POLITYKA ENERGETYCZNA – ENERGY POLICY JOURNAL

2026 ✦ Volume 29 ✦ Issue 3 ✦ 219–246

DOI: 10.33223/epj/215595

Bariq Abdullah Mohammed[1], Hussein Hayder Mohammed Ali[2], Afrah Awad[3]

A techno-economic investigation into performance enhancement of flat-plate solar collectors using reflective mirrors under atmospheric conditions in Kirkuk City, Iraq

Abstract: Solar energy, a sustainable and environmentally benign resource, has increasingly captivated scientific and engineering communities due to its ability to deliver clean energy with negligible operational expenses, notwithstanding its relatively high initial installation costs. The present investigation was undertaken to augment the thermal efficiency of a flat-plate solar collector by employing a reflective mirror under the climatic conditions of Kirkuk, Iraq. Two identical collectors were fabricated: one representing a conventional configuration and the other integrated with a reflective mirror to amplify the incident solar radiation and consequently elevate heat absorption. Experimental analyses were carried out during four consecutive months: December 2024 and January, February, and March 2025 at 1:00 p.m. In December, the mirror-assisted collector attained a thermal efficiency of 31.66%, compared with 28.99% for the conventional unit, indicating

✉ Corresponding Author: Hussein Hayder Mohammed Ali; e-mail: hussein_kahia@ntu.edu.iq

[1] Kirkuk Technical Engineering College, Northern Technical University; Renewable Energy Research Center Kirkuk, Northern Technical University, Iraq; ORCID iD: 0009-0002-0806-4714; e-mail: bariq.abdullah24gs@ntu.edu.iq

[2] Kirkuk Technical Engineering College, Northern Technical University; Renewable Energy Research Center Kirkuk, Northern Technical University, Iraq; ORCID iD: 0000-0003-4264-400X; e-mail: hussein_kahia@ntu.edu.iq

[3] Kirkuk Technical Engineering College, Northern Technical University; Renewable Energy Research Center Kirkuk, Northern Technical University, Iraq; ORCID iD: 0000-0003-3967-0821; e-mail: afrah.turki@ntu.edu.iq

a 9.21% enhancement. In January, efficiency increased from 28.67% to 37.86%, corresponding to a 32.05% improvement. February recorded values of 39.59% and 36.65%, showing an 8.02% gain. March demonstrated the most substantial enhancement, as the modified collector reached 59.40% compared with 35.64% for the conventional system, a 66.66% increase. The outcomes verify that reflective augmentation significantly enhances the collector's thermal performance, with the maximum efficiency observed in March due to the highest solar radiation intensity during this period.

KEYWORDS: thermal efficiency, solar still, cost evaluation, reflective mirrors, absorber plate

Introduction

Population expansion, technological advancements, and better living conditions have all contributed to a meteoric rise in the world's energy demands. Electricity and heat are the two most common forms of energy production. Generation methods and their potential effects on the environment have come under scrutiny in light of the enormous need for energy. As a result of this innovation, renewable or clean alternatives have emerged, which rely on collecting abundant solar radiation that hits the planet (Zarda et al. 2022). Greenhouse gas emissions might be mitigated if renewable energy sources met a greater share of energy needs. Photovoltaic (PV) systems turn the sun's rays directly into electricity, while solar collectors transform it into heat. In recent years, the need for renewable energy sources has grown significantly (Ali et al. 2025).

It is fascinating to see thermal collectors integrated into contemporary buildings' facades or roofs. Houses, apartment complexes, tourist attractions, hospitals, schools, and other buildings can all benefit from their use to heat sanitary water. Mounting flat solar radiation reflectors on thermal collectors can achieve an increase in thermal efficiency. The reflector is employed to focus both direct and diffuse solar energy onto the collector, so enhancing the temperature differential between the inlet and outlet water flow via the collector (Wells 2009).

Mulugata and Tesfay (2017) did an experiment to see if adding four external reflectors to the bottom, top, left, and right sides of a liquid-cooled flat-plate collector (specifically a syphon-type flat-plate collector) would improve its performance. Over the course of several days, the experiment was carried out on a flat-plate collector with and without reflectors, and the data was meticulously collected and stored according to the day. During daytime, the flat plate with a reflector attained the greatest liquid-cooled outlet temperature of 98°C with 1,200 W/m^2 of solar radiation. In contrast, on a sunny day, the flat plate without a reflector reached a maximum temperature of 70°C and a maximum solar radiation of 1,200 W/m^2. A collector with strategically placed reflectors generates a great deal more total thermal energy than one without them.

An experiment was done by Qiu et al. (2021) to see how well a solar trough collector worked. The collector has a transparent hot mirror shield to keep heat in and two symmetrical solar mirrors to make the solar radiation stronger. This research created a photo thermally coupled model. The model served as the basis for an initial comparison between the proposed receiver and a standard receiver as well as two previously developed modified receivers. According to the findings, the optical efficiency of the suggested receiver can reach 78.02%, surpassing that of previously modified receivers and just 0.22 percentage points below that of the standard receiver. It is possible for the suggested receiver to cut thermal loss by 11.2–89.6 W m^{-3}. This raises the efficiency of both the receiver and photo thermal processes by 0.03–5.26%. Solar water heaters that use a trapezoidal cavity as a concentrator and a linear Fresnel reflector were the subject of an experimental investigation by Ghodbane et al. (2018). To get the concentrating line hot, we tried out various configurations of reflective mirrors. The copper absorber tube had a black paint coating and a selectively appropriate surface. The heat that might be used by the absorber tubes was measured and compared with mirrors numbered 7, 9, and 11. Thanks to eleven reflecting mirrors, the water temperature peaked at 74°C. We achieved a maximum thermal efficiency of 29.21%.

Solar water heaters, both residential and commercial, can benefit greatly from the employed linear Fresnel concentrator in solar energy fields, according to the findings. This gadget serves as a cost-effective thermodynamic process for heating water through solar energy. Tabasi et al. (2019) did an experiment on the performance of a solar panel with reflecting mirrors. They found that panel and mirror tilt as well as mirror length affected system performance, including the rise in cell temperature. We sought out, debated, and modelled a wide range of potential layouts, lighting, and shading scenarios in a three-dimensional space. The optimal reflective mirror angle was found to be 0°, while the optimal solar panel tilt angle was determined to be 69.084°, according to the data. Solar panels equipped with reflective mirrors may provide an estimated 2.38 GJ (613.89 kWh) of electrical energy each annum, according to the findings.

An experimental model of a photovoltaic/thermal (PV/T) collector was developed and tested by Benkaddour et al. (2022). This model uses two moveable mirrors to concentrate solar radiation and improve its electrical and thermal energy. Scientists analyzed electrical and thermal efficiency in two scenarios one without mirrors and one with them strategically placed to prove that the mirrors were effective at generating thermal and electrical energy from the collector. The ideal angular positions for the lower reflector were found to be 14° in December and 42° in June, according to numerical calculations; for the upper reflector, the ideal positions were 5° in June and 30° in December. The findings showed that a PV/T collector's average daily electrical efficiency was 13.75% without mirrors and 14.09% with mirrors. A PV/T collector without mirrors produced 41.58 Wh of electrical energy, but one with mirrors produced 27.25 Wh. Because it is temperature dependent, the electrical efficiency of a mirrorless photovoltaic cell is greater than that of a mirror-containing cell. A photovoltaic/thermal air collector with mirrors achieves an average thermal efficiency of 46.17% per day, which is higher than the 46.10% achieved without mirrors.

Two aluminum foil reflectors were put on top and bottom of a flat-plate solar collector by Pavlovic and Kostic (2022). They then analyzed and tested the collector to see how the reflectors changed its performance. Results showed that December had the lowest optimal angle position for the lower reflecting mirrors (5°) and June the highest optimal angle position for the higher reflective mirrors (38°), with a collector angle of 45°. Compared to a collector devoid of reflectors, one with them strategically produced substantially more total heat energy. These findings show that aluminum foil reflectors are effective; a collector with reflectors can increase its energy output by 35 to 44 per percent throughout the summer.

An experiment and a theory by Ahmed and Bawa (2018) looked into what happens when reflecting mirrors are added to a photovoltaic/thermal hybrid collector that heats water and air and makes electricity. Research on the hybrid solar collector's efficiency focused on three controlled variables: the angle of the bottom reflector, the presence or absence of reflective mirrors, and the glass cover. The findings demonstrated that reflective mirrors caused the solar cell's temperature to rise. Its value was 92.70°C when the glass cover was used in conjunction with the lower and upper mirrors, 76.10°C when the lower mirrors were used alone, and 71.35°C when the reflective mirrors were not used. With two reflectors in use, the average daily overall efficiency was 81.03%, indicating a high level of thermal and electrical efficiency. The daily average overall efficiency was 589.5% with the glass cover and 499.7% without, indicating that the glass cover had a substantial impact on overall efficiency. Additionally, the use of reflectors improves overall efficiency.

Using external flat-plate reflectors and a parabolic collector mounted on arrays of flat-plate collectors, Nagaraju et al. (2021) enhanced a single-slope solar still by adding sand troughs to improve heat storage and evaporation. Experiments at 1–3 cm water depths showed the best performance at 1 cm, yielding 0.453 L/m^2 versus 0.2 L/m^2 without sand troughs. The modification increased daily productivity by 71.4% and efficiency from 37.9% to 65.08%. The cost of freshwater production was ₹0.801/L over 12 years, proving the design both efficient and economical. According to the findings, older flat-plate reflectors achieved a performance boost of more than 30% per year, or 100–120 kWh/m^2. Performance gains of up to 170 kWh/m^2 were possible when a reflector shaped like a parabolic collector was attached to a novel reflector material. This allowed for a 30% reduction in the amount of land and collector area needed for a given load.

