times (n - 81) \right] \dots \dots \dots (6)$$

Where n represents the sequence of days during the year.

2- Calculating the hour angle (h):

$$2.5.2 \quad h = 15^\circ \times (t - 12) \dots \dots \dots (7)$$

Where t represents solar time (from 8:00 to 17:00)

3- Calculating the solar azimuth angle (θ_z):

$$\cos(\theta_z) = \sin(\delta) \times \sin(\varphi) + \cos(\delta) \times \cos(\varphi) \times \cos(h) \dots (8)$$

4- Calculating the distance factor between the Earth and the Sun (E0):

$$2.5.3 \quad E_0 = 1 + 0.033 \times \cos[(360 \times n)/365] \dots (9)$$

5 - Calculating the solar radiation (I₀):

$$2.5.4 \quad I_0 = G_{sc} \times E_0 \times \cos(\theta_z) \dots (10)$$

6- Calculating solar radiation on a surface inclined at an angle of β and tracking the sun:

$$I_{tilted} = I_0 \times \cos(\beta) \times \text{Clearness index}(kt) \dots (11)$$

2.6 Practical Application

For the experimental days of April 7, 9, and 16, 2025, the adopted computational method was employed to estimate the hourly solar radiation between 8:00 a.m. and 5:00 p.m. The corresponding results are summarized in Tables 1 and 2, where the measured and calculated values are directly compared. These tables not only describe the daily variation in solar radiation but also serve as a verification tool for the accuracy of the applied model, confirming its reliability for use in subsequent thermal performance assessments.

Table 2: Solar radiation falling on the experimental area (Kirkuk Technical Institute) during the month of April and the experimental days only

Wednesday 4-16-2025				Wednesday 4-9-2025			Monday 4-7-2025		
Time	Azimuth angle	normal solar radiation	radiation on an inclined surface	Azimuth angle	normal solar radiation	radiation on an inclined surface	Azimuth angle	normal solar radiation	radiation on an inclined surface
	(°)	(W/m ²)	(W/m ²)	(°)	(W/m ²)	(W/m ²)	(°)	(W/m ²)	(W/m ²)
08:00	60.01	677.68	440.17	102.26	1361.0	648.07	102.96	1362.54	639.09
09:00	48.23	903.02	586.53	113.57	1361.0	875.77	114.32	1362.54	867.4
10:00	37.47	1075.93	698.84	128.71	1361.0	1050.48	129.48	1362.54	1042.6
11:00	29.09	1184.62	769.44	150.57	1361.0	1160.31	151.16	1362.54	1152.73
12:00	25.69	1221.70	793.52	180.0	1361.0	1197.77	180.0	1362.54	1190.29
13:00	29.09	1184.62	769.44	209.43	1361.0	1160.31	208.84	1362.54	1152.73
14:00	37.47	1075.93	698.84	231.29	1361.0	1050.48	230.52	1362.54	1042.6
15:00	48.23	903.02	586.53	246.43	1361.0	875.77	245.68	1362.54	867.4
16:00	60.01	677.68	440.17	257.74	1361.0	648.07	257.04	1362.54	639.09
17:00	72.16	415.27	269.73	267.15	1361.0	382.92	266.49	1362.54	373.21

2.7 Calculating the Heat Gain from the Solar Collector

To calculate the heat gain from the solar collector, as measured by experiments, the following steps will be followed:

Assumptions:

- This calculation assumes that the volumetric flow rate is constant throughout the day.
- The time between each reading is 30 minutes.
- The inlet and outlet temperatures are the basis for calculating the temperature differences.

Data:

Table 3: General data and constants in experiments of the solar collector

V_{water}	L/min	m ³ /sec	ρ_{water}	Kg/m ³	C_{water}	KJ/kg.°C	$A_{collector}$	m ²
	0.55	9.17×10^{-6}		1000		4.18		2

2.8 Calculation Steps

Table (3) presents the experimental values of the volumetric flow rate, which serve as the practical basis for calculating the mass flow rate. These values were applied in the conversion equation shown below, ensuring verification of the relationship between volumetric and mass flow rates and directly linking the results to the system's operating conditions during the tests.

