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Experimental Study of Electrical and Thermal Efficiencies of a Photovoltaic Thermal (PVT) Hybrid Solar Water collector with and without Glass Cover

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ABSTRACT

Investigating the thermal and electrical gains and efficiencies influence the designed photovoltaic thermal hybrid collector (PVT) under different weather conditions. The designed system was manufactured by attaching a fabricated cooling system made of serpentine tubes to a single PV panel and connecting it to an automatic controlling system for measuring, monitoring, and simultaneously collecting the required data. A removable glass cover had been used to study the effects of glazed and unglazed PVT panel situations. The research was conducted in February (winter) and July (summer), and March for daily solar radiation effects on efficiencies. The results indicated that electrical and thermal gains increased by the increase in solar radiation. The average rise in PVT water collectors' thermal energy efficiency with a glass cover for three cases was 5% compared with the unglazed PVT water collector. While the maximum total efficiencies of 79 % and 69.5 % for glazed and unglazed collectors were recorded under maximum solar radiation of 1100 W/m² and maximum water flow rate in the tubes system for July. The recorded result seemed promising and significant, indicating that the manufactured system is useful for adjusting PVT thermal and electrical efficiencies for cold and hot weather conditions.

Keywords: Photovoltaic thermal collector, Hybrid system, Electrical efficiency, Thermal efficiency

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دراسة تجريبية للكفاءات الحرارية والكهربائية لجامع الماء الحراري الكهروضوئي الهجين مع أو بدون غطاء زجاجي

هند مهند عباس
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الخلاصة

البحث الحالي درس تأثير الظروف الجوية المختلفة على معامل الكفاءة والحصيلة الحرارية والكهربائية لجامع حراري ضوئي هجين مصنع محلياً. تم تصنيع المنظومة عن طريق ادراج منظومة تبريد مصنعة مكونة من انابيب افعوانية على الجهة الخلفية للوح خلية فوتوفولطائية وربط المنظومة بنظام سيطرة الكتروني لقياس وجمع وتسجيل القراءات. اضيف لوح زجاجي متحرك للجهة الامامية للمنظومة لمحاكاة ظروف التشغيل المزججة وغير المزججة. تم دراسة سلوك وكفاءة المنظومة في فصل الشتاء (شهر شباط)، فصل الصيف (شهر تموز) بينما تمت دراسة تأثير الاشعاع الشمسي اليومي على كفاءة المنظومة في شهر اذار. اظهرت النتائج ان الحصيلة الحرارية والكهربائية قد ازدادت بازيد الاشعاع الشمسي بينما ازدادت كفاءة المنظومة للظروف المناخية المزججة بنسبة 5 % عن المنظومة غير المزججة. بينما تم تحصيل اعلى كفاءة كلية بنسبة 79 % للمنظومة المزججة و 69,5 % للمنظومة غير المزججة تحت اعلى قيمة مسجلة لاشعاع شمسي بلغت 1100 واط/م² واعلى معدل جريان للماء في الانابيب في شهر تموز. كانت النتائج المستحصلة من المنظومة واعدة وتعطي مؤشرا كبيرا على ان المنظومة المصنعة قادرة على تحسين الحصيلة الحرارية والكهربائية والكفاءة الكلية في الظروف الجوية الحارة والباردة.

الكلمات الرئيسية: جامع ضوئي حراري, منظومة هجينة, الكفاءة الحرارية, الكفاءة الكهربائية.

1. INTRODUCTION

One of the main drawbacks of using conventional energy sources is the disadvantages of generating gases like CO₂ and causing environmental pollution, also, that it is nonrenewable energy sources. Photovoltaic (PV) systems are one of the methods to eliminate its difficulties and meet the growing electricity demand worldwide. Iraq's electricity generation is mainly based on exhaustible fossil fuels that cause clear environmental pollution and facing a reduction in electricity generation, especially during peak demands. PV systems play a considerable function in obviating CO₂ emissions and reduce the gap between power generation and consumer demands (Hashim, et al., 2019). Solar energy seemed to be a suitable solution as it is safe, environmental, applicable, yet some issues related to cost and efficiency (Obaid et al., 2020).