A silicon photovoltaic (PV) system that makes use of inverters set at the ideal tilt angle was the subject of an experimental investigation by Malik and Chandel (2020). The results indicated that the PV inverter system's average power augmentation was 10% in the summer and 19.84% in the winter, with a difference of 13.23%. The inverter system performed best in the summer with a tilt angle of 40° and a tilt angle of 15°. Bhowmik and Amin (2017) executed an experimental investigation to evaluate a prototype flat-plate solar collector, both with and without a reflector, in Gazipur, Bangladesh, in January 2015. The collector's efficiency was 51% without a reflector and 61% with a reflector. The overall efficiency of a flat-plate solar collector is enhanced by around 10% when a reflector is employed with it. Naik and Palatel (2014) executed an experimental investigation to assess the efficacy of a solar water heater augmented with a planar reflector positioned at the upper edge of the collector in the tropical climate of Calicut. A significant improvement in the thermal and electrical performance of the system with the integrated reflector was observed compared to the system without the reflector. The system demonstrated that a reflector tilt angle between 85° and 100° was optimal for improving

Table 1. Summary of core performance evaluation criteria in reviewed studies

Tabela 1. Podsumowanie głównych kryteriów oceny wyników w przeanalizowanych badaniach

Authors	Enhancement Focus	Findings
Kedar et al. 2021	Optical enhancement using CPC reflectors	Optimum distance (20 mm) between ETC and CPC; Mylar reflector achieved 3.5 L/m^2·day vs. 1.9 L/m^2·day (aluminum foil).
Singh et al. 2023	Thermal enhancement using PCM and nanoparticles	PCM-based stills improved distillate yield: Tubular SS +218%, Single Basin +149%, Pyramidal +125%, Hemispherical +94%, Stepped +68%.
Yousef and Hassan 2019	Thermal conductivity enhancement using PCM, fins, and SWF	Yield: With PCM +9.5%, PCM+PF +16.8%, PCM+SWF +13%. Energy efficiency ↑17.9%, exergy ↑13.2% (PF).
Sonker et al. 2020	Utilizing CuO nanoparticles in PCM for passive stills	CuO nanoparticles improved the thermal conductivity of paraffin wax from 0.25 to 0.34 W/m.K
Sharshir et al. 2017	Explored synergistic effects of three enhancement techniques in hybrid stills.	Productivity enhancement reached 73.8% under the combined modification (D: FGN + PCM + film cooling).

output and thermal efficiency under winter conditions. The aim of the study is to experimentally evaluate how integrating upper and lower reflective mirrors with a conventional flat-plate solar collector can enhance its thermal performance and economic feasibility under the atmospheric conditions of Kirkuk, Iraq. The investigation focuses on quantifying improvements in outlet temperature, heat gain, and thermal efficiency across different seasons by conducting tests from December 2024 to March 2025. It further aims to assess the influence of varying volumetric flow rates, identify optimal mirror tilt angles for maximizing solar concentration, and compare the performance of the modified system with that of an identical conventional collector. Additionally, the study seeks to determine whether mirror-assisted solar concentration offers a cost-effective and practical enhancement technique relative to traditional configurations, thereby improving the overall energy yield and reducing the levelized cost of heat production.

1. Experimental methodologies

This study involved developing a dual-plate solar collector test system. The first collector served as the primary collector and operated using clean water only. The second collector was identical to the first in all aspects, including dimensions and specifications, but incorporated two reflective mirrors: one positioned above the flat collector (upper mirror) and another below it (lower mirror). Their purpose was to increase the concentration of solar radiation on the collector. The temperatures at the solar collector's inlet and outlet, as well as those of the glass surface and absorber plate, were determined using appropriate sensors. Several measurements were taken, including the volumetric flow rate of water and the amount of solar radiation reaching the collector. Figure 1 illustrates the test setup.

Fig. 1. The experimental layout

Rys. 1. Układ eksperymentu

1.1. Flat plate solar collector

The system comprises a square aluminum structure box (1 × 1) m, where there is a 5 cm-wide gap between the three plastic panels and the inner aluminum layer that forms the outer part. In the middle, insulating glass wool is sprayed, and then a layer of transparent glass, 4 mm thick, is placed over it. It is immovable. The thickness was selected to accommodate the extensive cross-sectional area of the module and safeguard it from damage and environmental degradation. It also maximizes the absorption of solar radiation from the top, which in turn allows heat to escape, reduces heat loss from the building, and provides insulation at the bottom and sides. The absorber plate has dimensions of (0.95 × 1) m, and there is a gap or distance of 2.5 cm between it and the glass cover. The copper tubes that make up the solar collector are 0.85 m long and have the following dimensions: The inner diameter of the head is 22.5 mm, and its thickness is

1.5 mm. The inner diameter of the riser pipes is 9.5 mm, and its thickness is 1 mm. Armaflex insulation is applied in two layers on the inner surfaces of the collector to insulate the pipes connecting the system components and ensure that no heat is lost to the outside environment. A network of plastic pipes connects the solar collectors of the system. Water is transported in the system through these channels, which have a diameter of 0.5 in. Several valves and connectors control the movement of fluids throughout the system. To ensure water circulation within the test system, two pumps were used for each collector, with a height of no less than 2.5 m. These two pumps played an important and effective role in moving water from the designated tank to the flat solar collector.

1.2. Reflective mirrors

The reflective mirrors consist of a rectangular iron box with dimensions of (1×0.5) m. Its unbreakability, heavy weight, stability, resistance to weather and strong winds, and affordability made iron the preferred metal. We coated it to prevent the metal surface from forming a thin layer of iron oxide, which leads to corrosion. Next, we place the flat mirrors inside the (0.97×0.47) m iron box shown in Figure 2. The mirrors are fixed to the iron frame with thermal silicone to prevent them from being affected by heat, which may cause the mirrors to shatter.

Fig. 2. The reflective mirror in the test system

Rys. 2. Lustro odbijające w układzie testowym

1.3. Solar collector measurement instruments and calibrations

A YF-S201 water flow sensor was used to track the rate of pure water flow. This sensor was capable of measuring fluid flow rates between 1 and 30 L/min and could withstand pressures up to 1.75 megapascals. The flow sensors were carefully arranged as shown in Figure 3. A mechanism was developed to record the temperature, flow rate, and radiation intensity of the fluid within the primary and secondary solar collectors to measure its thermal performance. The device was powered by an Arduino chip, and the Arduino UNO model was specifically selected due to its compatibility with the study variables. An external memory card (EMC) was used for long-term data storage, providing twelve input and output channels.

All seven data points were recorded in the test system: the inlet and outlet temperatures, absorber plate and cover glass temperatures, ambient temperature, flow rate, and radiation intensity. The memory drive shown in Figure 3 stored the hourly recorded readings. For temperature measurements, four digital Arduino-type (K) sensors and four analog NTC sensors were connected to the Arduino system. The sensors were positioned as follows: two thermocouples were installed at either end of the header tube to measure the inlet and outlet temperatures of the fluid as it flowing from the primary system to the flat-plate solar collector. Each system also had two thermal sensors mounted on the absorber plate to monitor its surface temperature, and two additional sensors were attached to the glass cover to measure its temperature. Thermal sensors were also placed near both experimental setups to record the ambient temperature. This configuration ensured precise and comprehensive data collection for accurate assessment of the system's thermal performance.

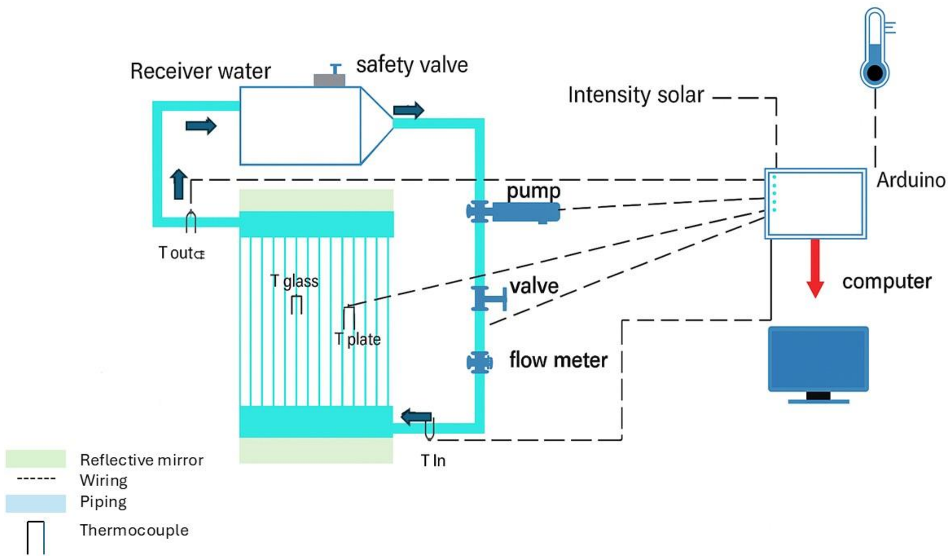

Fig. 3. A diagram of the flat solar collector

Rys. 3. Schemat płaskiego kolektora słonecznego

2. Theoretical methodology

Performance of flat plate solar water collectors (utilitarian energy): at steady state, the amount of usable energy produced by a solar water collector is (Tarik and Ali 2020; Ali et al. 2023):

$$Q_u = \dot{m} \cdot C_{p,w} \cdot \left(T_{w,co} - T_{w,ci}\right) \tag{1}$$

where:

- $\dot{m}$ – mass flow rate of the water [kg·s^{-1}],
- $C_{p,w}$ – specific heat of water [kJ (kg·K)$^{-1}$],
- $T_{w,ci}$ and $T_{w,co}$ – temperatures of the water at the input and exit of the solar collector, respectively [K].

The flat plate solar water collector's hourly efficiency η_{sc} is (Nassar et al. 2023; Miri et al. 2023):

$$\eta sc = \frac{\int_{t_1}^{t_2} Q_u \, dt}{A_{sc} \int_{t_1}^{t_2} I(t) dt} \cdot 100\% \tag{2}$$

where:

- $I(t)$ – instantaneous intensity of solar radiation [Wm^{-2}],
- A_{sc} – flat plate solar water collector area [m^{-2}],
- Q_u – thermal useful energy [W].

