Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage: https://semarakilmu.com.my/journals/index.php/fluid_mechanics_thermal_sciences/index
ISSN: 2289-7879

Thermal Performance Solar Flat Plate Collector and Influence of Flow Pipe Design

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ARTICLE INFO

Article history:
Received 2 June 2024
Received in revised form 27 August 2024
Accepted 11 September 2024
Available online 30 September 2024

Keywords:
Flat plate collectors; corrugated pipe; collector efficiency; water heating

ABSTRACT

Flat plate collectors are commonly utilized in both domestic and industrial applications to minimize energy consumption. In this study, solar flat plate collector (SFPC)) with corrugated flow pipe with ten turns placed over flat absorber plate and covered with single glass layer was fabricated and tested, in Al-Mussiab city, Babylon, Iraq (latitude 32.5◦N and longitude 44.3◦E). This research presents the effect flow pipe shape about the SFPC's thermal performance. The designed solar collector utilized employing of 12.5 mm-diameter corrugated copper tubing that extended 19500 mm in total length. According to different rates of water flow namely (50, 100, and 150 L/h). The results indicated that the working fluid's greatest temperature differential between the inlet and outlet of solar collector (12.9°C) at volumetric flow rate (50 L/h). The maximum thermal efficiency (ηth) rate of solar flat plate collector was (77%) at (150 L/ h). These results encourage the development of solar collector system and eventually help the sustainable use of solar power in home applications, including solar water heating system.

1. Introduction

The global quest of sustainable and clean energy solutions has propelled the evolution of solar technologies. An essential component of human existence is energy. Various energy sources are used nowadays, and renewable energies have drawn a lot of attention due to environmental concerns, rising energy needs, and the depletion of conventional energy sources.

Among the most significant and limitless renewable sources is solar energy [1]. Approximately 20% of the family's total energy usage is consumed for the solar water heating system [2]. The solar collectors function as heat exchangers inside the solar energy system. By turning radiation energy into heat energy, which is then further transformed to operating the fluid, such as water or air, solar thermal energy is generated. The solar collector has an absorber that enables the conversion process [3-6]. Al-Manea *et al.,* [7] examined was to increase the efficiency of SFPC by adding only one collecting tube with a serpentine design that was coated in plastic. In Al-Samawa, Iraq, modelling and experimental studies were carried out to assess the thermal performance of an active SFPC with an

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https://doi.org/10.37934/arfmts.121.2.132146

inner absorber tube. Using the experimental details a TRNSYS model was created and verified for the suggested FPSC. According to the data, there was an average 1% variation in collector efficiency and temperature differential between the models and the experiments. On a clear day, the average difference in temperature between the input and output was around 20°C, and the average efficiency was about 58%. Sakhaei and Valipour [8] This study looks at how the thermal behavior of SFPC is affected by helically corrugated heat collecting tubes and PCM as an energy storage device. According to the research, solar absorption rises by 3.7% while heat losses are reduced by 39.8% in corrugated heat collecting tubes as compared to plain heat collecting tubes. Additionally, PCM lowers the output temperature in the morning when charging, but raises it in the afternoon while discharging. At a Reynolds number (Re) of 5153.6, the working fluid's maximum output temperature in an FPC is 40.8. When using simple heat collecting tubes, the average thermal efficiency of FPC rises from 41.5% to 48.9%. Al-Zurfi *et al.,* [9] examine that phase change materials (PCMs) may be used to solar water heaters to increase their efficiency. Latent heat storage and release is a well-known property of PCMs, which may help stabilize the heat output of solar water heaters. It was discovered that the ideal PCM arrangement could sustain hotter water temperatures for longer periods of time, extending the useful life of solar water heating into the evening. Verma *et al.,* [10] (SFPC) are essential for residential and industrial water heating, but their efficiency is stagnant. A study explores a novel design and fabrication technique to improve efficiency. This work develops a single spiral-shaped collector tube for solar collectors, achieving 21.94% thermal efficiency and 6.73% exergy efficiency, resulting in material savings of around 30% and reduced manufacturing and maintenance costs. Saffarian *et al.,* [11] study simulated flat plate solar collectors using U-shaped, wavy, and spiral pipes to increase convective heat transfer coefficient. Results showed that wavy and spiral pipes significantly increased heat transfer coefficient and Nusselt number. According to the research, wavy pipes have the greatest pressure drop, and utilizing nanofluid boosts heat transfer coefficients. Outside of CuO 4%, the Nusselt number drops, with a 4% volume fraction leading in a 78.25% increase in heat transfer coefficient. Murugan *et al.,* [12] established that corrugated booster reflectors (CBR) in tests to improve the performance a solar collector with centrally finned twist (CFT). The CBR has a 1.6% larger effective reflector area than the FBR, Consequently, an 8.25% increase in the Nusselt number. The CFT with the lowest twist ratio has an 11.08% greater thermal efficiency, and developed. Hashim *et al.,* [13] discusses the performance of a solar water heating system for a flat plate collector. The system, designed with dimensions of 125*110 cm and width 25 cm, uses water as fluid flow at two flow rates (5.3 and 6.51 L/min). The results show higher efficiency and effectiveness, with maximum temperatures of 51.4°C and 49°C at 5.3L/min and 6.51 L/min, respectively. The twisted strips are added to flat plate solar water collectors to increase efficiency without changing the design or cost of the collectors [14]. Three collectors with different twisted ratios were evaluated, and the findings revealed that twisted ratio (3) had the maximum heat transfer rate, resulting in 49%, 57%, and 63% daily efficiencies. Shelke and Patil [15] analyzes the effect of variations in tube shape on solar water heaters, focusing on circular tubes with a 12.7mm diameter. Numerical analysis using ANSYS CFD FLUENT software shows good agreement between inlet and outlet temperatures for different heat flux and elliptical tube shapes. According to the results of the study, the elliptical tube of instance no. 5 (i.e., B = 0.5A) provides the highest water outlet temperature for the same heat flow and entrance temperature when compared to circular and other elliptical geometries. Additionally, it demonstrates that the difference in peak output temperature between elliptical and circular tubes is 4.17 °C. This demonstrates the benefit of elliptical tubes for home purposes in the future. Ameen *et al.*, [16] presents an experimental and numerical study that compares the heat transfer enhancement of a flat plat collector (FPC) using three types of twisted tapes (single twisted tape (ST), double twisted tape (DT), and mixed twisted tape (SDT)) to a plain tube with twist ratios (TR=2). Due to heat transfer enhancement, experimental data demonstrate that DT is more efficient than ST and SDT. The study reveals that outlet water temperature in mixed twisted tape collectors is 10°C higher than plain tube collectors, copper collectors 6°C higher than aluminum collectors, copper collectors 5°C lower than aluminum collectors, and collectors with two glass covers 4°C higher. It shows the importance of solar energy in heating process that experiment Kareem *et al.,* [17] used 12 kilograms of pure Iraqi black paraffin as a storage material. The initial design involved a vacuum tube solar collector (VTSC) that melts PCM in the shell regime using a tube and shell heating exchanger. The melting process was influenced by inner tube entrance and surrounding temperatures. The results showed that the melting process took three to 4 hours in summer and 14 to 16 hours in winter. The study has practical significance for companies that need storage materials to improve the efficiency of thermal storage systems. The inner tube entrance and surrounding temperatures significantly impacted the melting process. The study has practical implications for companies that need storage materials to enhance thermal storage system efficiency. At Zagazig University's engineering college, a prototype solar PV system with a capacity of 105 kWp was planned, run, and observed [18]. The system is meant to partly meet ZU's engineering school's electricity needs and is grid-connected. The system can produce 175,500 kWh annually with an annual capacity factor of 19.1%, according to a comprehensive detailed design that was completed. In comparison to the theoretical design, the system functioned reasonably well with a reduced repayment time of 7.9 years and an LCOE of 0.55 EGP/kWh without subsidies, financial analysis demonstrated the project's profitability. The project saves 1882.3 tons of CO_2 emissions throughout its 25-year lifespan in addition to the financial gains. The innovative design of a photovoltaic-thermal (PVT) unit using a cylindrical reflector is the main focus of this research [19]. Performance is improved by combining a nanofluid spectrum filter made of a combination of MgO and water with a layer of thermoelectric generators made of Cu_2SnS_3 (CTS) inside PVT. By contrasting the method's results with experimental data, its validity was confirmed. The addition of a duct for filter, fins, and a cylindrical reflector improves the performance by 36.3%. When there is a reflector present, the electrical performance improves by 37.7% due to the filter's increased velocity. The highest decrease in CO_2 emissions is achieved by combining a reflector, fins, and filter into a single system; this figure is two times greater than that of standard PV. Sheikholeslami and Khalili [20] explore the use of nanofluid filters in improving a concentrated photovoltaic thermal (CPVT) module. The nanofluid filters, a combination of silver and water, are used as a cooling fluid and spectrum filter due to their thermal properties and adjustable optical features. Three-dimensional models depict the solar radiation's spectrum distribution and the nanofluid filter's transmissivity is determined using empirical models. Two cooling duct designs are proposed: a straight bottom wall and a semi-wavy wall with triangle-shaped obstructions. The study found that the electricity effectiveness improves by 3.4% with the nanofluid's speed inside the filter section. However, the thermal performance increases by 5.68% when the concentration ratio is increased from 3 to 30. The filter also reduces cell temperature by 47.82% when applied within the cooling duct's second structure. This study presents a procedure that includes adding corrugated flow pipe over flat plate absorber and covered of single glass layer for SFPC. The main aim is obtaining highly efficient solar collectors for domestic and industrial applications. This study investigates the thermal performance of SFPC with corrugated flow pipe and various volumetric flow rates.