For the past few decades, the solar energy market witnessed a high increase in thermal or photovoltaic technologies. Developments in this field concentrated on increasing the efficiency of various types of solar collectors and PV-Panels. Photovoltaic thermal (PVT) hybrid collectors are one of the major developments (Chew, et al., 2012, Aste, et al., 2015, Hahsim and Abbood, 2016, Hasan and Farhan, 2020).

The PVT hybrid collector is a device that integrates between the solar thermal collector and PV panel to generate thermal and electric energy at the same time. In different researches, it can be concluded that the use of integrated PVT is more efficient than the use of separate PV panels and the thermal collectors (Al-Waeli, et al., 2017).



The ability of PVT hybrid water collectors to absorb two types of solar energy (thermal and photo), converting it into the two forms (heat and electricity) can be invested at the same time with high efficiency. The PVT water collector's overall efficiency is defined as the sum of electrical and thermal efficiency (Avezov, et al., 2011). One of the main problems with the thermal solar collector is that solar thermal radiation is not enough to heat the water during winter. Besides that, PV panel efficiency decreased as its temperature increase. Solar panels work by using incoming photons to excite electrons in a semiconductor to a higher energy level. But the hotter the panel is, the greater the number of electrons that are already in the excited state. This reduces the voltage that the panel can generate and lowers its efficiency. Higher temperatures also increase the electrical resistance of the circuits that convert the photovoltaic charge into AC electricity. Modern hybrid solar panels are designed to suffer less from the heat, but they can still lose 10 percent of their rated efficiency on hot days.

Many researchers reported practical solutions for the current issue and analyzed energy performance for PVT hybrid collector. Studying a parallel serpentine pipe flow-based unglazed PVT water collector and investigating energy and exergy performance of the PVT collector were experimentally investigated at different volume water flow rates from 0.5 L/min to 4 L/min by (Hossain, et al., 2019). The results showed that the maximum thermal energy efficiency is 76.58% at 2 L/min and the maximum electrical energy efficiency is 10.46%. On the other hand, Hamed Awwad (Hamed Awwad, 2019) evaluated the energy performance of an unglazed PV/T water collector (115 W_p, 1.43 m²) and compared it with a PV panel and thermal collector. The results revealed that the PVT collector and PV panel's electrical efficiency is close to each other 9%. Yet, The PV/T produced a good amount of electrical energy that varied depending on the amount of solar radiation reaching it. Sometimes up to 95 W at solar radiation exceeding 850 W/m².

With the shortage in the literature regarding energy analysis and comparison between glazed and unglazed PVT hybrid water collectors under Baghdad/Iraq's climate condition, the scope of the present work was to design and construct a tube and sheet type PVT hybrid water collector. Experimentally investigation of laminar and turbulent water flow rates affects enhancing the electrical and thermal efficiency of PVT water collector had been conducted, and all measurements had been recorded online via Arduino. Besides that, the effect of solar radiation variation controlled by manual orientation mechanism was investigated to innovate a new module with acceptable efficiency.

2 EXPERIMENTAL SETUP

2.1 System Design

A transparent cover (one sheet) of glass was fixed on an aluminum frame and attached to the PV panel's front side, as shown in **Fig. 1**. The glass cover was made to be removable to compare the performance of unglazed and glazed PVT hybrid water collectors.

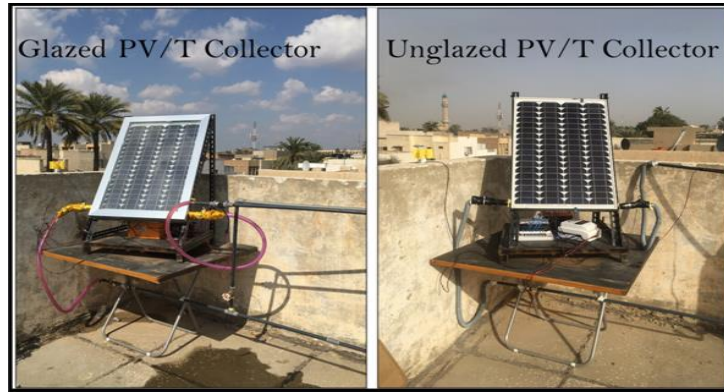


Figure 1. PV/T hybrid water collector with and without glass cover.