$$m_{\text{water}} = \rho_{\text{water}} \times V_{\text{water}} \dots\dots\dots (12)$$

$$Q_i = m_{\text{water}} \times C_{\text{water}} \times (T_{\text{out}} - T_{\text{in}}) \times \Delta T \dots\dots\dots (13)$$

$$2.8.1 \quad \eta_{\text{collector}} = \frac{Q_{\text{useful}}}{E_{\text{solar}}} \times 100\% \dots\dots\dots (14)$$

Where:

η : Thermal efficiency

Q_{useful} : The amount of useful heat gained from the collector (in joules)

E_{solar} : The amount of solar energy falling on the collector's surface (also in joules)

To calculate the incident solar radiation (E_{solar}), we use the equation:

$$E_{\text{solar}} = \sum_i G_i \times A \times \Delta t_i \dots\dots\dots (15)$$

G_i : Solar radiation incident on the collector in units (W/m^2)

A : Area of the solar collector in units (m^2)

Δt_i : Time per reading (second)

3 Experimental Work

Panel solar collectors are a metal structure that holds a set of tubes through which a liquid (usually water) passes. Upon entering the solar collector, this liquid is exposed to solar radiation, which is concentrated onto the tubes using a layer of glass and a black heat-absorbing plate. The liquid, after acquiring heat, is then transferred to a liquid reservoir. The details of the components of the solar collector will be explained in this chapter.

The solar collector consists of a metal support base manufactured in the laboratories of Kirkuk Technical Institute with the dimensions shown in Figure 4- with cross-sectional dimensions of (75 x 75 x 4) mm. It rests on the ground with four legs and is tilted at an angle of 30 degrees from the horizon, which is considered the best angle to receive the incident sunlight. Then, a wooden frame was manufactured to include all parts of the solar collector and contains grooves to support the weights of the components of the solar collector, such as the thermal insulator, water pipes, reflective glass, and absorption panels. The cross-sectional dimensions of the wooden frame are 90 x 90 mm, and its length is equal to the length of the metal support. As explained in the components of the solar collector in the first chapter, the thermal insulator is of great importance in preventing the transfer of thermal energy between the parts of the solar collector and the outside atmosphere. good thermal specifications. Two sizes of pipes were used to transport and circulate water inside the solar collector. One of them, with a

diameter of 48 mm, was used for the distribution and collection pipes, and the other, with a diameter of 16 mm, was used for the circulating pipes inside the solar collector. The pipes used were of the copper type, and metal sheets of aluminum were used, with a thickness of 0.85 mm and with dimensions equal to the dimensions of the solar collector, in two layers, one under the transfer pipes and the other above them. They were painted black to ensure the absorption of the largest amount of solar radiation. Finally, two layers of transparent glass, with a thickness of 4 mm, were used to cover the copper pipes and the global warming resulting from the reflection of sunlight from the heat-absorbing panels after the light refraction that occurs with the solar radiation falling on the collector. Figure 7 below shows the final shape of the device, which is different in the case of experiments using reflectors mounted on a side structure relative to the solar collector, which is shown in Figure 8.



Figure 1: Test Case for Solar Collector Without Reflector After Fabrication and Configuration



Figure 2: For solar collectors in case of using reflective mirrors

3.1 Measuring instruments

Data for each experiment were recorded in the experiments conducted on the device using K-type temperature sensors with a temperature range of -50 to 2501°C and 12 Chinese-made TM-902c temperature readers with a reading range of -50 to 1300°C , as shown in Figure 9. These were distributed in the locations specified by the research methodology.



Figure 3: The thermocouple and temperature reader are used in experiments.

3.2 Practical experiments

Table (4) summarizes the experimental setup, highlighting the key operating parameters and constraints. The cases differ mainly in flow rate, mirror usage and orientation, and glazing, providing the basis for comparative performance evaluation.

Table No. 4: experiment details and limitations				
cases	Water flow rate (liter /minutes)	Reflective mirror	Angle of mirror with collector	Layers of glass
Case1	0.55	No	no	One layer
Case2	1.15	No	N0	One layer
Case2	1.15	Yes	120°	One layer
Csae2	1.15	Yes	90°	One layer

4 Results Discussion

Figure 4 shows a gradual increase in the solar radiation distribution since the early morning hours, reaching its peak at midday with a value of about 1100 W/m², after which it begins to gradually decrease until the end of the day. The average heat gain followed the same behavior but recorded slightly higher values, reaching a maximum of about 450 W/m². This means that there is heat loss due to the leakage of thermal energy through the glass layer to the surroundings. We also note that the flow rate chosen for this experiment was 0.55 liters/minute, which is somewhat low, which led to an increase in the water residence time inside the solar collector, thus giving a somewhat negative pattern, which is an increase in heat loss. By the radiation curve.