2. Methodology

2.1 Description the Design of SFPC

The collector has dimensions of (2000*1000) mm and a rectangular shape. The system was built on an iron frame as shown in Figure 1. The tilt angle faced south and was fixed at 47° the collector used water as the working fluid. The fluid may traverse a pipe that spans a length of 19.5 meters, starting from its entrance point and ending at the output, as seen in Figure 2. Additionally, a glass cover was included while building a typical (SFPC). Copper pipes were attached above the absorber plate to facilitate the flow of water.

Fig. 1. Photograph of solar flat plate collector (SFPC)

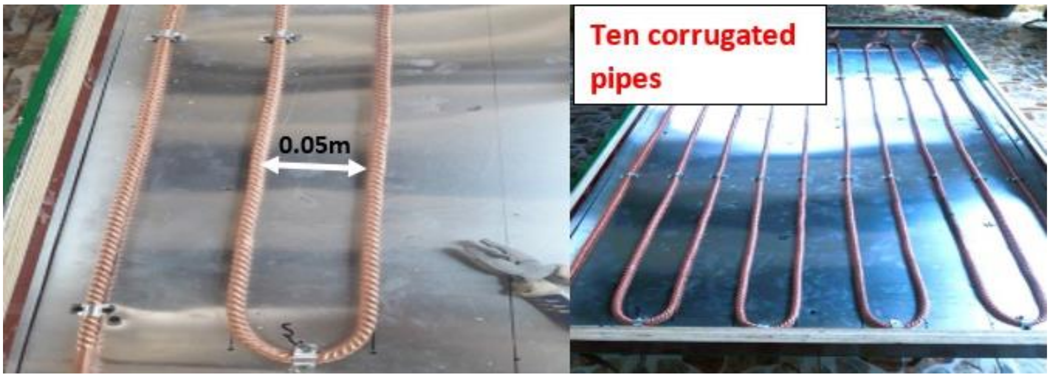

Fig. 2. Photograph of corrugated pipe

The SFPC comprises an exterior wooden casing with a 40 mm thickness, serving as a container and providing insulation to minimize heat losses. The absorber is made of aluminum and is covered with black paint to enhance its ability to absorb solar energy. The collector is covered with a single piece of glass, which has a thickness of 4mm, to prevent the solar radiation from escaping to the outside. Additionally, the copper pipes used in the collector have a diameter of 12.5 mm. As shown in Table 1. the specification of materials used in SFPC.

