American Journal of Technology Advancement 2997-9382, Vol 1, No. 8, 2024

Article

Enhanced Performance of Solar Box Collector with External Flat Reflector: A Comprehensive Evaluation

Nadhum H. Safir[1*], Hamza J. Hamad[2], Sabah M. Hadi[3], Nazih Ahmed Khmis Bin Abdun[4]

[1]*Forensic DNA Centre for Research and Training, Al-Nahrain University, Jadriya, Baghdad, Iraq*
[2,3]*Ministry of Higher Education and Scientific Research, IRAQ.*
[4]*Seiyun Community College Hadramout, Yemen*

Abstract: This research evaluates the performance of a solar box collector integrated with an external flat-top reflector. The externally mounted flat reflector, designed and manufactured locally, is positioned on the top side of the collector. Various calculations were performed, including efficiency calculations, recording solar radiation, and temperature measurements at selected points within the collector box. The variations in daily solar radiation absorbed by the collector, considering inclinations from the horizontal for both the collector and the reflector, were predicted. The thermal efficiency of the collector, oriented southward and tilted at 45 degrees, was found to be 53.36%, with an optical efficiency of 62.45%. The inclusion of the reflector maximizes the daily solar radiation absorbed by the collector. This novel technique enhances water heating and reduces heat loss by incorporating two solar thermal insulation chambers (STIC), which utilize the greenhouse effect as thermal insulation on both sides of the internal storage tank, replacing traditional methods. This innovative approach prevents heat dissipation from the internal storage tank at temperatures below 54 °C, resulting in a high collector performance coefficient of 0.13, a stagnation temperature of 74.75 °C, and a heat transfer coefficient of 3.84 W/m²·K. Consequently, the system can achieve temperatures up to 71 °C. The significance of this research lies in its potential to improve solar water heating efficiency and reduce energy losses, contributing to more sustainable and cost-effective energy solutions.

Keywords: **Solar Collectors; Solar Thermal Insulation; Solar Reflector Collector; Thermal Efficiency**

1. Introduction

Solar energy is among the many plentiful and essential sources of energy accessible to civilization [1-3]. Its renewable, clean, and eco-friendly nature makes it crucial for reducing reliance on fossil fuels. Solar energy is more widely accessible and evenly distributed than other renewable sources like wind, geothermal, hydropower, biomass, wave, and tidal energy [4, 5]. To fully utilize solar power, efficient collection methods are necessary. The flat plate absorber is an easy and economical apparatus that is commonly used to capture solar energy for low-temperature thermal applications, typically below 100 °C [6-8]. These collectors are key components in many solar systems, converting sunlight into heat [9,10], which can then be transferred to a fluid for various uses, such as space heating, water heating, power generation, crop drying, and cooking. Flat plate collectors are versatile and applicable to any process requiring thermal energy [11-13].

The use of solar energy dates back to the seventeenth century with the invention of a flat-plate solar detector. Since that time, technological advancements have improved the effective harnessing of solar radiation for various purposes, such as water heating, electricity generation, and cooling systems [14-17]. Flat plate collectors are generally designed to operate at temperatures of about 75 °C, enabling devices to provide power at a temperature as high as 100 °C above the surrounding temperature. The proposal has benefits including the ability to capture both simple and dispersed solar energy, the lack of requirements for solar direction, and minimum maintenance requirements [18, 19]. Studies from international efforts have shown the reliability and efficiency of flat plate collectors, with systems providing hot water with up to 80% solar reliability from February to October and between 61% and 65% in December [20]. Research from Europe and China reports efficiencies of 36% in winter and 55% during other seasons [21]. Solar water heating systems are widely used in residential homes, apartment complexes, schools, hospitals, and industries, reducing water heating costs by up to 70% and requiring easy installation and low maintenance [22, 23].