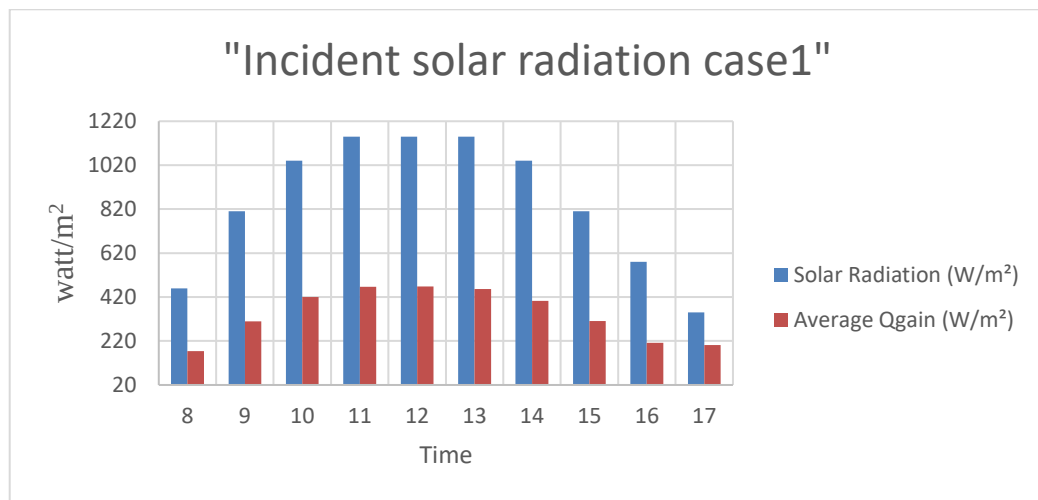


Figure 4: Hourly Variation of Incident Solar Radiation and Average Thermal Gain (Case 1)

Figure 5 shows that the usual pattern was followed similarly from the first case, with a peak of approximately 1100 W/m² at midday. The average heat gain gradually increased but did not reach its peak as in the first case, which reached 420 W/m². We note a rapid decrease in the rate of gain after 14 hours. This behavior of the curve is explained by the fact that the flow rate of 1.15 liters/minute reduced the time the water was exposed, which helped to lower the temperatures at the exit. Therefore, the heat gain decreased relatively. However, the increased heat flow rate contributed to improving the thermal distribution and reduced the loss of thermal energy compared to the first case.

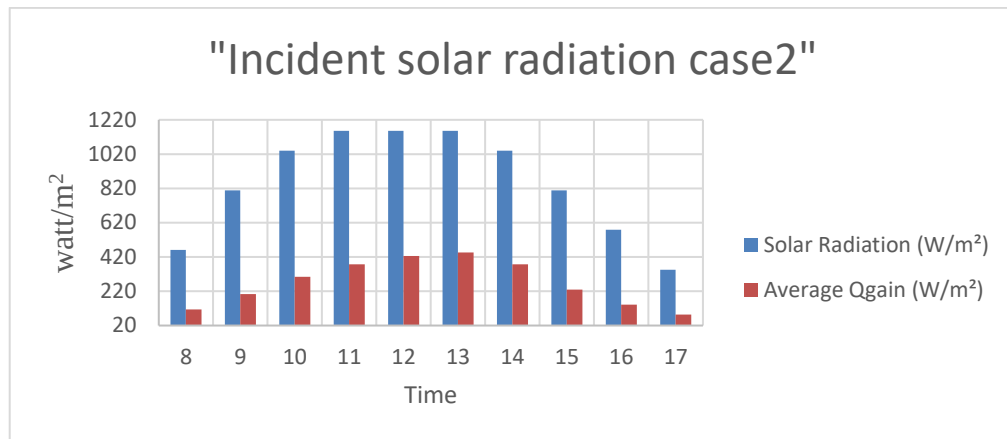


Figure 5 : Hourly Variation of Incident Solar Radiation and Average Thermal Gain (Case 2)

Figure 6 shows the experiment in which the reflective mirror was used at an angle of 120 degrees and a flow rate of 1.15 liters per minute. The figure shows the normal daily pattern of normal solar radiation and its peak, which is usually at noon. Note the significant increase in the value of the heat gain when compared to the previous cases, with the expansion of the peak performance in time, meaning a significant improvement in the thermal performance before and after noon. is because the radiation concentration by the mirror at an angle of approximately 120 degrees led to a reduction in the losses of incident solar radiation and an increase in the flux on the solar collector. The limitations in this case are the misalignment in the reflection and the presence of a single layer of glass, which keeps the thermal losses constant. The high flow rate maintained a suitable temperature difference, which gives stability in the thermal performance of the solar collector.