Table 1
The SFPC Specification

Parameter	Material	Dimension	Remark
External case	Wood	2m*1m*0.02 m	bottom an two sides
Absorber plate	Aluminum	2m*1m*0.005m	Black painted Aluminum
Flow tubes	Copper	D 0.0125 m L 19.5 m	Number of turns :10
Cover	Glass	2m*1m*0.006m	Number of covers :1

2.2 Experimental Procedure

The study was carried out started at 9:00 Am to 4:00 Pm. This time was chosen because it allows for the absorption of the greatest powerful and uniform radiation at the specific area where the setup is situated, taking into account the existing weather conditions. The research was conducted in (December2023, January 2024, February 2024), in Babylon, Iraq during the wintertime, and the weather conditions are (32.48389° latitude and 44.43111° longitude). Iraq is located in a northern geographic region that is very conducive to receiving a lot of solar energy. As shown in Table 2. the working fluid is water.

Table 2
Physical properties working fluid [21,22]

Operating fluid	K ($\boldsymbol{W}$/m.k)	CP ($\boldsymbol{J}$ /kg.k)	μ ($\boldsymbol{Pa}\cdot\boldsymbol{s}$)	ρ ($\boldsymbol{kg}$/m^3)
Water	0.576	4180	0.0008891	1000

Water flows in through the plastic water tank (100 L) to estimate the efficiency of the SFPC with corrugated pipe. Water circulation pump (Sxr40/63p) [Qmax35L/min-Hmax6m] pushes water pump before it reaches the collector. Its three-position selector switch regulates the maximum mass flow rate with Volumetric flow meter is mounted in the solar collector inlet pipe, in between the water pump and the collector. Its range is 0–250 liters per hour which is used to determine the amount of liquid entering the collector by the control valve. After the water enters through the input pipe, a solar power meter digital sun meter (pyrometer) model-1333, Range-1 to 2000 W/m2, measures the sum of solar irradiance that the SFPC is exposed to. The type (k) thermocouples that are used to record the temperature in various regions of the flat plate collector with used a data logger with sixteen channels is used to calculate the temperatures, and readings are recorded on aluminum plate, copper pipes, and glass cover. Readings are taken every thirty minutes on the designated day to determine the temperature of the water exiting out of the pipe, the amount of heat gained from solar irradiance (Ir) exposure, the efficiency of the collector to test the impact of the tube's shape and changes in flow rate on the thermal performance the solar collector. As shown in Figure 3.

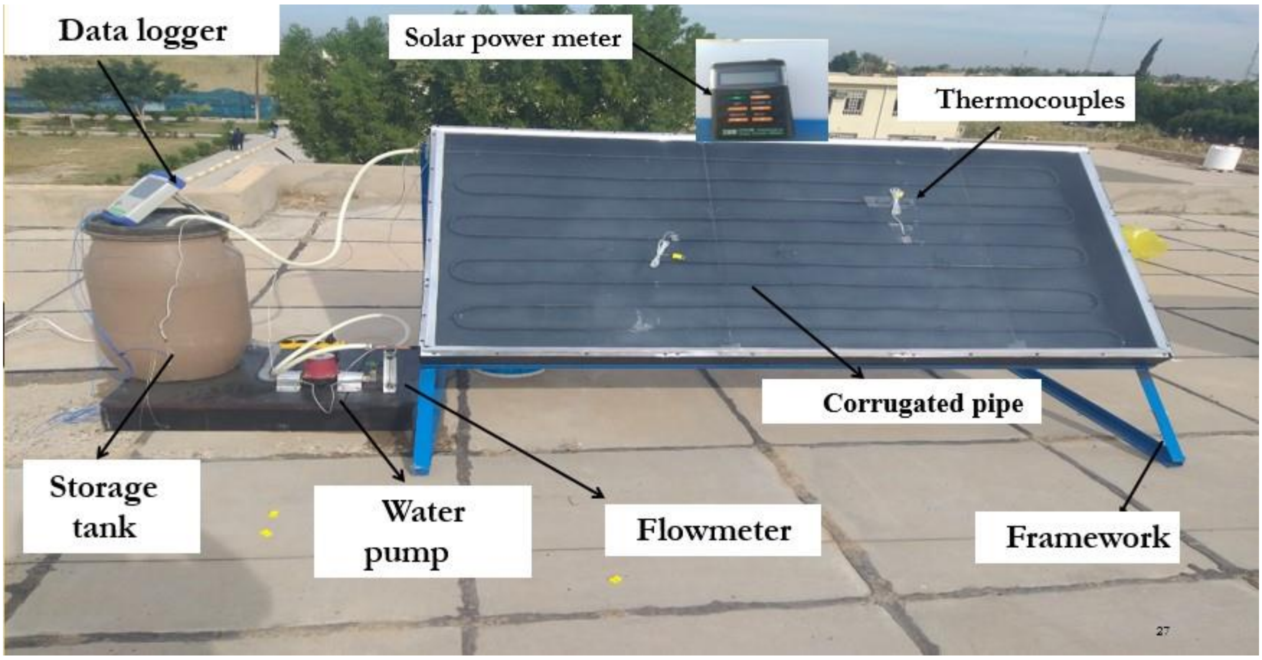

Fig. 3. SFPC with measuring devices

The accuracy of the equipment was checked before testing. The SFPC were subjected to the solar simulator for a predefined amount of time until a stable situation that is, the temperature differential between the intake and outlet stabilized—were reached. Measurements collection over the steady-state period, flow rate, and temperature measurements were continually collected. Variations in the testing used to determine how flow velocity affects SFPC performance. The tests were carried out again for various flow rates. Performance analysis checked using the parameters below were ascertained by analysis of the gathered data, heat transfer coefficient approximated from flow rate and temperature differential. The temperature at the SFPC outlet was taken there. Comparing the thermal behavior characteristics of the modified and standard SFPC to evaluate the influence of the corrugated pipes.

2.3 Thermocouples Locations

The temperatures of SFPC are recorded throughout the experiment in this work using nineteen thermocouples K-type. Thermocouples have a temperature measurement range of -100 to 1300 °C. Figure 4 shows these thermocouples, three locations were used to connect the thermocouples (the glass, the absorption surface, and the flow pipe).