The total solar radiation $G_{tot.col}$ on the PV/T collector surface with tilted plane angle β is the sum of several components, as shown in Figure 4, and including the following: the radiation that hits the collector surface directly ($G_{dir.col}$), the radiation that diffuses from the sky ($G_{dif.col}$), the radiation that is reflected from the ground ($G_{ref.gr}$), the radiation that is reflected from the bottom reflector ($G_{ref.r1}$ with tilted plane angle a_1), and the radiation that is reflected from the upper reflector ($G_{ref.r2}$ with tilted plane angle a_2) (Qader et al. 2023; Qader et al. 2024, Ali et al. 2025; Fattahi 2021).

$$G_{tot.\,col} = G_{dir.\,col} + G_{dif.col} + G_{ref.gr} + G_{ref.r1} + G_{ref.r2} \tag{3}$$

where:

$$G_{dir.col} = G_{in} \cdot \sin\left(\alpha + \beta\right) \tag{4}$$

$$G_{dif.col} = G_{dif} \cdot \frac{1 - \cos\beta}{2} \tag{5}$$

$$G_{ref.gr} = \rho_g \cdot G_h \cdot \frac{1-\cos\beta}{2} \tag{6}$$

$$G_{ref.r1} = \rho_{A1} \cdot G_{in} \cdot \sin_{\chi} \cdot \sin(\alpha - \alpha_1); \quad \chi = (\beta + 2)(\alpha_1 - \alpha) \tag{7}$$

$$G_{ref.r2} = \rho_{A1} \cdot G_{in} \cdot \sin\tau \cdot \cos(\alpha_2 + \alpha); \tau = (\alpha + 2)(\alpha_2 - \beta) \tag{8}$$

where:

α – solar altitude angle,
G_{in} – global solar incident radiation,
G_{dif} – diffuse radiation on horizontal surface,
G_h – global solar radiation on horizontal surface,
ρ_g – ground reflectance,
χ – incidence angle of the reflected solar radiation on the absorber surface,
ρ_{A1} – *A*l sheet reflectors reflectance.

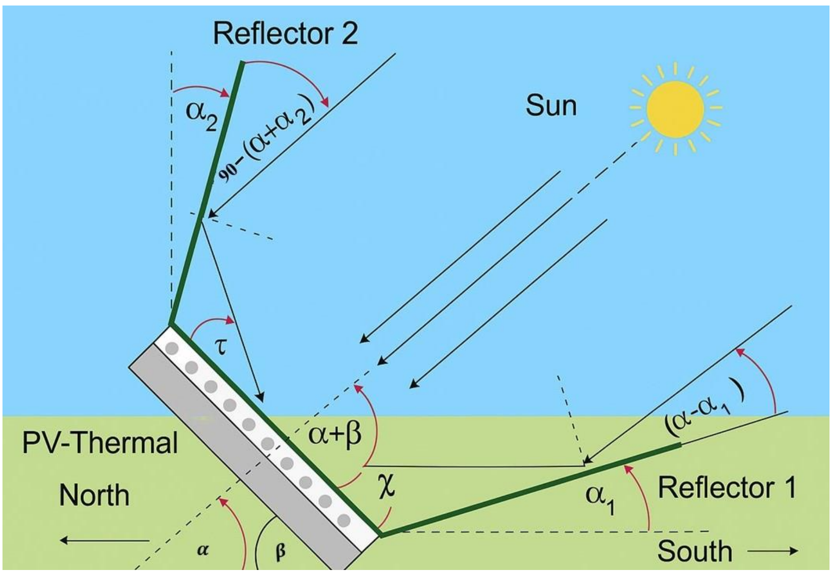

Fig. 4. Schematic diagram of the flat plate solar collector with solar radiation reflectors

Rys. 4. Schemat płaskiego kolektora słonecznego z elementami odbijającymi promieniowanie słoneczne

3. Result and discussions

This section presents a thorough examination of the data derived from practical experiments performed on flat-plate solar collectors over the months of December, January, February, and March. Testing commenced at 9:00 a.m. and persisted until 5:00 p.m. The tests aimed to enhance the operational efficiency of the collector, augment the thermal energy acquired, and improve the heat transfer coefficient. The impact of reflective mirrors was analyzed, and the system outcomes were compared with and without their utilization. The lower mirror was secured at an angle of Θ=5°, while the angle of the upper mirror was adjusted. The optimal angles for each of the four months were established as follows: 25°, 22°, 20°, and 18°, respectively. Distilled water served as the reference point for comparison. The flow rates were adjusted to 0.0089, 0.012, and 0.015 L/s.

Figure 5 illustrates the correlation between solar radiation and the daily average duration period of four months. Solar radiation is most intense between 9:00 a.m. and 11:00 p.m. during the four months because the sun is perpendicular to the Earth's surface during that period, which

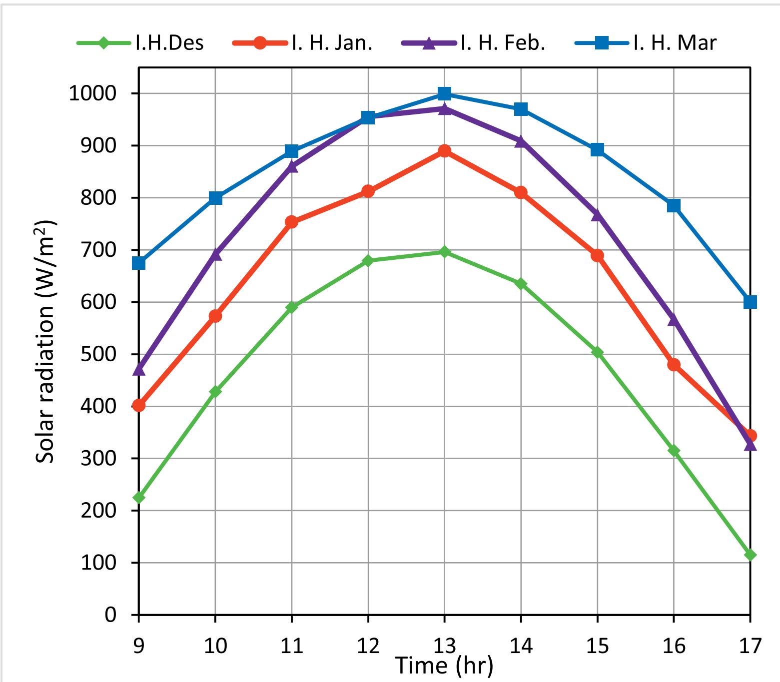

Fig. 5. The intensity of solar radiation in relation to daylight hours for December 2024 and the subsequent months of January, February, and March 2025 in Kirkuk, Iraq

Rys. 5. Natężenie promieniowania słonecznego w odniesieniu do liczby godzin dziennych w grudniu 2024 r. oraz w kolejnych miesiącach: styczniu, lutym i marcu 2025 r. w Kirkuku w Iraku increases the incidence of solar radiation. During the months of December, February, and March, it peaked at 696 W/m^2, 890 W/m^2, 972 W/m^2, and 999 W/m^2, respectively, at exactly 1:00 p.m. Because the sun is tilted relative to the Earth, its rays are less intense in the afternoon.

Figures 6 to 8 illustrate the correlation between outlet temperature and the monthly average for March during the study period at 3 p.m. is presented at various flow rates (0.0089, 0.012, 0.015 L/s) for both the conventional flat solar collector (lacking a reflective mirror), and the enhanced solar collector (featuring a reflective mirror). The optimal angle for the upper mirror was established for each of the four months specified (25°, 22°, 20°, 18°), while the lower mirror was maintained at a fixed angle of 5° for the distilled water utilized within the collector. The findings indicated that the exit temperature rises from 9:00 a.m. until 1:00 p.m. owing to the heightened intensity of solar radiation on the collector and subsequently declines from 1:00 p.m. to 5:00 p.m., as solar radiation diminishes on the collector for both the conventional and mirror-enhanced collectors.

Figure 6 illustrates that at a volumetric flow rate of 0.0089 L/s, the exit temperature of the mirror-enhanced solar collector attained 51°C, whereas the exit temperature of the traditional solar collector reached 47.97°C.

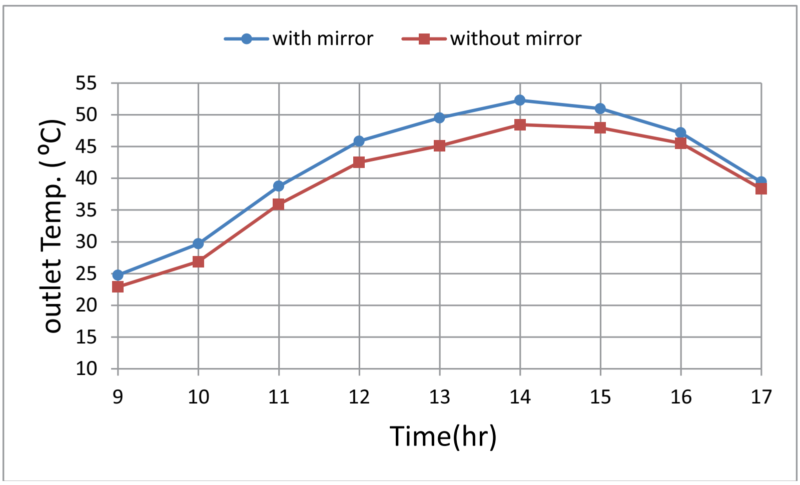

Fig. 6. The correlation between the output temperature and the time average for March at a specified volumetric flow rate at 0.0089 L/s

Rys. 6. Korelacja między temperaturą na wylocie a średnią czasową dla marca przy określonym natężeniu przepływu objętościowego wynoszącym 0,0089 l/s

Figure 7 illustrates that at a volumetric flow rate of 0.012 L/s, the exit temperature of the sun collector augmented with a reflective mirror attained 50.89°C, whereas the exit temperature of the traditional solar collector reached 47.76°C.

Figure 8 illustrates that at a volumetric flow rate of 0.015 L/s, the exit temperature of the solar collector augmented with a reflective mirror attained 50.55°C, whereas the exit temperature of the traditional solar collector reached 47.68°C.