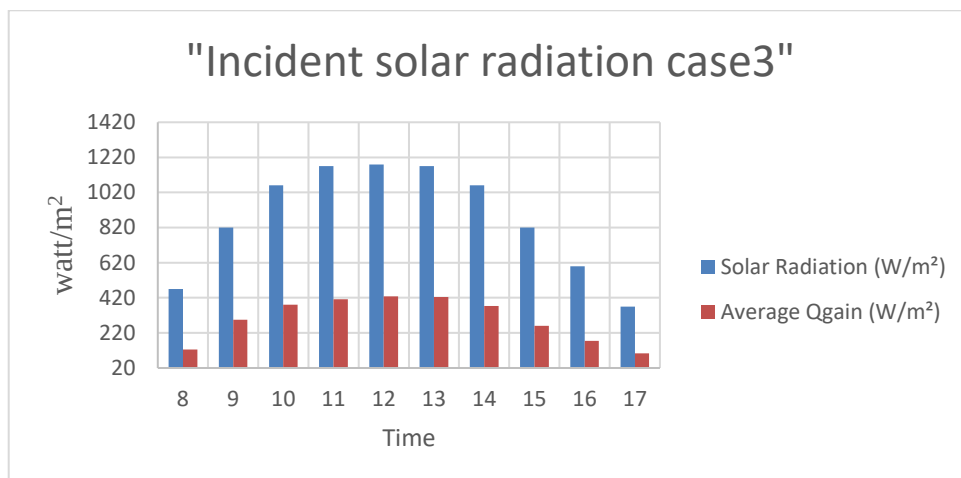


Figure 6 : Hourly Variation of Incident Solar Radiation and Average Thermal Gain (Case 3)

Figure 7 shows the experiment in which the reflective mirror was used at a 90-degree angle and a flow rate of 1.15 liters per minute. The figure shows the usual pattern of solar radiation and a clear improvement in the heat gain values compared to the previous cases and a limited expansion in the thermal performance area. the 90-degree reflection angle of the mirror gives a radiant flux on the solar collector when the incident sunlight is relatively vertical, but it is less high in the morning and evening periods, and the mirror capture decreases outside the reflection axis. There may be a slight possibility of shadows caused by the mirror, while the convection and radiation losses remain due to the use of a single layer of glass and the stability of the thermal distribution, which is due to the high flow rate as in the previous cases.

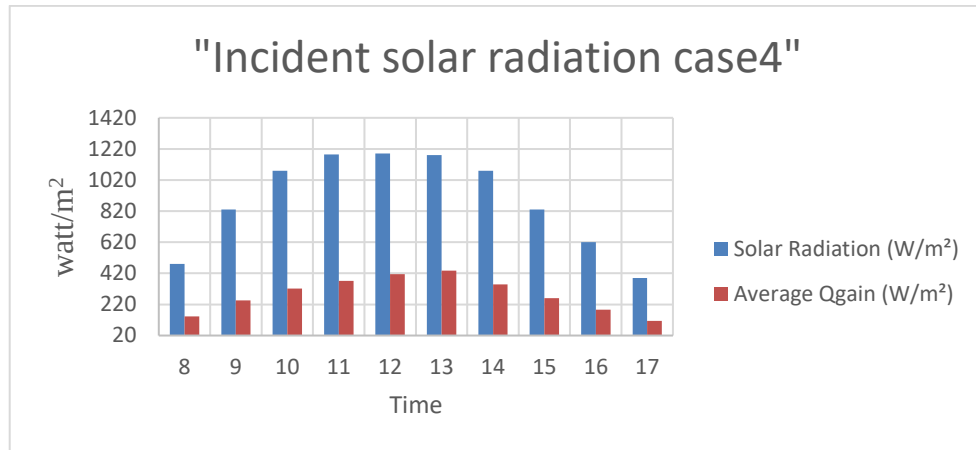


Figure 7 : Hourly Variation of Incident Solar Radiation and Average Thermal Gain (Case 4)