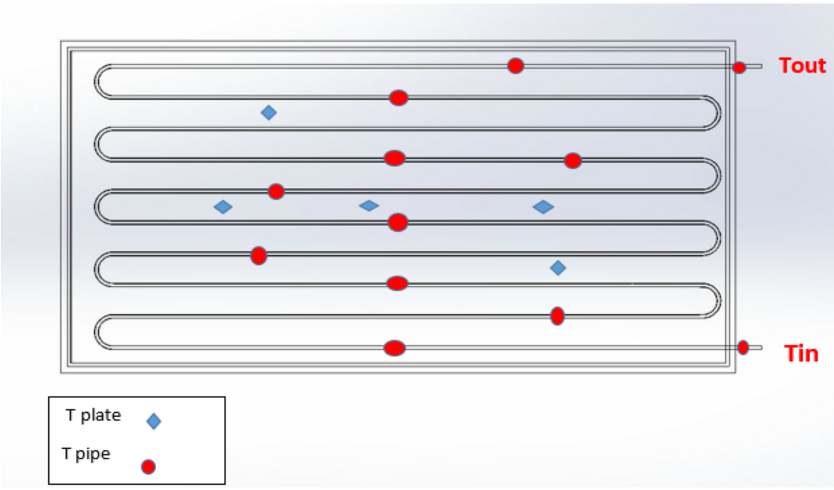

Fig. 4. Schematic of distribution thermocouples on SFPC

3. Mathematical Formulations

In a stable condition, the energy balance revealed the division of solar power incidence to advantageous power gains, optical losses, and heat losses, as well as the distribution of solar energy incidence description of the solar collator efficiency. Eq. (1) is utilized for estimating the working fluid's useful energy gain [23]

$$Q_u = mc_p(T_{out} - T_{in}) \tag{1}$$

$$\dot{m} = \rho Q$$

Eq. (2) may be used to compute (ɳ) collector, which is known in the proportion of the working fluid's useful heat gain to the energy affecting on the obtaining surface [24]

$$\eta sc = \frac{Q_u}{A_{cou} I_{Rad}} = \frac{mcp(Tout - Tin)}{Ac\ IRad} \tag{2}$$

The velocity of the water can be computed by dividing the volume flow rate (Q) over the pipe's cross section.

$$V = \frac{Q}{A_{pipe}} \tag{3}$$

$$T_f = \frac{T_{out} - T_{in}}{2} \tag{4}$$

The ratio of the collector's actual useful energy gain to the maximum useful gain that would be possible if the whole collector surface were at the fluid input temperature. In Eq. (5), the expression "Collector Heat Removal Factor" (FR) [25].

$$\text{FR} = \frac{mco(Tout - Tin)}{Asc[S - UL(Tout - Tin)} \tag{5}$$

4. Results and Discussion

This study presents results experimental for SFPC using absorber flat plat and corrugated flow pipe, the results are studied under the influence of solar radiation during (December2023, January, and February 2024) and variable water flow rate (50, 100, 150 LPH) to study the thermal behavior in the SFPC. The effect of volumetric flow rate on the mean temperatures of solar flat plate collectors with solar radiation is shown in Figure 5, Figure 6, and Figure 7 for model of (SFPC) with absorber flat plate and corrugated pipe. The mean temperatures of absorption plate (Tp), glass (Tg), and flow of water (Tf_w) in the collector are shown in these figures. Experimental tests show that temperature curves decrease as the water mass flow rate increases. This is due to increasing the water flow speed in the solar collector reduces the period available for heat gain from solar radiation, which causes temperatures to drop. We'll discuss about the temperature behavior of the absorbent plate, glass, and flow water in Figure 5, Figure 6, and Figure 7 It was reported that the absorbent plate temperature represents the maximum temperature achievable in (SFPC). The temperature (85.4.2, 79.6, 57.4°C), corresponding to flow rate of 50, 100, and 150 L/h respectively. As a result, compared to the other two values, the maximum temperature will be at m (50 L/h), followed by (100 L/h) and (150L/h). Because of the reduced flow this increases the time the plate is exposed to sunlight radiation, which increases the absorbed solar radiation. As a result, the absorber plate's temperature rises, as shown in figures. Additionally, the figures show that in the FPSC, the glass temperature is higher than the flow water temperature in the pipe and lower than the absorbent plate temperature. At ($V^{\cdot}$) of 50, 100, and 150 LPH, the temperature of the glass increases to 51.4 °C, 48.7 °C, and 42.7 °C, respectively, while the temperature of the water that flows increases to 47.2, 39.3, and 33.6 °C, respectively.

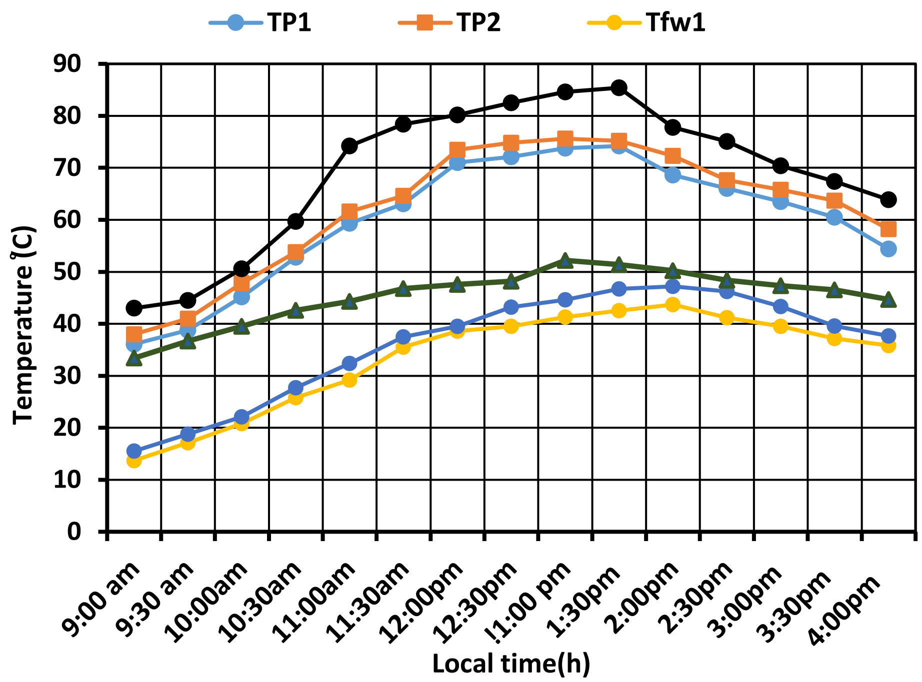

Fig. 5. The effect of volumetric flow rate (50 L/h) of water on temperatures of collector over time (h)