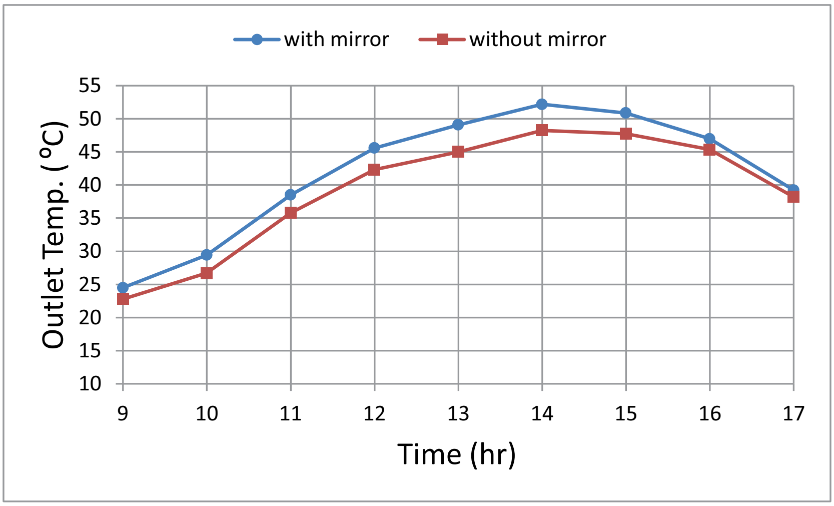

Fig. 7. The correlation between the output temperature and the time average for March at a specified volumetric flow rate at 0.012 L/s

Rys. 7. Korelacja między temperaturą na wylocie a średnią czasową dla marca przy określonym natężeniu przepływu objętościowego wynoszącym 0,012 l/s

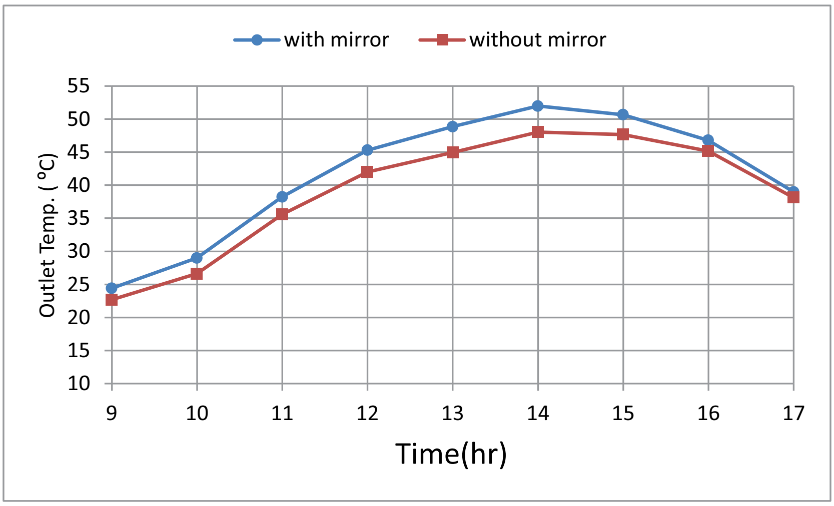

Fig. 8. The correlation between the output temperature and the time average for March at a specified volumetric flow rate at 0.015 L/s

Rys. 8. Korelacja między temperaturą na wylocie a średnią czasową dla marca przy określonym natężeniu przepływu objętościowego wynoszącym 0,015 l/s

Figures 9 to 12 illustrate the correlation between heat acquisition and the time average over four months (December 2024, January, February, and March 2025) for two types of solar collectors: a conventional flat-panel collector without a reflective mirror and an enhanced collector with a reflective mirror. The optimal upper mirror angles for each month are set at 25°, 22°, 20°, and 18°, respectively, while the lower mirror remains fixed at an angle of 5°. This analysis is based on a volumetric flow rate of 0.015 L/s of distilled water used within the collector. The findings indicated that the heat gained escalates from 9:00 a.m. to 1:00 p.m. as a result of heightened solar radiation intensity on the collector and subsequently diminishes from 1:00 p.m. to 5:00 p.m. due to reduced solar radiation on the collector for both the conventional and enhanced collectors utilizing a reflective mirror. The data indicates that the most heat gain occurred in the solar collector enhanced by the incorporation of a reflective mirror. This result signifies that an increased concentration of solar radiation incident on the collector enhances the thermal exchange between the collector tube wall and the distilled water contained within the collector.

In Figure 9 for December, the heat acquired by the enhanced solar collector utilizing a reflective mirror was 220.48 watts at 1 p.m., whereas the traditional solar collector without a reflective mirror acquired 201.85 watts, resulting in a percentage increase of 9.23% when comparing the two collectors.

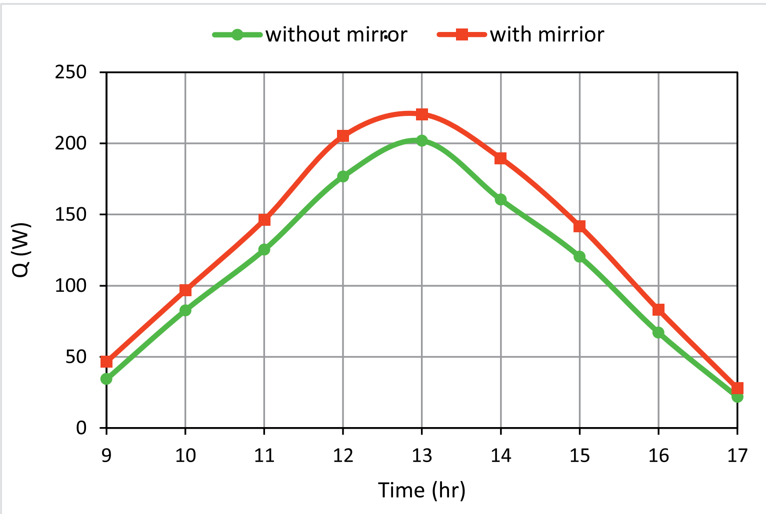

Fig. 9. Heat gain per day at a volumetric flow rate of 0.015 L/s for both the improved solar collector, which uses an upper reflective mirror at ϴ = 25° and a lower mirror at ϴ = 5°, and the conventional solar collector, measured in December 2024 in Kirkuk, Iraq

Rys. 9. Dzienne przyrosty ciepła przy natężeniu przepływu objętościowego wynoszącym 0,015 l/s zarówno dla ulepszonego kolektora słonecznego, wyposażonego w górne lustro odbijające o kącie nachylenia ϴ = 25° i dolne lustro o kącie nachylenia ϴ = 5°, jak i dla kolektora słonecznego konwencjonalnego, zmierzone w grudniu 2024 r. w Kirkuku w Iraku

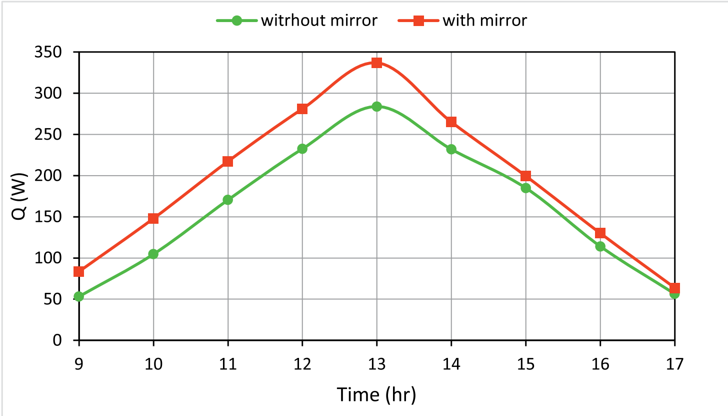

Fig. 10. Heat gain per day at a volumetric flow rate of 0.015 L/s for both the improved solar collector, which uses an upper reflective mirror at Ө = 25° and a lower mirror at Ө = 5°, and the conventional solar collector, measured in January 2025 in Kirkuk, Iraq

Rys. 10. Dzienne przyrosty ciepła przy natężeniu przepływu objętościowego wynoszącym 0,015 l/s zarówno dla ulepszonego kolektora słonecznego, wykorzystującego górne lustro odbijające pod kątem Ө = 25° i dolne lustro pod kątem Ө = 5°, jak i dla konwencjonalnego kolektora słonecznego, zmierzone w styczniu 2025 r. w Kirkuku w Iraku

In Figure 10 for January, the heat gained by the enhanced solar collector utilizing a reflective mirror was 296.03 watts at 1 p.m., whereas the traditional solar collector without a reflective mirror attained 255.13 watts. This indicates a 16.03% increase in heat acquisition when comparing the enhanced collector to the traditional model.

In Figure 11 for February, the heat gained by the enhanced solar collector utilizing a reflective mirror was 384.6 watts at 1 p.m., whereas the traditional solar collector without a reflective mirror garnered 318.44 watts, indicating a 20.78% increase in heat acquisition when comparing the improved and traditional collectors.

In Figure 12 for March, the heat gained by the enhanced solar collector utilizing a reflective mirror was 593.31 watts at 1 p.m., whereas the traditional solar collector without a reflective mirror garnered 356.06 watts, indicating a 66.63% increase in heat acquisition when comparing the improved and traditional collectors.

Figures 13 to 15 represent the variation of experimental thermal efficiency over time for three distinct volumetric flow rates: 0.0089, 0.012, and 0.015 L/s for the solar thermal collector, which is enhanced with a reflective mirror, during December 2024 and the months of January, February, and March 2025. The results indicate that practical efficiency enhances from 9:00 a.m. to 1:00 p.m. This result indicates that increased solar radiation enhances the efficiency of the solar collector. Although solar radiation intensity decreases after 12:00 p.m., the efficiency continues to increase to 1:00 p.m. This results from the thermal retention of the solar collector and the surrounding atmosphere, which reduces thermal losses, meaning that heat dissipation from the solar collector to the outside is minimal. Subsequent to 2:00 p.m., the collector performance decreases as solar radiation intensity decreases until 5:00 p.m.