Innovative techniques, such as the use of mirrors and reflectors, have been explored to enhance the efficiency of solar collectors. Tabor's pioneering study demonstrated improved solar energy collection through the combination of mirrors and flat plate collectors [22]. Further research by Kostic and Pavlovic [20] showed a 40% energy gain in summer for thermal collectors equipped with selective absorbers and flat plate reflectors. In recent years, various insulation methods have been investigated to boost collector performance further [24-27]. This study contributes to the field by proposing a novel solar thermal insulation chamber (STIC), which utilizes the greenhouse effect to enhance water heating efficiency and reduce heat loss. This approach aims to improve collector performance and overall system efficiency, offering a more sustainable and cost-effective energy solution that supports global efforts to mitigate climate change and promote the use of renewable energy sources.

2. Materials and Methods

Solar box collector system

The solar box system featured a wooden enclosure measuring 115 x 60 x 65 cm, with an aperture area of 0.67 m² designed to capture solar radiation and heat water stored in a solar tank located inside the collector, as illustrated in Fig. 1. Detailed design specifications can be found in Table 1. The absorber plate, made from galvanized metal and coated with black paint, was optimized to maximize the absorption of solar radiation. To minimize heat loss from the absorber and the tank, two triangular glass partitions with a 50 cm base and 52 cm height were positioned on either side of the fixed tank within the collector. A clear glass cover allowed sunlight to penetrate while also reducing heat loss. Insulation, comprising wood and cork, surrounded the system on the sides, bottom, and rear to limit thermal losses. A flat surface reflector, spanning 120 cm in length and 60 cm in height, was mounted above to enhance the daily absorption of solar energy. The solar cylinder effectively collected sunlight and supplied warm water as required, with icy water flowing via an opening and heated water departing via an outlet. The tank's triangular exterior had dimensions of 40 cm at the base, 40 cm in height, and 50 cm in length, with a capacity of 40 liters and a thickness of 1.5 mm.

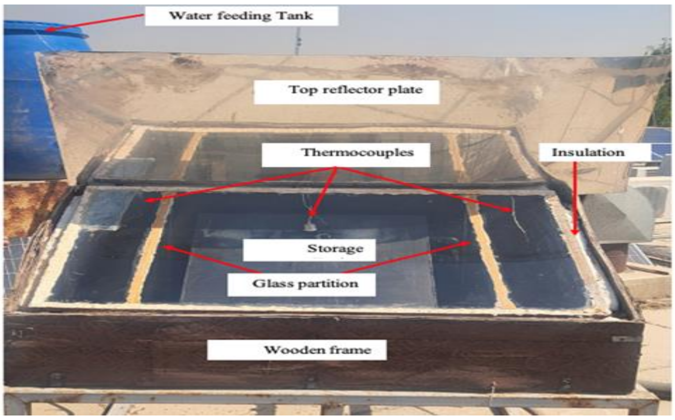

Fig. 1: Solar box collector system with reflector.

Table 1: Design specifications of the solar box collector.

No.	Items	Solar box collector
1	Dimensions of the box collector (cm)	**115 x 60 x 65**
2	Aperture area (m^2)	**0.67**
3	Capacity of tank (liters)	**40**
4	Dimensions of triangle storage tank (cm)	**40 x 40 x 50**
5	Dimension of the flat reflector plate (cm)	**120 x 60**
6	Insulator of collector	**Cork**
7	Thickness of insulator (cm)	**5**

Practical side

The solar collector system was mounted on the roof of the Renewable Research Centre under the Ministry of Science and Technology, positioned at a 45° angle relative to the horizon. The collector faced south to optimize solar radiation exposure. K-type thermocouples were installed at various key points within the system to monitor temperatures. One thermocouple was placed inside the tank of the solar collector, two were set at the collector's inlet for cold water, and an outlet for hot water, and three were distributed within the internal space of the collector, as illustrated in Fig 1. An additional thermocouple was installed near the solar collector to track ambient air temperature. All temperature data were recorded using a 12-channel data logger to capture readings throughout the day.

Theoretical Side

The next part discusses the equations governing theory and actual relationships employed to ascertain the impact of different factors on the efficiency of the Box Flat Plate Solar Collecting.