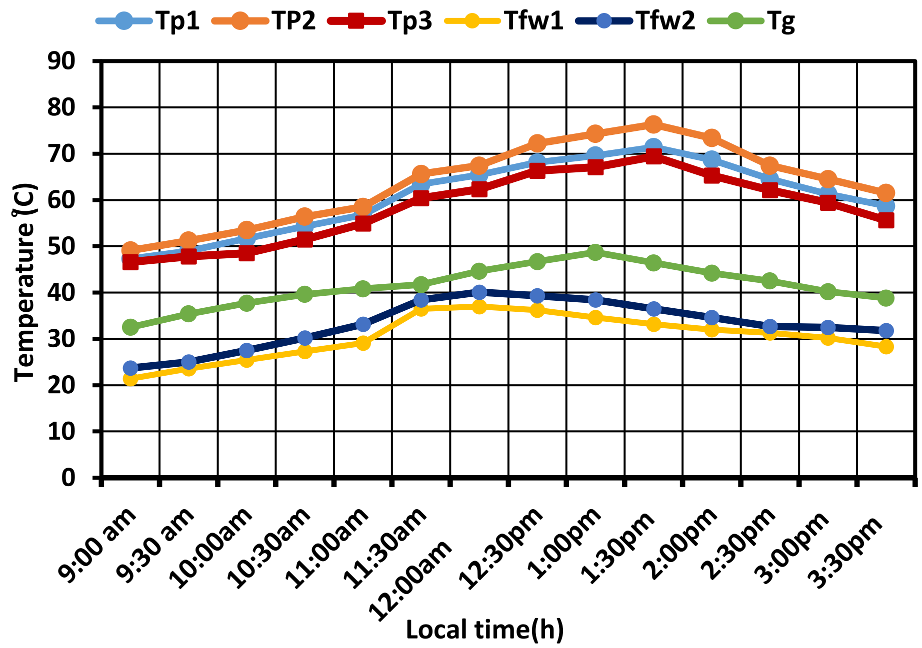

Fig. 6. The effect of volumetric flow rate (100 L/h) of water on temperatures of collector over time (h)

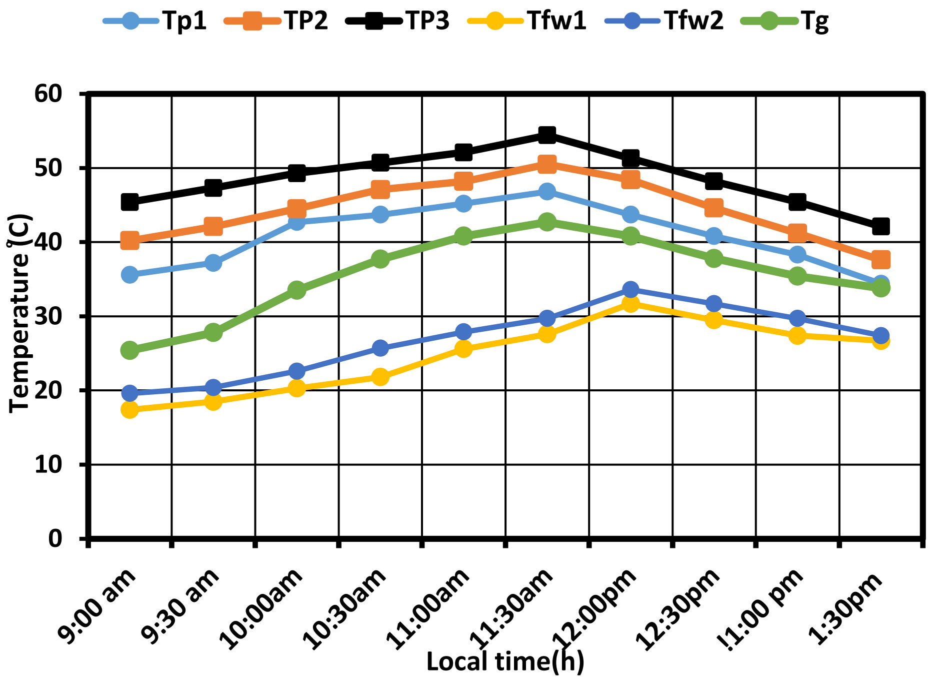

Fig. 7. The effect of volumetric flow rate (150 L/h) of water on temperatures of collector over local time (h)

4.1 Temperature Difference Results

The work fluid's flow rate has an influence on the temperature differential between the water's the entrance and output. The temperature differential at the water output, which has volumetric flow rates of 50, 100, and 150 LPH, as shown in Figure 8. Since heat transmission through the tube to the liquid takes time and low flow rates cause the liquid to move more slowly, which contributes to the temperature increase by absorbing more radiation. it was discovered that decreasing the stream rate increases the temperature differential between the inlet and the outlet. As shown in figure, the largest temperature difference was 12.9°C at 50 LPH. Figure 8 shows a difference in the outlet and inlet temperatures of the tubes at volumetric flow rates (50, 100, and 150 LPH), where the maximum difference in temperature was (12.9°C), 10.1°C, 8.5°C), respectively. The temperature difference increased approximately at 12:00 pm and decreased after that.

The Figure 9 comparison the temperature difference at the inlet and outlet for working fluid in the FPSC between two different days at a similar (V)˙. Figure 9 shows that the day of (4-Feb) at the volumetric flow rate of (50 L/h) had the highest temperature difference (12.9°C) than the other day, that is due to the effect of solar radiation in (4-Feb) which was higher than on the other day (31-Dec), reaching its maximum value (916.75 W/m^2) at 12:00 pm.