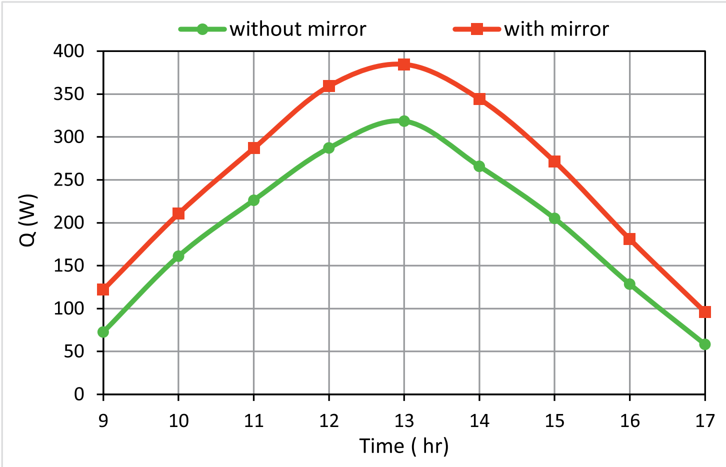

Fig. 11. Heat gain per day at a volumetric flow rate of 0.015 L/s for both the improved solar collector, which uses an upper reflective mirror at Θ = 25° and a lower mirror at Θ = 5°, and the conventional solar collector, measured in February 2025 in Kirkuk, Iraq

Rys. 11. Dzienne przyrosty ciepła przy natężeniu przepływu objętościowego wynoszącym 0,015 l/s zarówno dla ulepszonego kolektora słonecznego, wyposażonego w górne lustro odbijające o kącie nachylenia Θ = 25° i dolne lustro o kącie nachylenia Θ = 5°, jak i dla kolektora słonecznego konwencjonalnego, zmierzone w lutym 2025 r. w Kirkuku w Iraku

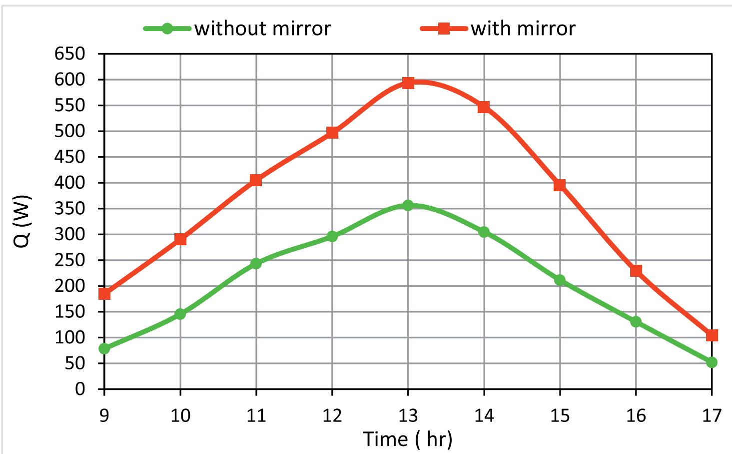

Fig. 12. Heat gain per day at a volumetric flow rate of 0.015 L/s for both the improved solar collector, which uses an upper reflective mirror at Θ = 25° and a lower mirror at Θ = 5°, and the conventional solar collector, measured in March 2025 in Kirkuk, Iraq

Rys. 12. Dzienne przyrosty ciepła przy natężeniu przepływu objętościowego wynoszącym 0,015 l/s zarówno dla ulepszonego kolektora słonecznego, wyposażonego w górne lustro odbijające o kącie nachylenia Θ = 25° i dolne lustro o kącie nachylenia Θ = 5°, jak i dla kolektora słonecznego konwencjonalnego, zmierzone w marcu 2025 r. w Kirkuku w Iraku

In December, Figure 13 shows that the maximum efficiency corresponds to the maximum volumetric flow rate of 0.015 L/s. This phenomenon is because increasing the volumetric flow rate leads to the breakdown of adjacent layers in the pipes, which enhances heat transfer from the pipe surface to the fluid. The results indicated that the highest efficiency was for the volumetric flow rate of 0.015 L/s, equal to 31.66% at 1:00 p.m., while for the volumetric flow rate 0.012 L/s it equaled 29.53% at 1:00 p.m., and for the volumetric flow rate 0.0089 L/s its equal to 26.91%. This means that the percentage enhancement of efficiency for the volumetric flow rate 0.015 L/s over 0.012 L/s is 7.21%, and the percentage enhancement of efficiency for the volumetric flow rate 0.015 L/s over 0.0089 L/s is 17.65%.

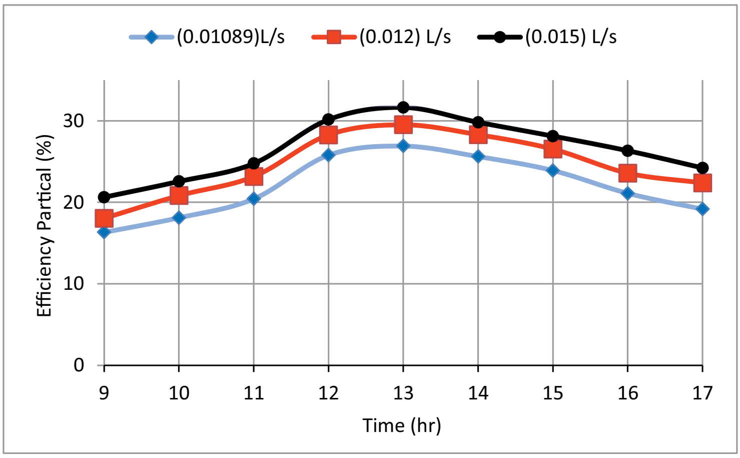

Fig. 13. The effects of daylight hours on the thermal efficiency at various volumetric flow rates of the enhanced collector utilizing a using the upper reflecting mirror at Ɵ = 25° and the lower mirror at Ɵ = 5° for December 2024, Kirkuk, Iraq

Rys. 13. Wpływ długości dnia na sprawność cieplną przy różnych natężeniach przepływu objętościowego w ulepszonym kolektorze wykorzystującym górne lustro odbijające pod kątem Ɵ = 25° i dolne lustro pod kątem Ɵ = 5° w grudniu 2024 r. w Kirkuku w Iraku

As for January, Figure 14 shows that the maximum efficiency corresponds to the maximum volumetric flow rate of 0.015 L/s. This difference is because increasing the volumetric flow rate leads to the breakdown of adjacent layers in the pipes, which enhances heat transfer from the pipe surface to the fluid. The results indicated that the highest efficiency was for the volumetric flow rate of 0.015 L/s, equaling 37.86% at 1:00 p.m., while for the volumetric flow rate of 0.012 L/s its equaled 35.85% at 1:00 p.m., and for the volumetric flow rate of 0.0089 L/s it equaled 27.62%. This means that the percentage enhancement of efficiency for the volumetric flow rate 0.015 L/s over 0.012 L/s is 5.69%, and the percentage enhancement of efficiency for the volumetric flow rate 0.015 L/s over 0.0089 L/s is 37.07%.

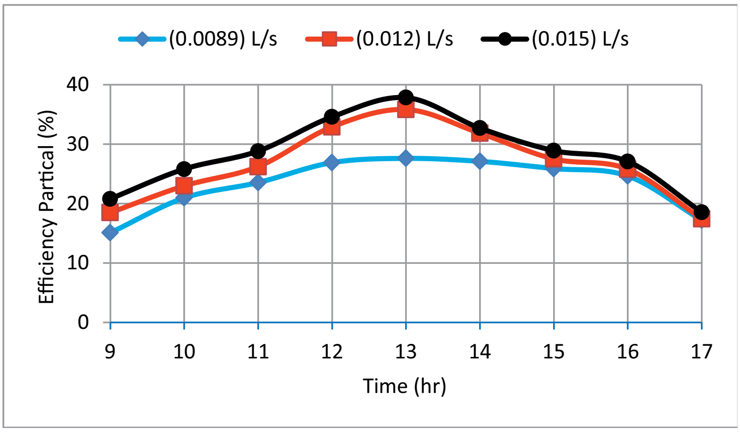

Fig. 14. The effects of daylight hours on the thermal efficiency at various volumetric flow rates of the improved collector a using the upper reflecting mirror at Ө = 22º and the lower mirror at Ө = 5º for January 2025, Kirkuk, Iraq

Rys. 14. Wpływ długości dnia na sprawność cieplną przy różnych natężeniach przepływu objętościowego ulepszonego kolektora a, wykorzystującego górne lustro odbijające pod kątem Ө = 22º i dolne lustro pod kątem Ө = 5º, w styczniu 2025 r. w Kirkuku w Iraku

As for February, Figure 15 shows that the maximum efficiency corresponds to the maximum volumetric flow rate 0.015 L/s. This difference is because increasing the volumetric flow rate leads to the breakdown of adjacent layers in the pipes, which enhances heat transfer from the pipe surface to the fluid. The results indicated that the highest efficiency was for the volumetric flow rate 0.015 L/s, equaling 39.59% at 1:00 p.m., while for the volumetric flow rate 0.012 L/s it

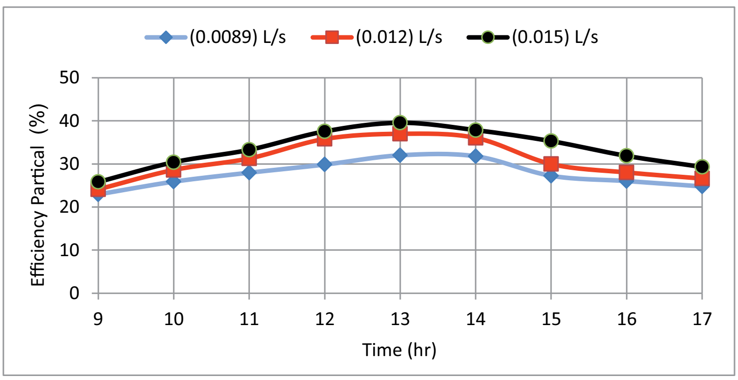

Fig. 15. The effects of daylight hours on the thermal efficiency at various volumetric flow rates of the improved collector a using the upper reflecting mirror at Ө = 20º and the lower mirror at Ө = 5º for February 2025, Kirkuk, Iraq

Rys. 15. Wpływ długości dnia na sprawność cieplną przy różnych natężeniach przepływu objętościowego ulepszonego kolektora a, wykorzystującego górne lustro odbijające pod kątem Ө=20º i dolne lustro pod kątem Ө=5º, w lutym 2025 r. w Kirkuku w Iraku equaled 37.03% at 1:00 p.m., and for the volumetric flow rate of 0.0089 L/s it equaled 32.04%. This means that the percentage enhancement of efficiency for the volumetric flow rate 0.015 L/s over 0.012 L/s is 6.91%, and the percentage enhancement of efficiency for the volumetric flow rate 0.015 L/s over 0.0089 L/s is 23.56%.