Energy balance of solar collector box

The efficacy of a flat plate solar collector in continuous operation was assessed by calculating an energy balance that delineated the distribution of receiving solar energy between useful energy gain, heat harm, and optical degradation [28]. On an hourly basis, the collector $\dot{Q}_{abs}$ absorbed solar radiation equal to the form of direct incident solar energy I_{dn} absorber aperture area, A_a and optical efficiency η_{opt}, as stated in Eq. (1). The thermal loss from the collector to the environment was evaluated using comprehensive heat transfer equations. Eq. (2) calculates the useful energy output of a flat plate collector $\dot{Q}_u$ as the difference between absorbed solar radiation and thermal loss $\dot{Q}_{loss}$ given in watts (W) when I_{dn} was expressed in W/m².

$$\dot{Q}_{abs} = A_a \, \eta_{opt} \, I_{dn} \quad (1)$$

$$\dot{Q}_u = \dot{Q}_{abs} - \dot{Q}_{loss} \quad (2)$$

Equation (3) was used to calculate the amount of solar energy that the glass cover, absorber plate, and internal storage tank (as depicted in Fig. 1) absorbed. Equation (4) was used to calculate the energy lost from the glass cover as a result of convection and radiation to the outside world.

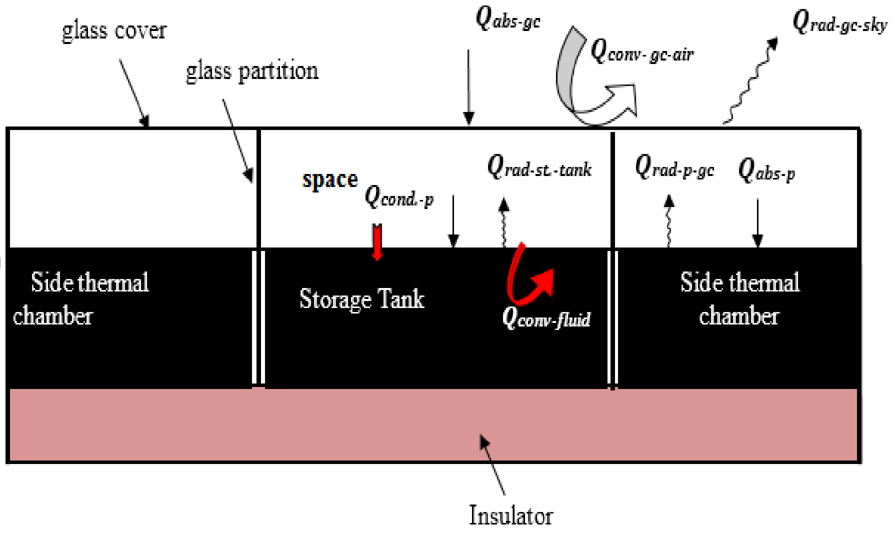

Fig. 2: Energy components in a box flat plate collector.

$$\dot{Q}_{abs.} = \dot{Q}_{abs.-g.c.} + \dot{Q}_{abs.-st.} + \dot{Q}_{abs.-p.} \quad (3)$$

Where $\dot{Q}_{abs}$ is the solar radiation that has been absorbed (W), $\dot{Q}_{abs\text{-}gc}$ is the solar radiation absorbed by the glass cover (W), $\dot{Q}_{abs\text{-}st}$ is the solar radiation that has been absorbed by the inner storage tank (W), and $\dot{Q}_{abs\text{-}p}$ is the solar radiation absorbed by plate (W), as shown in Equation 4.

$$\dot{Q}_{loss} = \dot{Q}_{rad\_gc\_sky} + \dot{Q}_{conv.\_gc\_air} \quad (4)$$

Where $\dot{Q}$ rad-gc-sky is the radiation heat transfer from the outer glass cover (W), and Qconv-gc-air is the convection heat transfer from the outer glass cover (W), as shown in Equation 5 [21].