The upper absorber plate (PV panel) upon which the solar radiation falls and gets absorbed is shown in **Table 1**, and testing of the selected PV panel was carried out.

Table 1. PV panel properties.

No.	Parameter	Value
1	Rated maximum power	50 W
2	Current at P max.	2.9 A
3	The voltage at P max.	17.2 V
4	Short-circuit current	3.25 A
5	Open-circuit voltage	21.8 V
6	Nominal operation cell temp.	25 °C
7	Wight	6 kg
8	Dimensions	845*545*35 mm
9	Maximum system voltage	800 V DC

The backside absorber plate (A flat plate collector) was made of copper material, as shown in **Fig. 2**. The tube-and-sheet collector is a special kind of heat exchangers that transform the remaining solar radiation energy to the transport medium's internal energy and removes excess heat from the PV module.

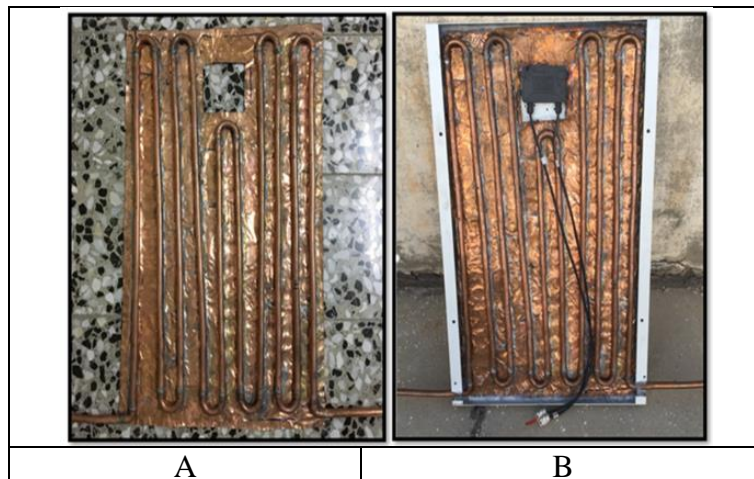


Figure 2. The tube-and-sheet type thermal collector. A) Before adhesion B) After adhesion with the PV module.



A vertical cylindrical tank had been used in the experiment for storing water. The tank had been insulated by a fiberglass insulator to maintain constant water temperature water. The system holder had been integrated with an orientation mechanism consisting of ball bearing and two different dimensions of wood plates. The first plate was fixed while the other was mobile by a ball bearing, as shown in **Fig. 3**.



Figure 3. Manual orientation mechanism and holder structure.

The whole process is entirely automatic without the need for human intervention. The MPPT controller had been wired following to wiring order, as shown in **Fig. 4**.

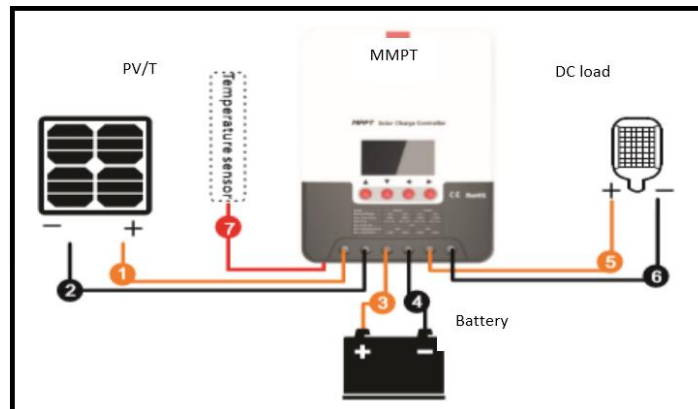


Figure 4. Wiring diagram of the electrical circuit.

2.2 Controlling System and Sensors

Arduino kit proved to be an effective tool for monitoring and controlling the system's electrical parts employed by researchers with similar solar systems (Kadhim and Aljubury, 2020). The Arduino board was placed inside the plastic box and linked with all sensors used to take the PVT hybrid water collector's performance data. The measured data had been saved directly by the use of an attached Micro SD Card Reader Module. A 16x4 LCD module blue backlight had been connected with Arduino to display the main parameters, flow rate, solar radiation, and absorber plate temperature values.