As for March, Figure 16 shows that the maximum efficiency corresponds to the maximum volumetric flow rate of 0.015 L/s. This is because increasing the volumetric flow rate leads to the breakdown of adjacent layers in the pipes, which enhances heat transfer from the pipe surface to the fluid. The results indicated that the highest efficiency was for the volumetric flow rate of 0.015 L/s, equaling 59.4% at 1:00 p.m., while for the volumetric flow rate 0.012 L/s it equaled 48.66% at 1:00 p.m., and for the volumetric flow rate 0.0089 L/s it equal to 37.7%. This means that the percentage enhancement of efficiency for the volumetric flow rate 0.015 L/s over 0.012 L/s is 22.07%, and the percentage enhancement of efficiency for the volumetric flow rate 0.015 L/s over 0.0089 L/s is 57.56%.

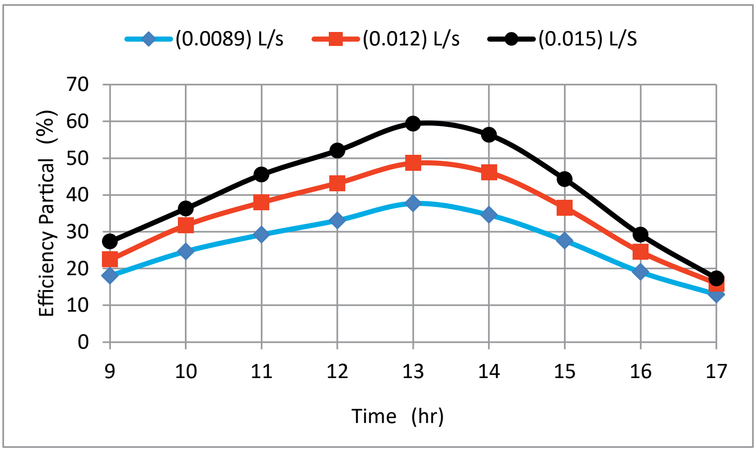

Fig. 16. The effects of daylight hours on the thermal efficiency at various volumetric flow rates of the improved collector using the upper reflecting mirror at ϴ = 18° and the lower mirror at ϴ = 5° March 2025, Kirkuk, Iraq

Rys. 16. Wpływ długości dnia na sprawność cieplną przy różnych natężeniach przepływu objętościowego ulepszonego kolektora wykorzystującego górne lustro odbijające pod kątem ϴ = 18° i dolne lustro pod kątem ϴ = 5°. Marzec 2025 r., Kirkuk, Irak

Figures 17–19 show the association between the thermal efficiency and the temporal mean for the four-month period (December 2024, January, February, and March of 2025) for a conventional flat-plate collector (without a reflective mirror) and an enhanced collector (with a reflective mirror). The optimal angle for the upper mirror was established for each of the four months specified (25°, 22°, 20°, 18°), while the lower mirror was maintained at a fixed angle of 5°) with a volumetric flow rate of 0.015 L/s of distilled water used inside the collector. The findings indicated that thermal efficiency rises from 9:00 a.m. to 1:00 p.m. as a result of heightened solar radiation intensity. Incident on the collector and decreases from 1:00 p.m. to 5:00 p.m. due to the decreased solar radiation incident on the collector for both collectors (conventional and enhanced with a reflective mirror). It is noted in the above figures that the maximum thermal efficiency was achieved in the enhanced collector using a reflective mirror. This result indicates that the greater the concentration of solar radiation incident on the collector, the greater the improvement in the thermal exchange between the collector tube walls and the distilled water used within the collector.

In Figure 17 for December, the efficiency of the thermal energy of the improved solar collector utilizing a reflective mirror was 31.66% at 1:00 p.m., while the efficiency of the thermal energy of the conventional solar collector without utilizing a reflective mirror was 28.99%, meaning the percentage increase in thermal efficiency was 9.21% when comparing the improved and conventional solar collectors.

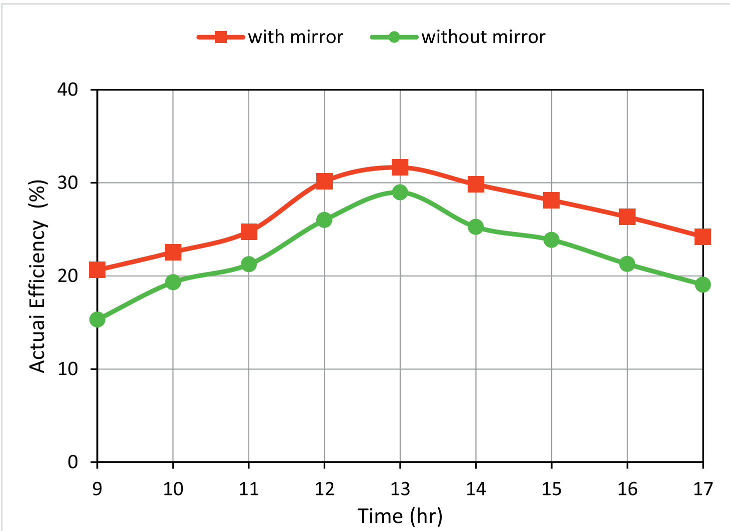

Fig. 17. The effects of daylight hours on the thermal efficiency at various volumetric flow rate of 0.015 L/s for both the improved solar collector, which uses upper reflecting mirror at Θ = 25° and the lower mirror at Θ = 5°, and the conventional solar collector, specifically for December 2024 in Kirkuk, Iraq

Rys. 17. Wpływ długości dnia na sprawność cieplną przy różnych natężeniach przepływu objętościowego wynoszących 0,015 l/s zarówno w przypadku ulepszonego kolektora słonecznego, wykorzystującego górne lustro odbijające pod kątem Θ = 25° i dolne lustro pod kątem Θ = 5°, jak i w przypadku konwencjonalnego kolektora słonecznego, w szczególności w grudniu 2024 r. w Kirkuku w Iraku

In Figure 18 for January, the efficiency of the thermal energy of the improved solar collector utilizing a reflective mirror was 37.86% at 1:00 p.m., while the efficiency of the thermal energy of the conventional solar collector without utilizing a reflective mirror was 28.67%, meaning the percentage increase in thermal efficiency was 32.05% when comparing the improved and conventional solar collectors.

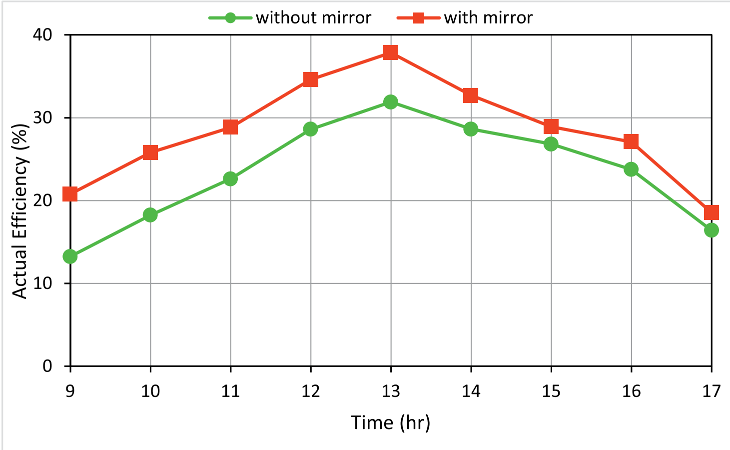

Fig. 18. The effects of daylight hours on the thermal efficiency at various volumetric flow rate of 0.015 L/s for both the improved solar collector, which uses an upper reflecting mirror at Θ = 22° and a lower mirror at Θ = 5°, and the conventional solar collector, specifically for January 2025 in Kirkuk, Iraq

Rys. 18. Wpływ długości dnia na sprawność cieplną przy różnych natężeniach przepływu objętościowego wynoszących 0,015 l/s zarówno w przypadku ulepszonego kolektora słonecznego, wykorzystującego górne lustro odbijające pod kątem Θ = 22° i dolne lustro pod kątem Θ = 5°, jak i w przypadku konwencjonalnego kolektora słonecznego, w szczególności w styczniu 2025 r. w Kirkuku w Iraku

In Figure 19 for the month of February, the efficiency of the thermal energy of the improved solar collector utilizing a reflective mirror was equal to 39.59% at 1:00 p.m., while the efficiency of the thermal energy of the traditional solar collector without utilizing a reflective mirror was equal to 36.65%, meaning the percentage increase in thermal efficiency was 8.02% when comparing the improved and traditional solar collectors.

In Figure 20 for the month of March, the efficiency of the thermal energy of the improved solar collector utilizing a reflective mirror was equal to 59.4% at 1:00 p.m., while the efficiency of the thermal energy of the traditional solar collector without utilizing a reflective mirror was equal to 35.64%, meaning the percentage increase in the amount of heat acquired was 66.66% when comparing the improved solar collector and the traditional one.