Outlines how the heat lost from the glass cover's outer surface to the surrounding environment through convection and radiation balanced the heat absorbed by the glass cover from solar radiation, the inner storage tank, and the absorber plate via conduction. This means that:

$$\dot{Q}_{abs\_gc} + \dot{Q}_{cond\_gc} = \dot{Q}_{conv\_gc\_air} + \dot{Q}_{rad\_gc\_sky} \quad (5)$$

Where $\dot{Q}_{cond\text{-}gc}$ denoted the heat transmission (W) by conduction through the glass cover, in the case of the absorber plate and the inner storage tank, Equation (6) states that the heat lost by conduction through the glass cover is equal to the heat received through radiation from the glass cover.

$$\dot{Q}_{rad-p} + \dot{Q}_{rad-\,st} = \dot{Q}_{cond\_gc} \qquad (6)$$

Where Q̇ rad-p + Q̇rad-st is the radiation heat transfer through the collector space between the absorber flat plate and glass cover (W) [29-32]. The heat conducted to the absorber storage tank is equal to the heat transferred from the absorber storage tank to the fluid through convection, as shown in Equation (7)

$$\dot{Q}_{cond-st} = \dot{Q}_{conv\_fluid} \quad (7)$$

Where $\dot{Q}_{conv\text{-}fluid}$ is the convection heat transfer to the fluid (W).

Collector Efficiency

In steady-state circumstances, the performance of a collector for solar power is characterized by an equilibrium of energy that delineates the allocation of entering solar energy into usable energy, heat damage, and loss of optical energy. The solar radiation collected by the collection device per area of the absorber is determined by subtracting the amount of optical loss of the incoming solar energy, as shown in Equation (8).

$$S = I_b R_b (\tau\alpha)_b + I_d (\tau\alpha)_d \left(\frac{1+cos\beta}{2}\right) + \rho_g I (\tau\alpha)_g \left(\frac{1-cos\beta}{2}\right) \qquad (8)$$

The thermal energy lost from the collector to the environment through conduction, convection, and infrared radiation was calculated using the heat transfer coefficient and the difference between the mean absorber plate temperature and the ambient temperature. As stated in Equation (9), the usable energy output of a collector in a steady state, given its area, is the difference between the absorbed solar radiation and the thermal losses.

$$Q_u = A_c\left[S - U_L\left(T_{pm} - T_a\right)\right] \qquad (9)$$

The complexity of the formula stems from the difficulties in determining the mean plate absorber temperature because it is affected by variables like collect design, incoming solar energy, and fluid inlet conditions. Equation (9) functions as a power rate equation, so when articulated in SI units, it yields the usable energy gain in watts (J/s) when S is measured in W/m² and the heat transfer coefficient UL is in W/m²·K. Hours serve as an increasingly pragmatic measure for quantifying solar radiation than seconds, aligning with conventional meteorological reporting standards. Although several symbols may be used to distinguish between rates and hourly integrated numbers (such as Q̇u and Qu), the context offers enough clarity, rendering distinct symbols for instantaneous and hourly energy gains superfluous. The collection effectiveness, a metric of collector efficiency, is described as the percentage of useable gain to incoming solar energy during a particular period, as articulated in Eq. (10) [33].

$$\text{E}\eta = \frac{\int \dot{Q}_u \, dt}{A_c \int GT dt} \qquad (10)$$

If circumstances remain equal throughout a duration, the efficiency simplifies to Equation (11):

$$\eta = \frac{Q_u}{T_t A_c} \qquad (11)$$

3. Results and Discussion

The experiments took place over multiple days in November and December, with solar radiation measurements taken during clear weather conditions. These measurements were represented graphically (Fig. 3). Solar radiation peaked around midday and then gradually declined as the sun's angle of incidence decreased.