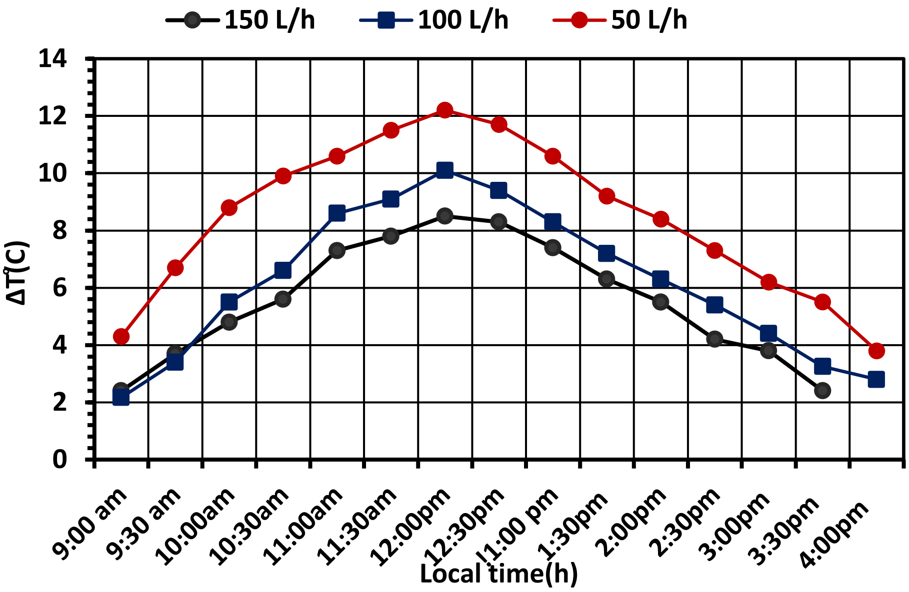

Fig. 8. Temperature Difference variation of water at various volumetric flow rates over Local time(h)

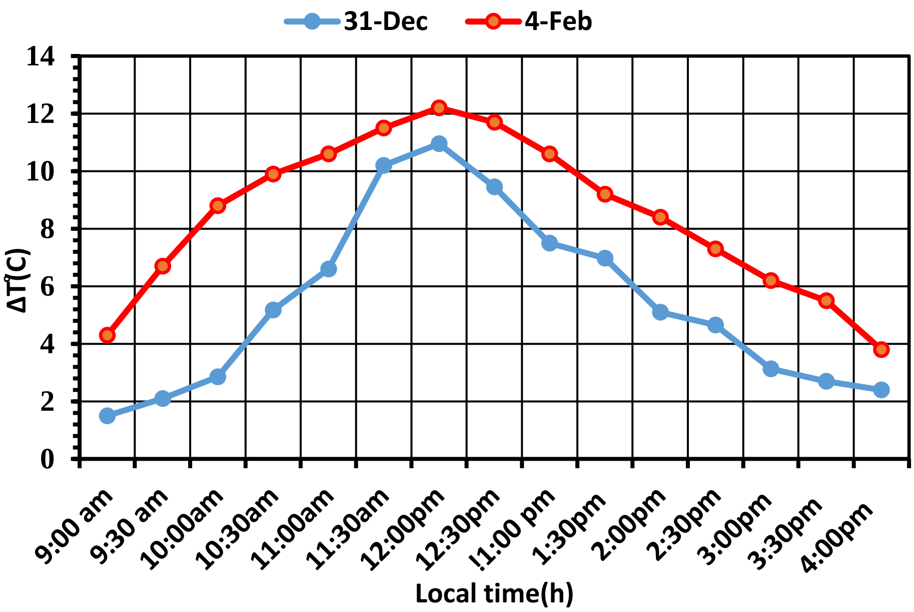

Fig. 9. Comparison the temperature difference between (31Dec, 4Feb) at volumetric flow rate(50L/h) over local time (h)

4.2 Solar Radiation Results

Using a solar power meter, the local solar radiation data from the atmosphere was measured daily in December 2023, January 2024, and February 2024 at volumetric flow rates of (50, 100, and 150 LPH). As shown in Figure 10, it was discovered that the solar radiation (SR) was at its peak during the midday hour. The solar radiation starts to rise at 9:00 am and then progressively increases until reaching its peak at approximately 12:00 pm, at which point it starts to gradually decrease. The sun's disk was gotten almost horizontal in relation to the solar collector. with the greatest solar radiation occurring between 11:00 am and 1:00 pm, after which it the solar radiation decreases further at approximately 4:00 pm. The e maximum solar radiation was (994 w/m^2). This gives the solar collector more efficient thermal conductivity with the difference in volume flow rate in SFPC.

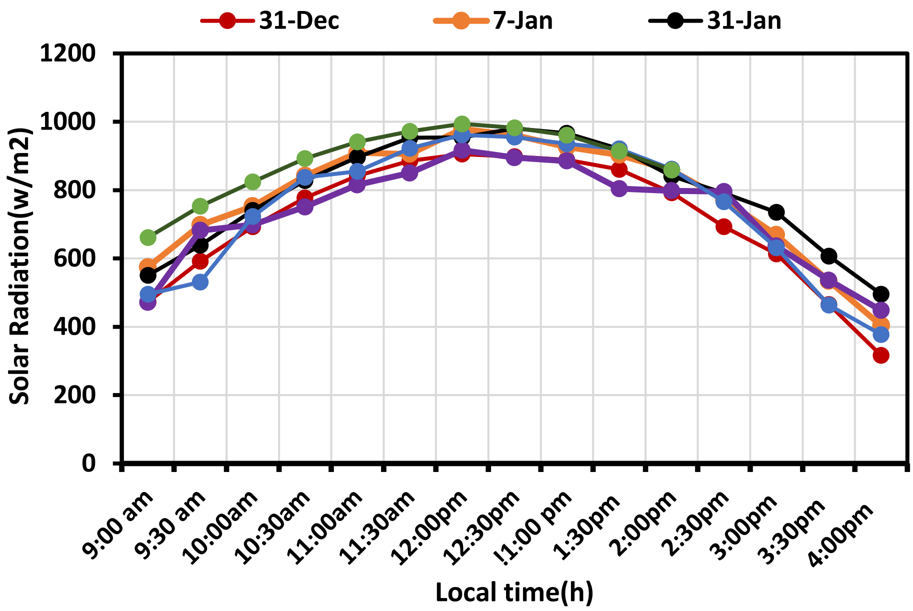

Fig. 10. The variation of solar radiation in (Dec2023, Jan, and Feb2024) over local time

In Figure 11, the impact of differences in solar radiation on the variations in the operation fluid temperatures between the inlet and outlet of FPSC, at volumetric flow rate (50 L/h), It has been shown that as solar radiation increase, the temperature difference also increases. that's happens due to the solar collector was absorb the higher amount of solar radiation raises, The fluid's exit temperature. The temperature difference has therefore increased, as seen in the following figure.