In general, if we make a comprehensive comparison of the four cases discussed, the first case maintained a stable thermal efficiency, especially from 10 am to 2 pm, with an approximate value of 40%, with a clear superiority in the late morning and afternoon periods. The third case, with the mirror at a 120-degree angle, achieved an early start and efficiency throughout the experiment during the day, and it was even better than the fourth case, with the mirror at a 90-degree reflection angle, especially at the ends of the time. As for the second case, it was the weakest in general, despite the high flow rate.

4.1 Solar collector efficiency over time

From following Figure 8, there are four curves. In the curve of case 1, we notice a rapid rise in the early morning hours with a wide efficiency area of 40% for the period from 10 am to 1 pm, and then a gradual decline, indicating a good thermal balance and a balance between the flow and the rate of heat loss. As for the curve of case 3, with the presence of a reflective mirror at an angle of 120 degrees, the thermal efficiency of the collector witnesses an early rise and a noticeable stability with values of 35 to 75%. The reason is attributed to the improvement of the angle of incidence, especially at the end of the experiment time. From observing the curve of case 4, with the presence of a reflective mirror at an angle of 90 degrees, the sharp peak in the afternoon indicates a rapid rise in efficiency values and a faster decline, the reasons for which are attributed to losses resulting from the specific angle of the mirror. As for the second case, it is relatively weaker with a peak confined between 12 and 13 pm due to the increase in flow and the decrease in the temperature difference due to the decrease in radiation and the increase in heat loss, especially after 2 pm. From the above, the curve generally shows the superiority of the thermal performance of cases 1 and 3 compared to cases 2 and 4.

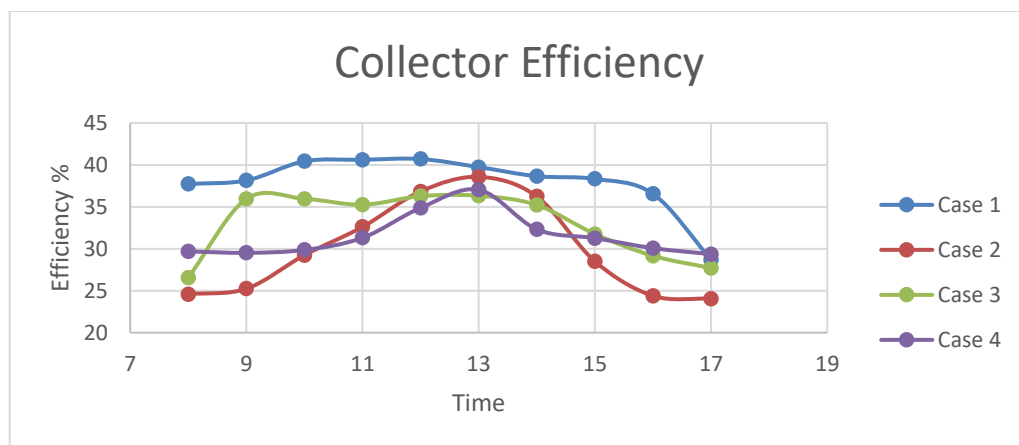


Figure 8 "Hourly Variation of Collector Efficiency for Different Cases"

4.2 Total daily efficiency

Figure 9 and Table 5 show the performance ranking for the four cases, which reached 28% for the first case, 25% for the third case, 25% for the fourth case, and 23% for the second case, which reflects the integration of efficiency throughout the day. In general, the four cases maintained performance in the morning and afternoon, harvesting a higher percentage of heat gain, as the use of reflective mirrors and the high volumetric flow rate of water reduced the heat gain, while the thermal-hydraulic balance in the other cases had a better daily outcome.