Temperature sensors were used to measure input and output temperature of water in the serpentine pipe and measure the temperature of the absorber plate of PVT collector using five sensors, distributed it like a cross (X) shown in Fig. 5. The sealed digital temperature probe lets us precisely measure temperatures in wet and dry environments with a simple 1-wire interface every 3 min.

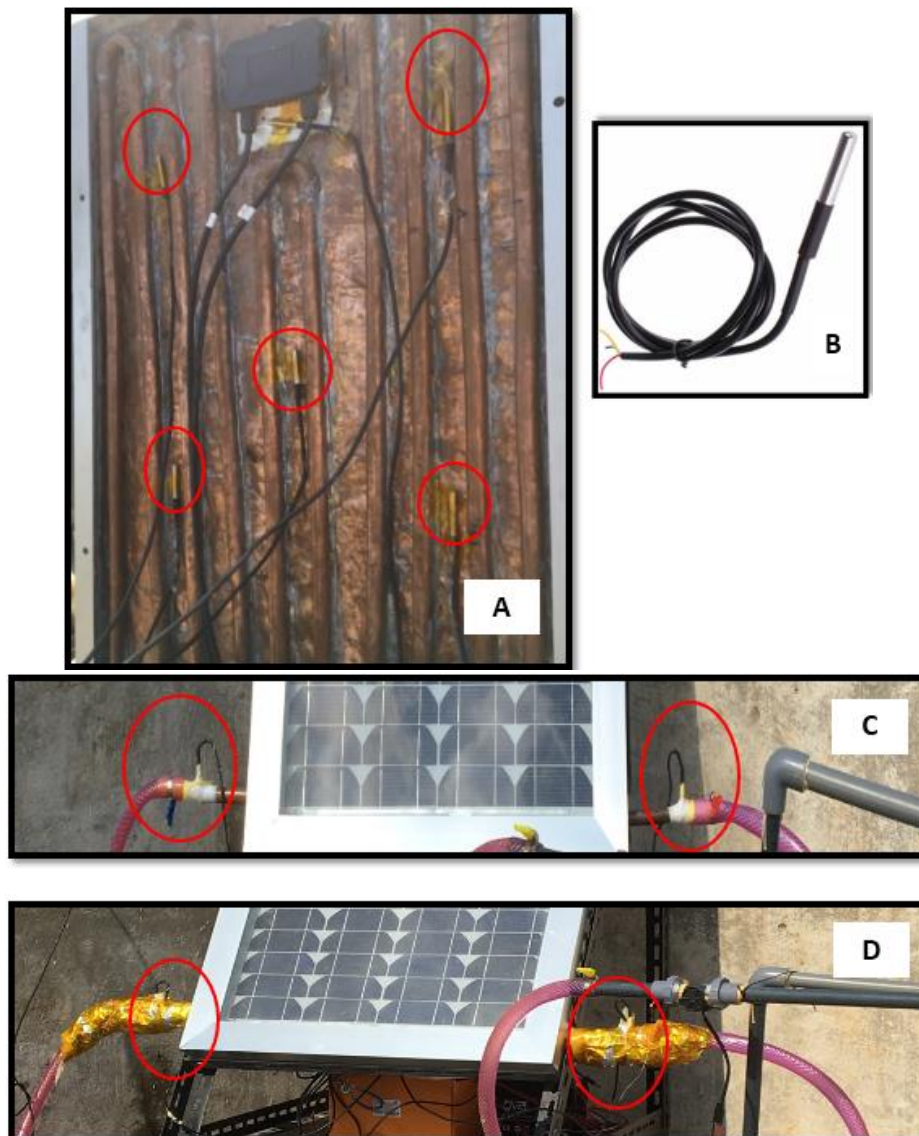


Figure 5. A) Installing the heat sensors under the absorber plate. B) Heat Sensor. C) and D) Installing the heat sensors on the water copper pipe.