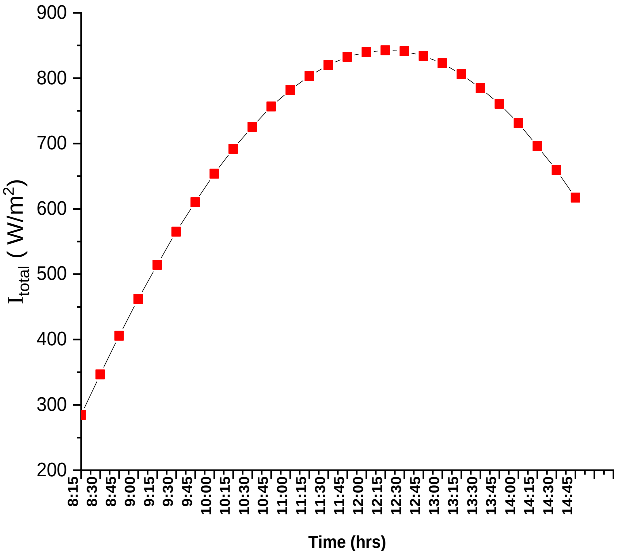

Fig. 4 illustrates the change in storage tank temperature with and without the use of a reflector.

The maximum temperatures recorded for the solar collector with a reflector and without it were 71.2 °C and 62.3 °C, respectively. The solar collector equipped with a reflector consistently reached higher temperatures, providing an improvement of 8.9 °C. It was also observed that below 54 °C (as shown in Fig. 5), the temperature difference was minimal, likely due to the influence of the Solar Thermal Insulation Chamber (STIC). By positioning a reflector on the top side of the solar collector at an optimal angle of 30°, both diffuse and direct radiation were captured. The storage tank temperature directly correlated with solar radiation levels: as solar radiation increased, the storage tank temperature rose, and as radiation decreased, so did the temperature. The heat transfer behaviour of the collector is defined by the equation in Eq. (12).

$$Q = -23385.59851 + 1849.54412\,T - 52.96613T^2 + 0.6613T^3 - 0.00308T^4 \quad (12)$$

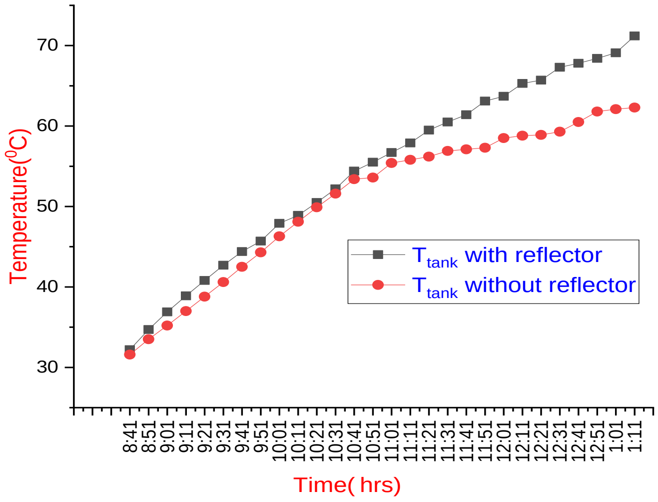

Fig. 4: The variation storage tank temperature with and without reflector.

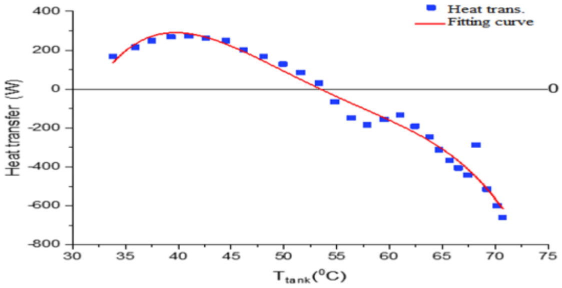

Fig. 5: Effect of Solar Thermal Insulation Chamber (STIC) on heat transfer and storage tank temperature.

Temperature measurements were recorded on November 28th under clear sky conditions. As depicted in Fig. 6, the temperature was initially low in the early morning, attributed to the low solar radiation caused by the sun's low incidence angle. The temperature steadily rose until it peaked at midday, after which it gradually decreased during the later hours of the day. This trend is a result of the variations in solar radiation and the sun's angle of incidence over the day.