Table 5: Experimental Cases: Maximum Hourly vs. Overall Efficiency

Experiment	Hour Achieved	Maximum Hourly Efficiency (%)	Overall Efficiency (%)
Case 1	10 :00 - 11:00	40.43	38.47
Case 2	13:00 - 14:00	38.5714	31.5974
Case 3	13:00 - 14:00	36.3248	34.1451
Case 4	13:00 - 14:00	37.0339	32.0643

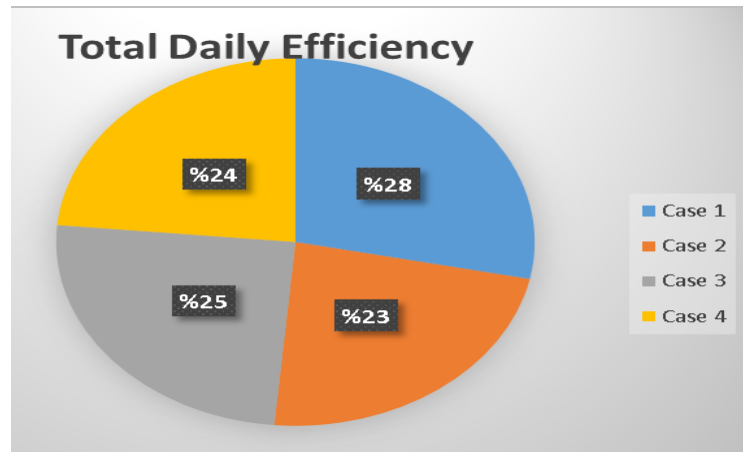


Figure 9 "Total Daily Efficiency Distribution Among Cases"

The experimental results for the four tested configurations are presented in Tables (6–9). Each table reports the hourly thermal gain, absorbed energy, incident solar radiation, and the corresponding thermal efficiency throughout the measurement period (08:00–18:00). The data allow for a systematic evaluation of both instantaneous and daily integrated performance. For example, In Tables (6 and 7), in the first case, the total efficiency reached its peak at noon and was 40% with a low flow rate, while it was observed to decrease in the second case without a mirror and with a higher flow rate despite the uniform heat distribution. Also in Tables (8 and 9), the efficiency was shown to be stable during the morning and afternoon in the third case with a mirror at an angle of 120°, and in the fourth case with a mirror at an angle of 90°, a higher efficiency was shown at noon with lower performance at peak time, which reflects the behavior of the reflective mirror depending on the installation angles.

Table 6: Results and details of experiment No. 1

Hour	Qgain1 (W/m ²)	Qgain2 (W/m ²)	Average Qgain (W/m ²)	Absorbed Energy (W) = Average × 2	Solar Radiation (W/m ²)	Area × Radiation (W)	Efficiency (%)	Total Daily Efficiency
8–9	157.2	189.8	173.5	347	460	920	37.72	38.47
9–10	278.3	339.8	309	618	810	1620	38.15	
10–11	398.2	441.8	420.5	841	1040	2080	40.43	
11–12	457.1	476.9	467	934	1150	2300	40.61	
12–13	466.4	469.8	468	936	1150	2300	40.70	

Hour	Qgain1 (W/m ²)	Qgain2 (W/m ²)	Average Qgain (W/m ²)	Absorbed Energy (W) = Average × 2	Solar Radiation (W/m ²)	Area × Radiation (W)	Efficiency (%)	Total Daily Efficiency
13–14	463.2	451	457	914	1150	2300	39.74	
14–15	405.7	398.2	402	804	1040	2080	38.65	
15–16	321.8	298	310.5	621	810	1620	38.33	
16–17	218.9	205	212	424	580	1160	36.55	
17–18	203.1	198.9	201	402	350	1400	28.71	

Table 7: Results and details of experiment No. 2

Experimental Results – Case 2								
Hour	Qgain1 (W/m ²)	Qgain2 (W/m ²)	Average Qgain (W/m ²)	Absorbed Energy (W) = Average × 2	Solar Radiation (W/m ²)	Area × Radiation (W)	Efficiency (%)	Total Daily Efficiency
8–9	90.2	136.1	113.6	227.2	462	924	24.5887	
9–10	167.5	239.4	203.95	407.9	808	1616	25.2413	
10–11	279	328.7	303.85	607.7	1039	2078	29.2445	
11–12	348.7	404.5	376.6	753.2	1155	2310	32.6061	
12–13	432.5	418.5	425.5	851	1155	2310	36.8398	
13–14	426	465	445.5	891	1155	2310	38.5714	31.5974
14–15	400.5	352.4	376.5	753	1039	2078	36.2368	
15–16	269.2	192.4	230.3	460.6	808	1616	28.5025	
16–17	184.4	98.6	141	282	578	1156	24.3945	
17–18	86.1	81	83.2	166.4	346	692	24.0462	