Humidity and ambient temperature sensor were placed near the PVT hybrid collector in a shaded area to measure and record ambient temperature and humidity. A pinwheel sensor had been attached to the water line to measure water flow rate flooding into the system. Besides that, two light sensors had used to measure the intense solar radiation with a wide range and high resolution. The PV panel's current and voltage were measured using two sensors at different times with different solar radiation and water flow rate values. Measurements of current and voltage obtained when connected DC load (LED Lights).

2.3 Experimental Procedure

Unglazed and Glazed PVT water collector for different flow rates 0 – 3 L/ min. (no flow, laminar and turbulent flow) had been studied in the following cases.

Case I: Winter Weather

At different solar radiation levels (200, 400, 600, 800, 1000, 1100 W/m²) in February 2019.

Case II: Summer Weather

At different solar radiation levels (200, 400, 600, 800, 1000, 1100 W/m²) in July 2019.

Case III: Average Weather

Hourly variation of solar radiation was from 8 am to 4 pm in March 2019.

The first two cases had been conducted by manipulating the solar radiation via the orientation mechanism for constant water flow rate. The orientation mechanism made it easy to deal with the system for measuring requirements and movements to maintain constant solar radiation until getting steady-state temperatures. This usually was conducted during the first and the second weeks of the specified month for unglazed experiments and the third and fourth weeks for glazed experiments. The transparent cover of glass is used to reduce the convection and radiation heat losses. For the third case, fixed orientation facing south was adopted with a tilt angle of 45°. The measurements lasted from 8 am to 4 pm with the variation of flow rate. The same arrangement of unglazed and glazed experiments followed in terms of operation weeks.

Outdoor experiments were conducted at Bagdad / Iraq in the specified months at a 16 m high building roof at latitude 33.3° North and 44.3° East. For the unglazed collector, the water flow rate was sated on a certain value of 0.2 L/min by the control valve. Solar radiation was fixed on a certain value of 200W by manual orientation mechanism. The value of flow rate and solar radiation kept constant for a certain time (transient period) until the absorber plate temperature reached a steady state. After that, the solar radiation was raised to a value of 400W by the manual orientation mechanism under the same value of water flow rate until the absorber plate temperature reaches a steady state. The process continued for all solar radiation levels from 200W to 1100 W with the same value of water flow rate 0.2 L/min and repeated for a flow rate of 0.4 L/min and beyond reaching flow rate value of 3 L/min.

All valves had been closed in no water flow, and the remaining water in the serpentine pipe had been drained. For the glazed collector, the same unglazed collector procedure was followed after installing a glass cover above the PV model.



2.4 Theoretical Definitions

Reynold number can be expressed as follows:

$$Re = \frac{4 \times \dot{m}}{\pi \times D_i \times \mu} \tag{1}$$

Where \dot{m} can be calculated as:

$$\dot{m} = \frac{\rho \times v_p}{60000} \tag{2}$$

D_i is the pipe's inner diameter, v_p is the water velocity, ρ is density, and μ is viscosity.

The thermal efficiency (η_{thE}) of the flat plate hybrid solar collector calculated using the following formulae as shown in the equation below (Hossain, et al., 2019, Duffie and Beckman, 2013):

$$\eta_{thE} = \frac{E_{th}}{E_{in}} \times 100 \tag{3}$$

Where E_{th} is the thermal gain, and E_{in} is the inlet energy.

The useful thermal gain (E_{th}) of a PV/T collector is:

$$E_{th} = \dot{Q}_u = \dot{m} C_p (T_{out} - T_{in}) \tag{4}$$

PV energy efficiency (η_{pvE}) is the percentage of PV power converted and collected and can be calculated as:

$$\eta_{pvE} = \frac{E_{pv}}{A \times G} \times 100 \tag{5}$$

The electrical gain or PV power output (E_{pv}) of a PV/T collector is:

$$E_{pv} = I \times V \tag{6}$$

The performance of a PVT hybrid collector can be depicted by the combination of efficiency expression, which comprises the electrical efficiency η_{pvE} and the thermal efficiency η_{thE} . It usually includes the ratio of the electrical gain and useful thermal gain of the system to the incident solar radiation on the collector within a specific time. The overall efficiency (η_{ovE}) used to evaluate the overall efficiency of the PVT hybrid collector (Hossain, et al., 2019, Duffie and Beckman, 2013):