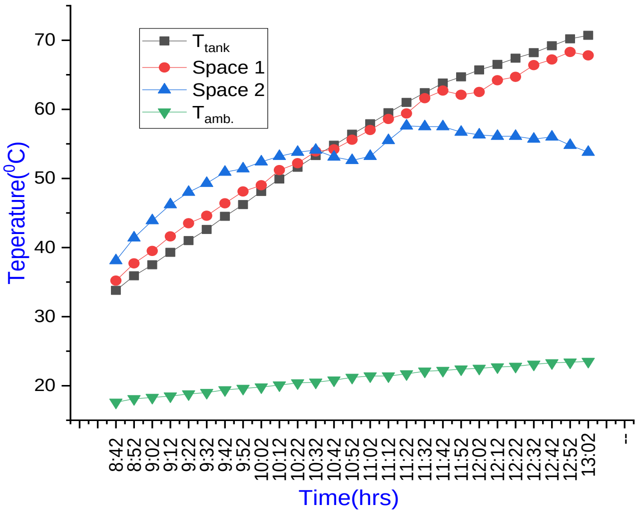

Fig. 6: Temperatures with time for day 28 of November 2023.

The impact of the fluid's operating temperature $(T_m-T_a)/It$ on the collector's efficiency is illustrated in Fig. 7. The efficiency showed only a slight decrease over the observed temperature range. The data indicates that the efficiency values were plotted against the operating temperature parameter (T_m-T_a/I_t), with a value of 0.13 being achieved. This outcome is attributed to an innovative method that enhanced water heating and minimized heat loss by incorporating two glass partitions as thermal chambers (greenhouse effect) on the sides of the internal storage tank for insulation. This design effectively prevented heat from escaping the storage tank, allowing the system to reach a stagnation temperature of 74.75 °C. This parameter is critical for evaluating the performance of all collector types, especially flat plate collectors. The plot showed a straight line with a slight negative slope, reflecting minor variations in efficiency with changes in the operating temperature. As the mean fluid temperature in the collector rose, heat losses increased, causing a reduction in efficiency. In this study, a high collector performance coefficient of 0.13 was obtained by integrating a reflector with a flat plate collector using the STIC technique, outperforming other flat plate reflector collectors, as shown in Table 2.

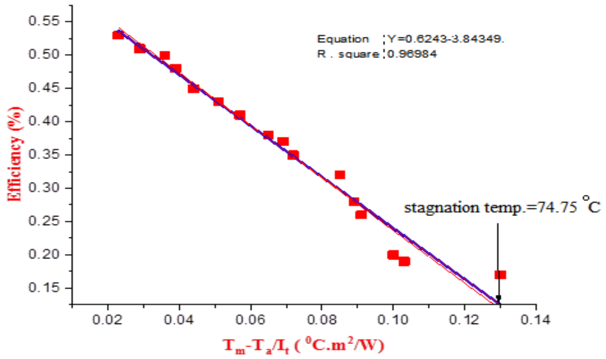

Fig. 7: The efficiency of the collector system as a function of the mean temperature to the total solar radiation.

Table 2: Survey of various collector performance coefficients.

S/No.	Recent researches titles	Collector performance coefficient (Tm-Ta)/It	References
1	Analysis of a Flat-plate Solar Collector.	0.09	[34]
2	Theoretical and Experimental Investigations of Heat Transfer in a Flat-Plate Solar Collector.	0.05	[35]
3	Experimental and numerical study of heat transfer properties in solar flat plate collector using nanofluids.	0.108	[36]
4	Experimental and Theoretical Investigation of Energy Efficiency in a Flat Plate Solar Collector Using Monolayer Graphene Nanofluids.	0.06	[37]
5	Impact of operating conditions on the efficiency of solar energy utilization in flat plate solar collectors.	0.05	[38]
6	STIC technique	0.13	This work