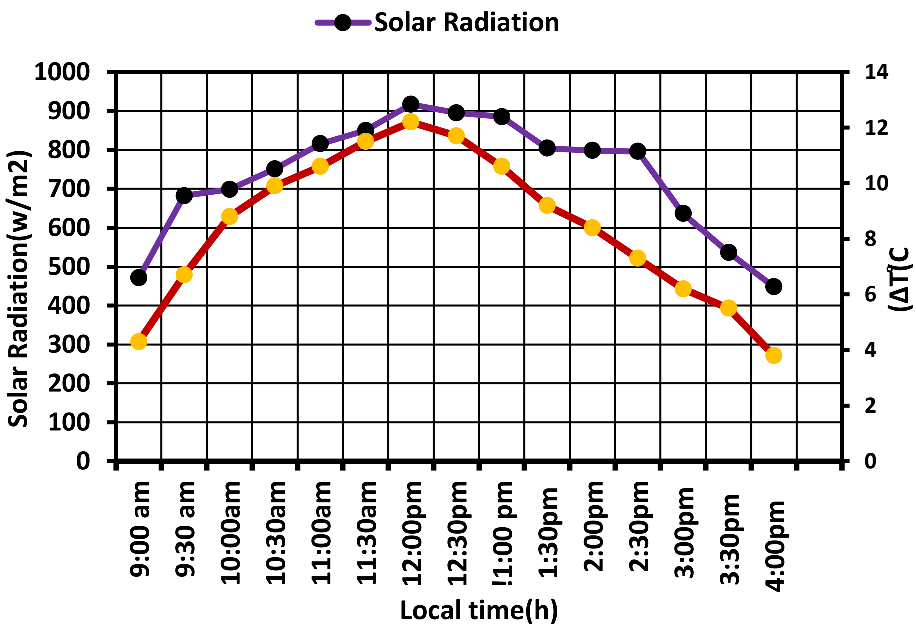

Fig. 11. The effect of solar radiation on temperature over hours day at (4-Feb)

4.3 The Useful Gained Energy Results

Figure 12 depicts the variation of the useful energy in FPSC with effect of changing volumetric flow rate, where three volumetric flow rates (50, 100, and 150 L/h) were selected. the results showed that increasing the flow rates increases the useful energy. it has been shown from experience that the energy at flow rate (150 L/h) higher than the useful energy at the other two flow rates as shown in Figure 12. The solar energy begins increasing from 9:00am until it reaches to maximum value at 12:00pm, then it goes back down to the lowest value at4:00pm. The maximum solar energy was (1490.2 W) at (V˙) 150 L/h. As shown in the figure.

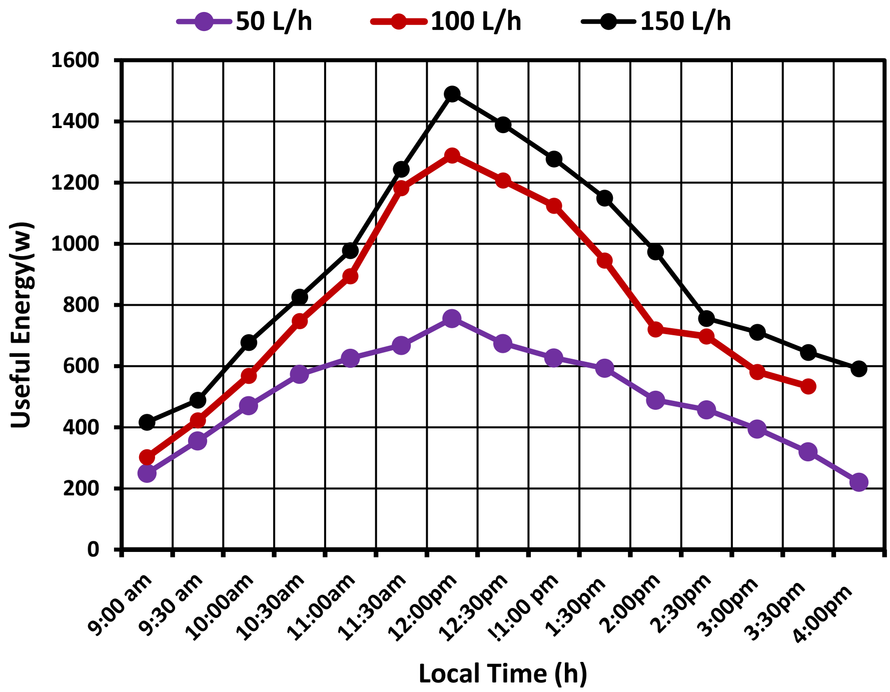

Fig. 12. Variation of Useful energy with (V˙) over hours day(h)

Figure 13 relation between the variation of the useful gain energy with incident solar radiation on SFPC at volumetric flow rate (150 L/h) over hours day from (9:00am to 4:00pm). The results have shown that useful energy was similar to the solar radiation which starts increasing from 9:00am, it until reaches to peak at 12:00, then decreases to lowest value at 4:00 pm. As shown in Figure 13.

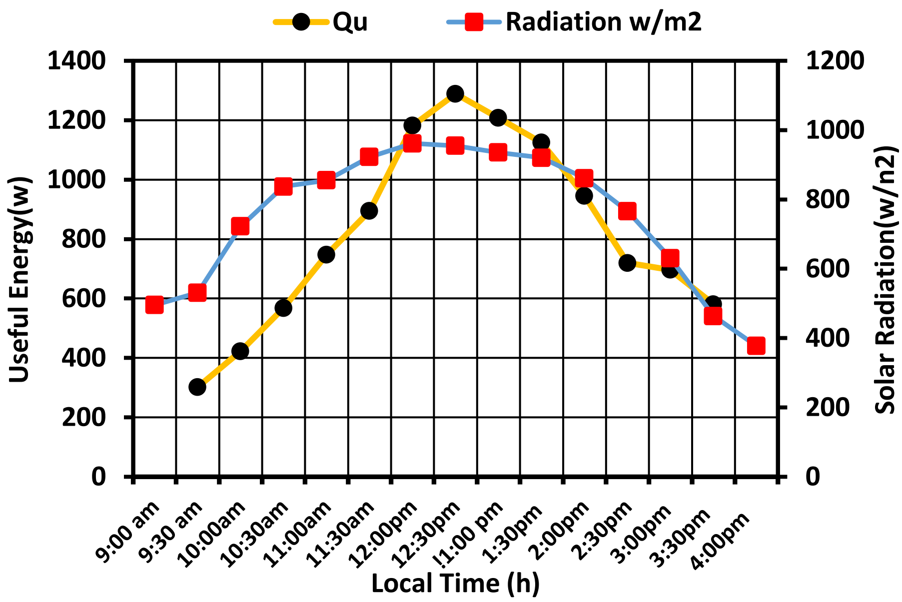

Fig. 13. Variation Useful energy with Solar radiation at (v) (150L/h)