$$\eta_{ovE} = \eta_{thE} + \eta_{pvE} \tag{7}$$

3. RESULTS and DISCUSSION

3.1 Efficiency for Cases I and II (Thermal, Electrical, and Overall)

3.1.1 Thermal efficiency η_{thE}

With low sensitivity to the increase of solar radiation, thermal efficiency increased in linear proportional with laminar water flow rate, as presented in Fig. 6 and 7 for both cases. For the turbulent flow regime, thermal efficiency increased slightly with the increase of solar radiation increase due to low water temperature rise (ΔT). The higher thermal efficiency was obtained for the glazed collector for case I as shown in Figure 6. The thermal efficiency was 57.1% and 53.7% for a glazed and unglazed collector, respectively, at solar radiation of 1100 W/m² and Reynold number of 1800. On the other hand, for case II, The thermal efficiency was 52.6% and 51.5% for the glazed and unglazed collector, respectively, at 1100 w/m² of solar radiation and Reynold



number of 2300 as it can be seen in **Fig. 7**. At Reynold number value of 1800, thermal efficiency has risen from 44.3 % to 52.6% as solar radiation increased from 200 W/m² to 1100 W/m² for the glazed collector.

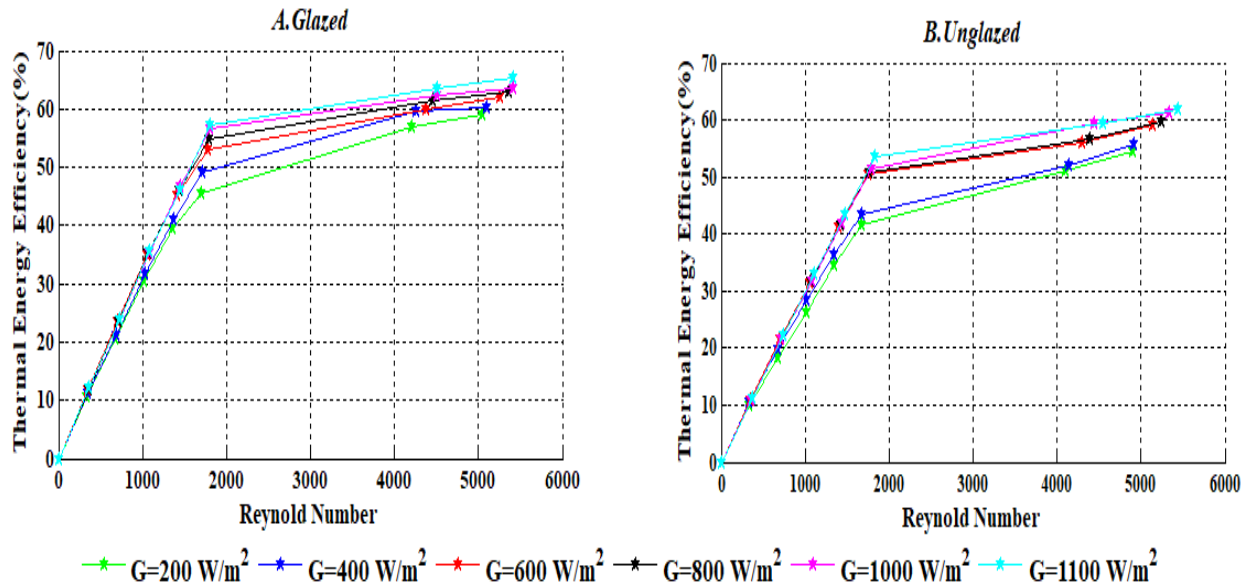


Figure 6. Changes in the thermal energy efficiency of PVT hybrid water collector with the Reynold No. under different solar irradiation levels for February.