4. Conclusion

The experimental results and calculations revealed that the addition of a reflector substantially enhanced the efficiency of the solar water heating system. The radiation from the absorbing plate and storage tank was effectively trapped within the thermal chamber and transparent glass cover, optimizing the collector's performance. The highest temperatures recorded for the storage tank were 71.2 °C with the reflector and 62.3 °C without it. The solar box collector equipped with the Solar Thermal Insulation Chamber (STIC) showed impressive efficiency, remaining high despite the relatively small absorber area, thanks to the insulation provided by durable materials like soda lime glass. Furthermore, the manufacturing cost of this collector was significantly lower compared to other systems, making it an attractive option for adoption. This solar thermal insulation technique holds promise for solar thermal systems operating at high temperatures, offering clear advantages over conventional flat plate collectors.

REFERENCES

[1] A.O Maka and J.M Alabid, “Solar energy technology and its roles in sustainable development.” Clean Energy, vol. 6, no. 3, pp. 476-483, 2022.

[2] C.M.S Kumar, S Singh, M.K Gupta, Y.M Nimdeo, R Raushan, A.V Deorankar, and A.D Nannaware, “Solar energy: A promising renewable source for meeting energy demand in Indian agriculture applications.” Sustain. Energy Technol. Assess., vol. 55, pp. 102905, 2023.

[3] F.J Nijsse, J.F Mercure, N Ameli, F Larosa, S Kothari, J Rickman, and H Pollitt, “The momentum of the solar energy transition.” Nat. Commun., vol. 14, no. 1, pp. 6542, 2023.

[4] Zekai Sen. Solar Energy Fundamentals and Modeling Techniques. Springer-Verlag, London Limited, 2008.

[5] S.P Sukhatme, Solar Energy Principles of Thermal Collection and Storage. Tata McGraw Hill, New Delhi, 1980.

[6] M.K El-Fakharany, A.E.A Abo-Samra, A.M Abdelmaqsoud, and S.A Marzouk, “Enhanced performance assessment of an integrated evacuated tube and flat plate collector solar air heater with thermal storage material.” Appl. Therm. Eng., vol. 243, pp. 122653, 2024.

[7] F.N Elwekeel, and A.M Abdala, “Numerical and experimental investigation of the performance of a new circular flat plate collector.” Renew. Energy, vol. 209, pp. 581-590, 2023.

[8] T.R Desisa, “Experimental and numerical investigation of heat transfer characteristics in solar flat plate collector using nanofluids.” Int. J. Thermofluids, vol. 18, pp. 100325, 2023.

[9] L.A Omeiza, M Abid, A Dhanasekaran, Y Subramanian, V Raj, K Kozak, A.K Azad, “Application of solar thermal collectors for energy consumption in public buildings-an updated technical review.” J. Eng. Res., 2023.

[10] C Liu, L Geng, T Xiao, Q Liu, S Zhang, H.M Ali, and J Zhao, “Recent advances of plasmonic nanofluids in solar harvesting and energy storage.” J. Energy Storage, vol. 72, pp. 108329, 2023.

[11] K Masera, H Tannous, V Stojceska, and S Tassou, “An investigation of the recent advances of the integration of solar thermal energy systems to the dairy processes.” Renew. Sustain. Energy Rev., vol. 172, pp. 113028, 2023.

[12] A Kumar, V.P Singh, C.S Meena, and N Dutt, (Eds.). Thermal energy systems: Design, computational techniques, and applications. CRC Press, 2023.

[13] W Platzer, and R Stieglitz, Solar Thermal Energy Systems: Fundamentals, Technology, Applications. Springer Nature, 2024.

[14] K.M Κουτσογιάννης, "Solar thermal systems for domestic water heating in Cyprus and review of the latest advances." (Bachelor's thesis), 2023.

[15] E.B Agyekum, T Khan, and N.C Giri, "Evaluating the Technical, Economic, and Environmental Performance of Solar Water Heating System for Residential Applications–Comparison of Two Different Working Fluids (Water and Glycol)." Sustainability, vol. 15, no. 19, pp. 14555, 2023.