Figure 21 illustrates a comparison of the practical thermal efficiencies between the present study and those conducted by prior studies. The figure indicates that the highest efficiency was attained through the enhancement involving a reflective mirror (the current study) in comparison to the enhancement utilizing a source Hussein et al. (2024a) nanofluid. Factors potentially influencing the efficacy of the enhancement with the nanofluid include the detachment of nanoparticles from the fluid and the impact of the nanofluid on altering meteorological circumstances. This technique contrasts with the reflective mirror employed to enhance the efficiency of the solar collector in the present investigation. This mirror substantially enhances the efficiency of the flat-plate solar collector by amplifying the concentration of solar radiation and thereby augmenting its thermal storage capacity. This

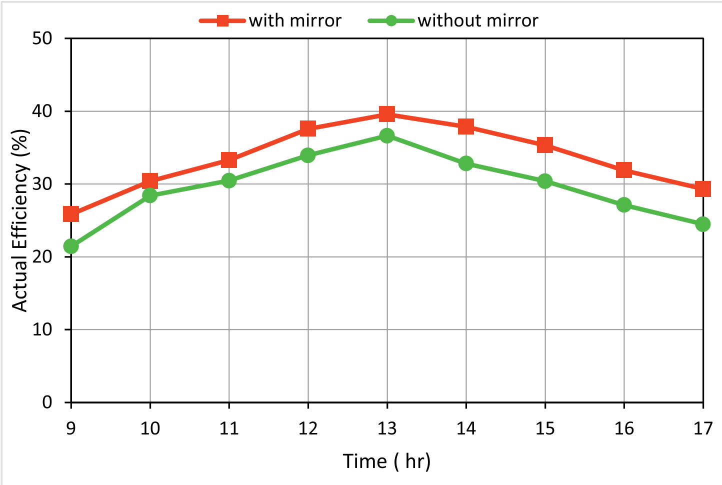

Fig. 19. The effects of daylight hours on the thermal efficiency at various volumetric flow rate of 0.015 L/s for both the improved solar collector, which uses an upper reflecting mirror at Θ = 20º and a lower mirror at Θ = 5º, and the conventional solar collector, specifically for February 2025 in Kirkuk, Iraq

Rys. 19. Wpływ długości dnia na sprawność cieplną przy różnych natężeniach przepływu objętościowego wynoszących 0,015 l/s zarówno w przypadku ulepszonego kolektora słonecznego, wykorzystującego górne lustro odbijające pod kątem Θ = 20º i dolne lustro pod kątem Θ = 5º, jak i w przypadku konwencjonalnego kolektora słonecznego, w szczególności w lutym 2025 r. w Kirkuku w Iraku

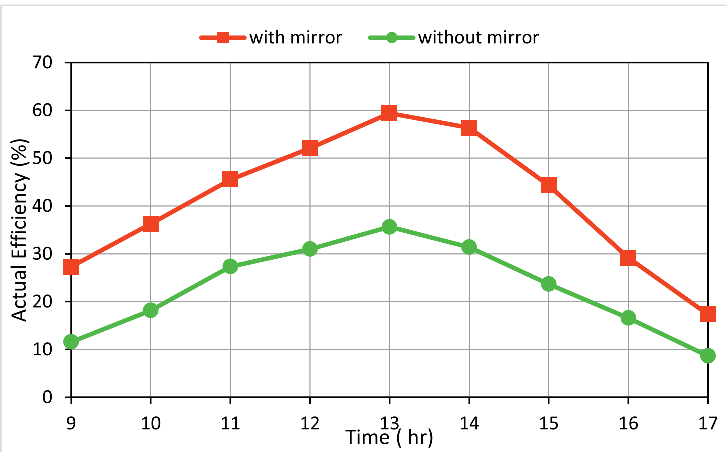

Fig. 20. The effects of daylight hours on the thermal efficiency at various volumetric flow rate of 0.015 L/s for both the improved solar collector, which uses an upper reflecting mirror at Θ = 18º and a lower mirror at Θ = 5º, and the conventional solar collector, specifically for March 2025 in Kirkuk, Iraq

Rys. 20. Wpływ długości dnia na sprawność cieplną przy różnych natężeniach przepływu objętościowego wynoszących 0,015 l/s zarówno w przypadku ulepszonego kolektora słonecznego, wykorzystującego górne lustro odbijające pod kątem Θ = 18º i dolne lustro pod kątem Θ = 5º, jak i w przypadku konwencjonalnego kolektora słonecznego, w szczególności w marcu 2025 r. w Kirkuku w Iraku results in prolonged maintenance of optimal efficiency and expedited heat transfer between the collector tubes and distilled water.

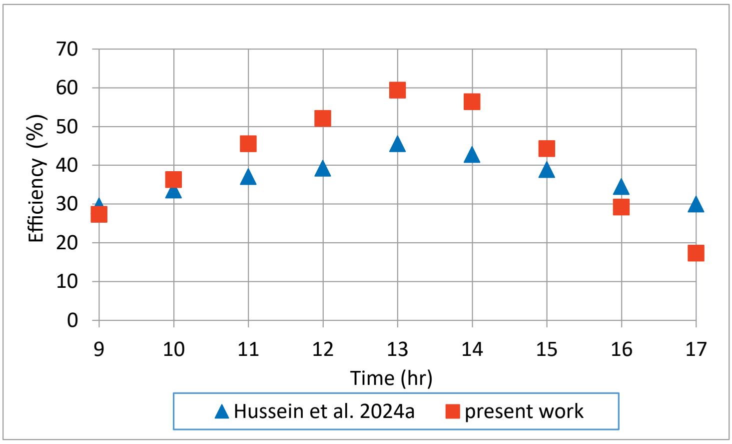

Fig. 21. A comparison between the practical thermal efficiencies of the current study and those of previous researchers

Rys. 21. Porównanie rzeczywistych sprawności cieplnych uzyskanych w niniejszym badaniu z wynikami uzyskanymi przez poprzednich badaczy

Figure 22 compares the thermal efficiency and economic performance of flat-plate solar collectors with and without reflective mirrors from December 2024 to March 2025 in Kirkuk, Iraq. The mirror-equipped collector consistently achieved higher efficiency, improving from

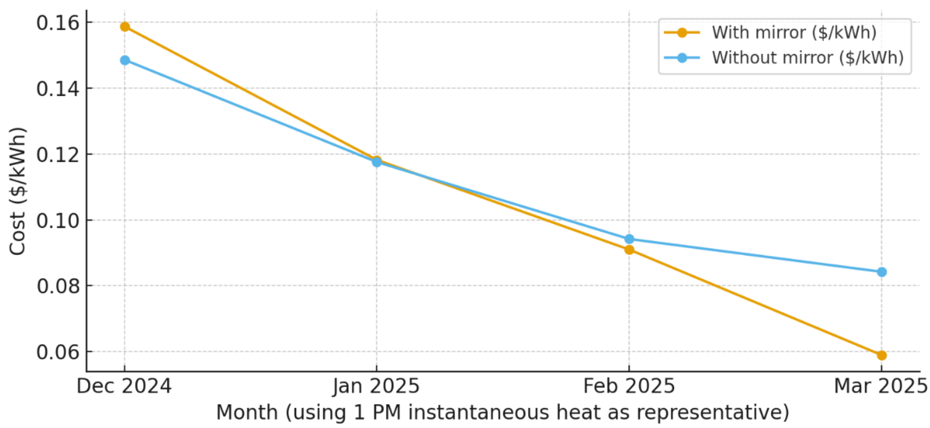

Fig. 22. Estimated upfront-Copex-Levelized cost per kwh for flat-plate solar collectors with and without reflective mirrors (Dec 2024–Mar 2025)

Rys. 22. Szacunkowe koszty początkowe, koszty operacyjne (Copex) oraz uśredniony koszt za kWh dla płaskich kolektorów słonecznych z lustrami odbijającymi i bez nich (grudzień 2024–marzec 2025)

9.21% in December to 66.66% in March, leading to greater energy yield and reduced cost per unit of heat produced. Overall, the figure demonstrates that incorporating reflective mirrors enhances both thermal performance and economic feasibility by increasing energy output and improving cost-effectiveness.

Conclusions

Based on the practical experiments conducted on both the conventional flat-plate solar collector and the enhanced collector equipped with reflective mirrors during December 2024 and January to March 2025, it was concluded that the efficiency of the solar collector increased steadily from 9:00 a.m. to 1:00 p.m., corresponding to the rise in solar radiation intensity. Although solar radiation intensity began to decline after 12:00 p.m., the collector's performance continued to rise until 2:00 p.m. due to the high thermal storage capacity of the collector and the surrounding atmosphere. Beyond 2:00 p.m., efficiency gradually decreased as the stored thermal energy diminished. The experimental findings confirmed that the solar collector enhanced with a reflective mirror consistently achieved higher thermal performance than the conventional system. This improvement was attributed to the increased concentration of solar radiation on the absorber surface, which strengthened the thermal exchange between the collector tube walls and the working fluid.

The results demonstrated monthly variations in performance:

- In December, the enhanced collector achieved 31.66% efficiency versus 28.99% for the conventional collector, representing a 9.21% increase.
- In January, efficiency improved by 32.05%, reaching 37.86% compared to 28.67% for the conventional system.
- In February, the enhancement yielded an 8.02% increase (39.59% vs. 36.65%).
- In March, the highest performance was recorded, with the enhanced collector achieving 59.4% efficiency, compared to 35.64% for the conventional collector, a 66.66% improvement.

The maximum thermal performance was observed in March, corresponding to the highest volumetric flow rate of 0.015 L/s and peak solar radiation intensity. These findings clearly demonstrate that integrating reflective mirrors with flat-plate solar collectors significantly enhances thermal efficiency, particularly under high-radiation conditions.

References

Ahmed, O.K. and Bawa, S.M. 2018. Reflective mirrors effect on the performance of the hybrid PV/thermal water collector. *Energy for Sustainable Development* 43, pp. 235–246, https://doi.org/10.1016/j.esd.2018.02.001.

Ali et al. 2025 – Ali, A.A., Abdullah, Z.I., Ali, H.H.M. and Mohammed, A. 2025. Efficiency enhancement of parabolic trough solar collector using ZnO/water nanofluid. *Journal of Advanced Research in Micro and Nano Engineering* 1(1), pp. 88–99, https://doi.org/10.37934/armne.27.1.8899.

Benkaddour et al. 2022 – Benkaddour, A., Boulaich, H. and Aroudam, E. 2022. Solar photovoltaic/ thermal air collector with mirrors for optimal tilts. *International Journal of Electrical and Computer Engineering* 12(3), pp. 2273–2284, https://doi.org/10.11591/ijece.v12i3.pp2273-2284.

Bhowmik, H. and Amin, R. 2017. Efficiency improvement of flat plate solar collector using reflector. *Energy Reports* 3, pp. 119–123, https://doi.org/10.1016/j.egyr.2017.08.002.

Fattahi, A. 2021. The effect of cross-section geometry on the performance of a solar nanofluid heater in a parabolic solar receiver: A comparison study. *Journal of the Taiwan Institute of Chemical Engineers* 124, pp. 17–28, https://doi.org/10.1016/j.jtice.2021.05.014.