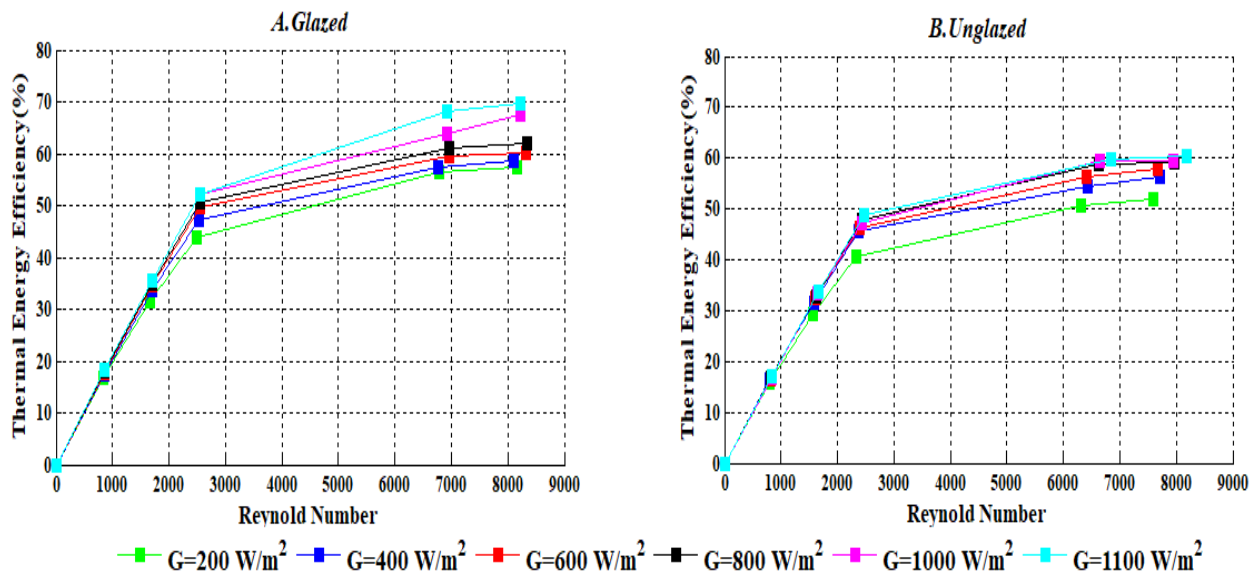


Figure 7. Changes in the thermal energy efficiency of PVT hybrid water collector with the Reynold No. under different solar irradiation levels for July.

3.1.2 Electrical efficiency η_{pvE}



For the laminar regime, electrical efficiency sensitivity increased with the increase of solar radiation for both glazed and unglazed collectors for both cases, as shown in **Fig. 8 and 9**. The behavior seemed to be identical in terms of pattern and recorded values for glazed and unglazed collectors for case I, as shown in **Fig. 8**. On the other hand, as the Reynold number increased, no significant increase in electrical efficiency was noticed. At 1100 W/m² of solar radiation, electrical efficiency changes from 8.4% to 9.8% as the Reynold number varies from 0 to 5500 for the unglazed collector. July measurements were presented in **Fig. 9**. The unglazed collector was scored higher efficiency than a glazed collector. At 1100 W/m² solar radiation, electrical efficiency varied from 8.3% to 9.7% as Reynold number changed from 0 to 8000 for the unglazed collector.