Table 8: Results and details of experiment No. 3

Hour	Qgain1 (W/m ²)	Qgain2 (W/m ²)	Average Qgain (W/m ²)	Absorbed Energy (W) = Average × 2	Solar Radiation (W/m ²)	Area × Radiation (W)	Efficiency (%)	Total Daily Efficiency
8–9	90.5	159.2	124.85	249.7	470	940	26.5638	
9–10	270.5	318.9	294.7	589.4	820	1640	35.939	
10–11	369.8	393.6	381.2	762.4	1060	2120	35.9623	
11–12	403.6	421	412.5	825	1170	2340	35.2564	
12–13	426	431	428	856	1180	2360	36.2712	
13–14	432	421	425	850	1170	2340	36.3248	34.1451
14–15	398	348	373.3	746.6	1060	2120	35.217	
15–16	286	234	260.45	520.9	820	1640	31.7622	
16–17	196.6	152	174.95	349.9	600	1200	29.1583	
17–18	116	90	102.5	205	370	740	27.7027	

Table 9: Results and details of experiment No. 4

Hour	Qgain1 (W/m ²)	Qgain2 (W/m ²)	Average Qgain (W/m ²)	Absorbed Energy (W) = Average × 2	Solar Radiation (W/m ²)	Area × Radiation (W)	Efficiency (%)	Total Daily Efficiency
8–9	113	172	142.5	285	480	960	29.6875	
9–10	247	242	245	490	830	1660	29.5181	
10–11	290	354	322.5	645	1080	2160	29.8611	32.0643
11–12	360	384	371	742	1185	2370	31.308	

12–13	412	418	415	830	1190	2380	34.8739
13–14	424	450	437	874	1180	2360	37.0339
14–15	366	334	349	698	1080	2160	32.3148
15–16	282	239	259.5	519	830	1660	31.2651
16–17	201	172	186.5	373	620	1240	30.0806
17–18	125	103	114.5	229	390	780	29.359

5 Comparative Analysis with Previous Studies and Theoretical Insights

When comparing the study with previous studies. Alvarez (2010) [20] found that the thermal balance depends on the flow rate, as the heat flow decreases in the collector with increasing flow rate, thus determining the overall thermal efficiency. This is consistent with this study, as in Case 2, where a flow rate of 1.15 liter/minute significantly reduced the thermal efficiency value, with stable thermal energy gain compared to Case 1, which included a low flow. Similarly, Jiandong (2015) [19] also highlighted that enhancing optical quality leads to improved thermal performance of optical reflectors, a finding mirrored in this study in Cases 3 and 4 where the use of reflective mirrors significantly improved the morning and evening thermal performance

Finally, Bellos (2023) [22] reported that instantaneous peaks in thermal efficiency throughout the day are important, but maintaining a constant and stable thermal efficiency over extended periods is even more important. This is consistent with this study, which in turn confirmed that temporal stability is more important than instantaneous peaks, as all results confirm that optimizing a solar collector depends on several factors, including heat loss management, optical alignment, and hydraulic thermal stability.

6 Conclusions

1. The overall efficiency was (28%) in case 1 at a low flow rate due to the thermal-hydraulic balance and low optical losses.
2. Overall efficiency decreases due to the temperature difference between the inlet and outlet, despite the improvement and stability of the instantaneous performance with the increase in the flow rate in Case 2.
3. In case 3, with the reflective mirror and a 120° angle of inclination, thermal performance was improved and usage periods were increased during the morning and evening hours compared to the other cases.
4. In case 4, the efficiency of the collector decreased when the mirror was used at a 90° angle, despite the improvement in heat gain at midday.
5. The study showed that high instantaneous peaks of thermal efficiency can be achieved when the temporal thermal performance of daily efficiency is maintained.
- 6 In all cases, limited overall efficiency was demonstrated when using a single layer of glass due to free convection heat losses.
7. Limiting the efficiency of mirror coatings due to optical factors such as reflectivity, resolution, and shading.
8. Improving the optical properties of mirrors will improve the thermal performance of solar collectors in the future or avoid heat losses by using multiple layers of glass.
9. This study presented the improvement of solar collectors in arid and semi-arid climates where sustained efficiency throughout the day.
10. This study can be used as a future reference in the design of flat-plate solar collectors, especially those integrated with a reflective mirror, to enhance thermal performance.

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