Ghodbane et al. 2018 – Ghodbane, M., Boumeddane, B. and Said, N. 2018. Design and experimental study of a solar system for heating water utilizing a linear Fresnel reflector. *Journal of Fundamental and Applied Sciences* 8(3), pp. 804–825, https://doi.org/10.4314/jfas.v8i3.8.

Hussein et al. 2024a – Hussein, A.M., Ali, H.H.M. and Ali, Z. 2024. Assessing the efficacy of flat-plate solar collectors using nanofluids in the climatic context of Kirkuk city, Iraq. *Acta Polytechnica* 64(1), pp. 25–33, https://doi.org/10.14311/AP.2024.64.0025.

Hussein et al. 2024b – Hussein, A.M., Awad, A.T. and Ali, H.H.M. 2024. Evaluation of the thermal efficiency of nanofluid flows in flat plate solar collector. *Journal of Thermal Engineering* 10(2), pp. 299–307, https://doi.org/10.18186/thermal.1448578.

Kedar et al. 2021 – Kedar, S.A., Bewoor, A.K., Murali, G., Kumar, R., Sadeghzadeh, M. and Issakhov, A. 2021. Effect of reflecting material on CPC to improve the performance of hybrid groundwater solar desalination system. *International Journal of Photoenergy* 2021(1), https://doi.org/10.1155/2021/6675236.

Kostić, L.T. and Pavlović, Z.T. 2012. Optimal position of flat plate reflectors of solar thermal collector. *Energy and Buildings* 45, pp. 161–168, https://doi.org/10.1016/j.enbuild.2011.10.059.

Kostić et al. 2010 – Kostić, L.T., Pavlović, T.M. and Pavlović, Z.T. 2010. Optimal design of orientation of PV/T collector with reflectors. *Applied Energy* 87(10), pp. 3023–3029, https://doi.org/10.1016/j.apenergy.2010.02.015.

Malik, P. and Chandel, S.S. 2020. Performance enhancement of multi-crystalline silicon photovoltaic modules using mirror reflectors under Western Himalayan climatic conditions. *Renewable Energy* 154, pp. 966–975, https://doi.org/10.1016/j.renene.2020.03.048.

Miri et al. 2023 – Miri, R., Mliki, B., Mohamad, B.A., Abbassi, M.A., Oreijah, M., Guedri, K. and Abderafi, S. 2023. Entropy generation and heat transfer rate for MHD forced convection of nanoliquid in presence of viscous dissipation term. *CFD Letters* 15(12), pp. 77–106, https://doi.org/10.37934/cfdl.15.12.77106.

Mulugata, N. and Tesfay, T. 2017. Improving efficiency of flat plate collector integrated with reflectors. *International Journal of Engineering and Technical Research* 7(2), pp. 2454–4698.

Nagaraju et al. 2022 – Nagaraju, V., Murali, G., Bewoor, A. K., Kumar, R., Sharifpur, M., El Haj Assad, M., and Awad, M.M. 2022. Experimental study on performance of single slope solar still integrated with sand troughs. *Sustainable Energy Technologies and Assessments* 50, https://doi.org/10.1016/j.seta.2021.101884.

Naik, P.S. and Palatel, A. 2014. Energy and exergy analysis of a plane reflector integrated photovoltaic-thermal water heating system. *ISRN Renewable Energy,* https://doi.org/10.1155/2014/180618.

Nassar et al. 2023 – Nassar, Y.F., Amer, K.A., El-Khozondar, H.J., Ahmed, A.A., Alsharif, A.H., Khaleel, M.M., Elnaggar, M.M., El-Khozondar, R.J. and Salem, A. 2023. Thermoelectrical analysis of a new hybrid PV-thermal flat plate solar collector. [In:] *2023 8th International Engineering Conference on Renewable Energy & Sustainability* (*ieCRES*), pp. 1–5.

Qader et al. 2023 – Qader, F., Hussein, A., Danook, S., Mohamad, B. and Khaleel, O. 2023. Enhancement of double-pipe heat exchanger effectiveness by using porous media and TiO_2-water. *CFD Letters* 15(4), pp. 31–42, https://doi.org/10.37934/cfdl.15.4.3142.

Qader et al. 2023 – Qader, F.F., Mohammed, F.Z. and Mohamad, B. 2023. Thermodynamic analysis and optimization of flat plate solar collector using TiO_2/water nanofluid. *Journal of Harbin Institute of Technology* (New Series) 31(4), pp. 61–73, https://doi.org/10.11916/j.issn.1005-9113.

Qader et al. 2024 – Qader, F.F., Mohamad, B., Hussein, A.M. and Danook, S.H. 2024. Numerical study of heat transfer in circular pipe filled with porous medium. *Pollack Periodica* 19(1), pp. 137–142, https://doi.org/10.1556/606.2023.00869.

Qiu et al. 2021 – Qiu, Y., Xu, Y., Li, Q., Wang, J., Wang, Q. and Liu, B. 2021. Efficiency enhancement of a solar trough collector by combining solar and hot mirrors. *Applied Energy* 299, https://doi.org/10.1016/j.apenergy.2021.117290.

Sharshir et al. 2017 – Sharshir, S.W., Peng, G., Wu, L., Essa, F.A., Kabeel, A.E. and Yang, N. 2017. The effects of flake graphite nanoparticles, phase change material, and film cooling on the solar still performance. *Applied Energy* 191, pp. 358–366, https://doi.org/10.1016/j.apenergy.2017.01.067.

Singh et al. 2023 – Singh, D., Buddhi, D. and Karthick, A. 2023. Productivity enhancement of solar still through heat transfer enhancement techniques in latent heat storage system: a review. *Environmental Science and Pollution Research* 30(1), pp. 44–77, https://doi.org/10.1007/s11356-022-23964-z.

Sonker et al. 2021 – Sonker, V.K., Singh, R.K., Chakraborty, J.P. and Sarkar, A. 2021. Performance assessment of a passive solar still integrated with thermal energy storage and nanoparticle stored in copper cylinders. *International Journal of Energy Research* 45, pp. 2856–2869, https://doi.org/10.1002/er.5982.

Tabasi et al. 2019 – Tabasi, S., Yousefi, H., Noorollahi, Y. and Aramesh, M. 2019. A detailed investigation and performance optimization of a photovoltaic panel integrated with a reflecting mirror. *Applied Thermal Engineering* 160, https://doi.org/10.1016/j.applthermaleng.2019.114074.

Tarik Ahmed, S. and Hayder Mohammed Ali, H. 2020. Experimental investigation of new design of solar water distillation coupled with flat plate solar water collector. *Iraqi Journal of Mechanical and Materials Engineering* 20(3), pp. 193–207, https://doi.org/10.32852/iqjfmme.v20i3.512.

Tarik Ahmed, S. and Hayder Mohammed Ali, H. 2020. Theoretical study of the conventional and modified solar still. *Iraqi Journal of Mechanical and Materials Engineering* 20(2), pp. 122–142, https://doi.org/10.32852/iqjfmme.v20i2.493.

Wells, D.N. 2009. Improved boost mirror for low-concentration photovoltaic solar power systems. *High and Low Concentration Systems for Solar Electric Applications* IV, 74070M, https://doi.org/10.1117/12.828312.

Yousef, M.S. and Hassan, H. 2019. Energetic and exergetic performance assessment of the inclusion of phase change materials (PCM) in a solar distillation system. *Energy Conversion and Management* 179, pp. 349–361, https://doi.org/10.1016/j.enconman.2018.10.078.

Zarda et al. 2022 – Zarda, F., Hussein, A., Danook, S. and Mohamad, B. 2022. Enhancement of thermal efficiency of nanofluid flows in a flat solar collector using CFD. *Diagnostyka* 23(4), pp. 1–9, https://doi.org/10.29354/diag/156384.

Bariq Abdullah Mohammed, Hussein Hayder Mohammed Ali, Afrah Awad

Analiza techniczno-ekonomiczna dotycząca poprawy wydajności płaskich kolektorów słonecznych z wykorzystaniem luster odbijających w warunkach atmosferycznych w mieście Kirkuk w Iraku

Streszczenie

Energia słoneczna, jako zrównoważone i przyjazne dla środowiska źródło energii, coraz bardziej przyciąga uwagę środowisk naukowych i inżynieryjnych ze względu na swoją zdolność do dostarczania czystej energii przy znikomych kosztach eksploatacyjnych, pomimo stosunkowo wysokich początkowych kosztów instalacji. Niniejsze badanie przeprowadzono w celu zwiększenia sprawności cieplnej płaskiego kolektora słonecznego poprzez zastosowanie lustra odbijającego w warunkach klimatycznych panujących w Kirkuku w Iraku. Wykonano dwa identyczne kolektory: jeden o konfiguracji konwencjonalnej, a drugi wyposażony w lustro odbijające, mające na celu wzmocnienie padającego promieniowania słonecznego, a co za tym idzie – zwiększenie absorpcji ciepła. Analizy eksperymentalne przeprowadzono w ciągu czterech kolejnych miesięcy: w grudniu 2024 r. oraz w styczniu, lutym i marcu 2025 r. o godz. 13:00. W grudniu kolektor z lustrem osiągnął sprawność cieplną na poziomie 31,66%, w porównaniu z 28,99% w przypadku urządzenia konwencjonalnego, co wskazuje na poprawę o 9,21%. W styczniu sprawność wzrosła z 28,67% do 37,86%, co odpowiada poprawie o 32,05%. W lutym odnotowano wartości 39,59 i 36,65%, co oznacza wzrost o 8,02%. W marcu odnotowano najbardziej znaczący wzrost, ponieważ zmodyfikowany kolektor osiągnął sprawność 59,40% w porównaniu z 35,64% w przypadku systemu konwencjonalnego, co stanowi wzrost o 66,66%. Wyniki potwierdzają, że zastosowanie powłoki odblaskowej znacząco poprawia wydajność termiczną kolektora, przy czym maksymalną wydajność odnotowano w marcu ze względu na najwyższe natężenie promieniowania słonecznego w tym okresie.

Słowa kluczowe: sprawność termiczna, destylator słoneczny, ocena kosztów, lustra odbijające, płyta absorpcyjna