[16] F Odoi-Yorke, R Akpahou, R Opoku, and L.D Mensah, "Technical, financial, and emissions analyses of solar water heating systems for supplying sustainable energy for hotels in Ghana." Solar Compass, vol. 7, pp. 100051, 2023.

[17] J Perlin, Let it shine: the 6,000-year story of solar energy. New World Library, 2022.

[18] J.A Duffie, W.A Beckman, and N Blair, Solar engineering of thermal processes, photovoltaics and wind. John Wiley & Sons, 2020.

[19] A Zarem, D Erway, Introduction to the utilization of solar energy, 1963.

[20] L.T Kostić, and Z.T Pavlović, "Optimal position of flat plate reflectors of solar thermal collector." Energy Build., vol. 45, pp. 161-168, 2012.

[21] I Din, and M.A Rosen, Thermal energy storage: systems and applications. John Wiley & Sons, 2011.

[22] H Tabor, "Mirror boosters for solar collectors." Solar Energy, vol. 10, no. 3, pp. 111-118, 1996.

[23] S.K Pathak, V.V Tyagi, K Chopra, R Rejikumar, and A.K Pandey, "Integration of emerging PCMs and nano-enhanced PCMs with different solar water heating systems for sustainable energy future: A systematic review." Sol. Energy Mater. Sol. Cells, vol. 254, pp. 112237, 2023.

[24] F Afshari, B Muratçobanoğlu, E Mandev, M.A Ceviz, and Z Mirzaee, "Effects of double glazing, black wall, black carpeted floor and insulation on thermal performance of solar-glazed balconies." Energy Build., vol. 285, pp. 112919, 2023.

[25] J Zheng, R Febrer, J Castro, D Kizildag, and J Rigola, "A new high-performance flat plate solar collector. Numerical modelling and experimental validation." Appl. Energy, vol. 355, pp. 122221, 2024.

[26] V Shemelin, and T Matuška, "Quantitative review on recent developments of flat-plate solar collector design. Part 1: Front-side heat loss reduction." Energy Rep., vol. 9, pp. 64-69, 2023.

[27] M Qu, D.H Archer, and H Yin, "A linear parabolic trough solar collector performance model." In Energy Sustain., vol. 47977, pp. 663-670, 2007.

[28] S.I Abdel-Khalik, "Heat removal factor for a flat-plate solar collector with a serpentine tube." Sol. Energy, vol. 18, no. 1, pp. 59-64, 1976.

[29] A.S.H.R.A.E Standard, "Methods of testing to determine the thermal performance of solar collectors." ASHRAE, pp. 93-77, 1997.

[30] W.A Beckman, S.A Klein, and J.A Duffie, "Solar heating design, by the f-chart method." NASA STI/Recon Tech Rep A, vol. 78, pp. 31071, 1997.

[31] I Budihardjo, and G.L Morrison, “Performance of water-in-glass evacuated tube solar water heaters.” Sol. Energy, vol. 83, no. 1, pp. 49-56, 2009.

[32] R.V Dunkle, “A proposed method for the evaluation of performance parameters of flat-plate solar collectors,” 1975.

[33] F Struckmann, “Analysis of a flat-plate solar collector.” Heat Mass Transp., Project Report, 2008.

[34] B.O Bolaji, and I.O Abiala, “Theoretical and experimental analyses of heat transfer in a flat-plate solar collector.” Walailak J. Sci. Technol., vol. 9, no. 3, pp. 239-248, 2012.

[35] Alawi, H.M Kamar, A.R Mallah, H.A Mohammed, M.A.S Sabrudin, K.M.S Newaz, and Z.M Yaseen, “Experimental and theoretical analysis of energy efficiency in a flat plate solar collector using monolayer graphene nanofluids.” Sustainability, vol. 13, no. 10, pp. 5416, 2021.

[36] S Xiao, Y Zhang, K Xia, and J Long, “Influence of operating conditions on solar energy utilization efficiency of flat plate solar collector.” Renewables: Wind, Water, Sol., vol. 9, no. 1, pp. 2, 2022.