Figure 14 depicts relation between average solar energy (Qu) of (SFPC) with average thermal efficiency (Ƞ) at variation of volumetric flow rates (50, 100, and 150 L/h). The results have shown that efficiency increases when the useful energy increasing because the efficiency represent ratio the solar energy (Qu) to the incident solar radiation on (SFPC). Also, its show the efficiency increases when flow rate (V˙) increase. the maximum average efficiency was (77%) at(V˙) (150L/h) as shown in Figure 14.

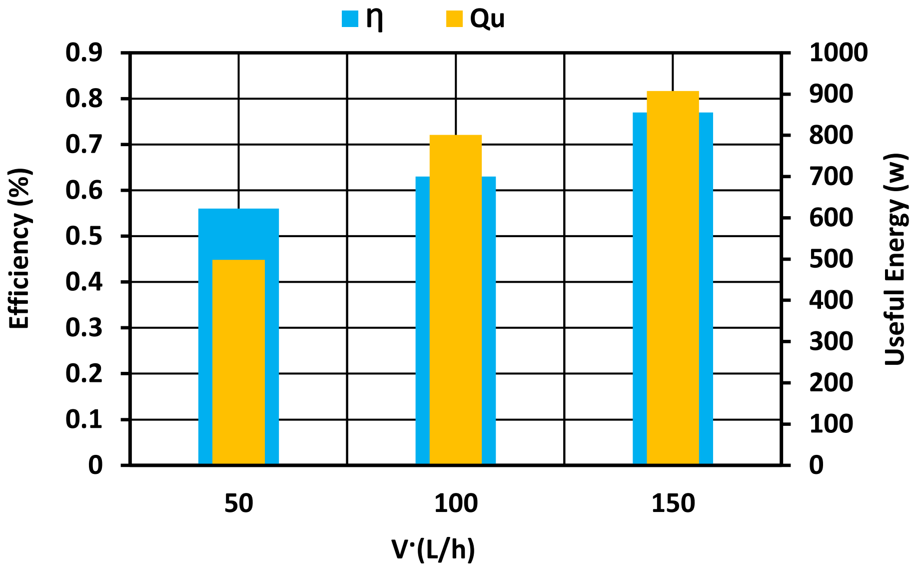

Fig. 14. Relation between average solar energy (w) and thermal efficiency at variation (V˙) (50,100,150L/h)

Figure 15 depicts the comparison between the present study and earlier research of Verma *et al.,* [10], the previous study used spiral shaped of solar collector design, while our current study used corrugated pipe design. The comparison was in terms of the SFPC's thermal efficiency as shown in Figure 15 predicated on the collector's flow pipe design at the variations dimensionless in working fluid flow rates for each study. The findings demonstrated that our present study using corrugated pipe was approximately more efficient with 37.5% than previous study.

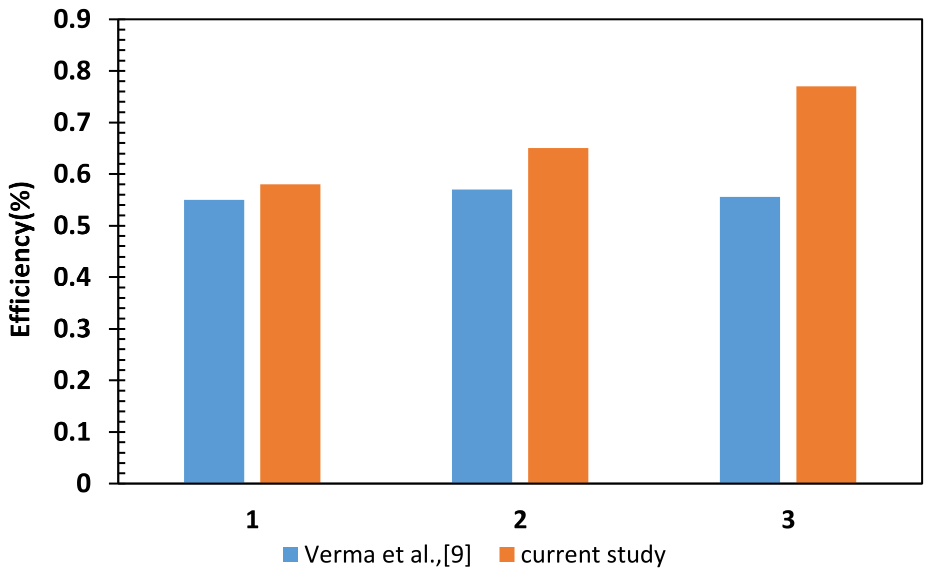

Fig. 15. The efficiency of SFPC with different dimensionless flow rate

5. Conclusion

Important renewable energy sources include solar energy, which will be important in future technology and can heat water and air. Power plants, residences, and companies use hot water. The current work analyses the behavior of a solar flat plate collector (SFPC) with corrugated pipes designed inside the collector in operation heating. The goal of this work is to assess the possible advantages of corrugated pipes, especially their impact on improving heat transmission and thermal efficiency. An SFPC was utilized flow pipe with ten turns and the diameter (12.5 mm), total length of pipe (19500mm). Different volumetric flow water rate(V) was experimented (50,100, and 150 L/h). This study was carried out t in Babylon city, Iraq in winter time. The data show that the corrugated pipes greatly improve the heat transfer rate within the SFPC. which raises the output temperature. The highest temperature differential in the working fluid between the input point and the exit was reached (12.9°C) at ($V^{\cdot}$) (50L/h). The maximum efficiency rate of solar flat plate collector was (77%) at ($V^{\cdot}$) (150L/h). The performance of this design improves when compared with other pipe designs. This enhancement is ascribed to the turbulence and larger surface area that the corrugated form produces for flow pipe. These results further solar power technology and eventually help the sustainable use of renewable energy.

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