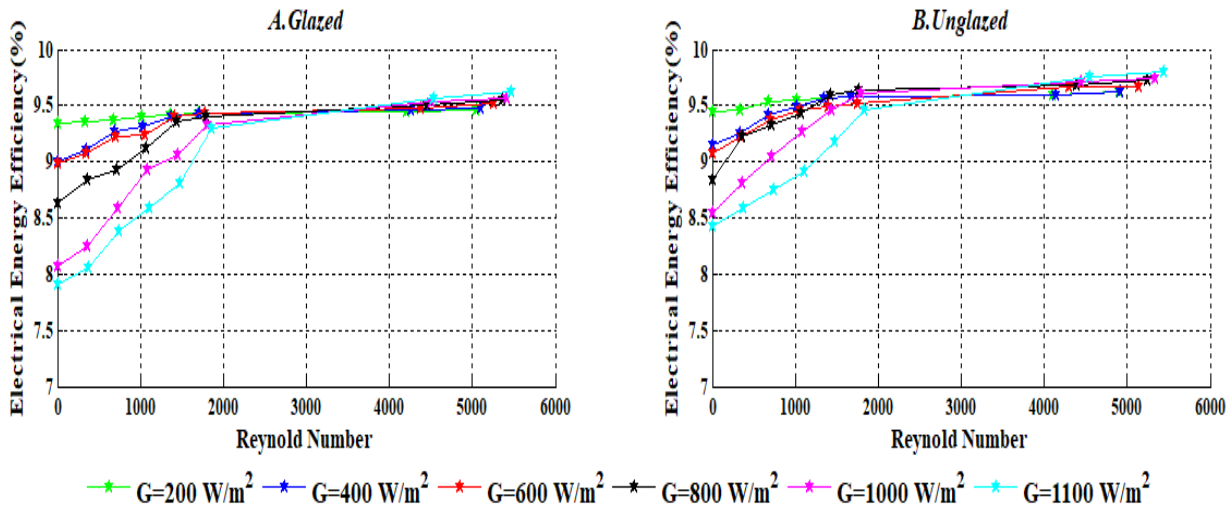


Figure 8. Changes in the electrical energy efficiency of PVT hybrid water collector with the Reynold No. under different solar irradiation levels in February.

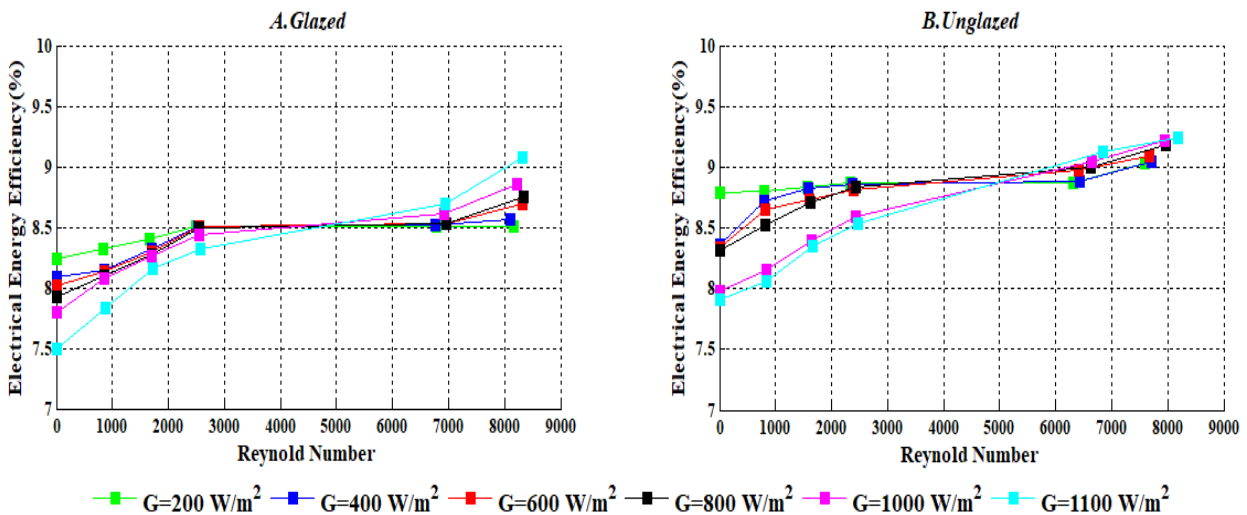


Figure 9. Changes in the electrical energy efficiency of PVT hybrid water collector with the Reynold No. under different solar irradiation levels in July.

3.1.3 Overall Efficiency η_{ovE}



Overall efficiency had the same profile as the profile of thermal energy efficiency for both cases, as presented in Fig. 10 and 11. While in terms of recorded values, overall efficiency was higher than electrical efficiency, with a percent of 10%. Consequently, for February, glazed collector overall efficiency was higher with a maximum total efficiency of 74.89% comparing with 71.76% for unglazed collector under solar irradiation of 1100 W/m² and maximum flow rate as can be concluded from Fig. 10. The same behavior was noticed for July measurements, as indicated in Fig. 11. Maximum total efficiencies of 79 % and 69.5 % for glazed and unglazed collectors were recorded for higher solar irradiation and flow rate values.

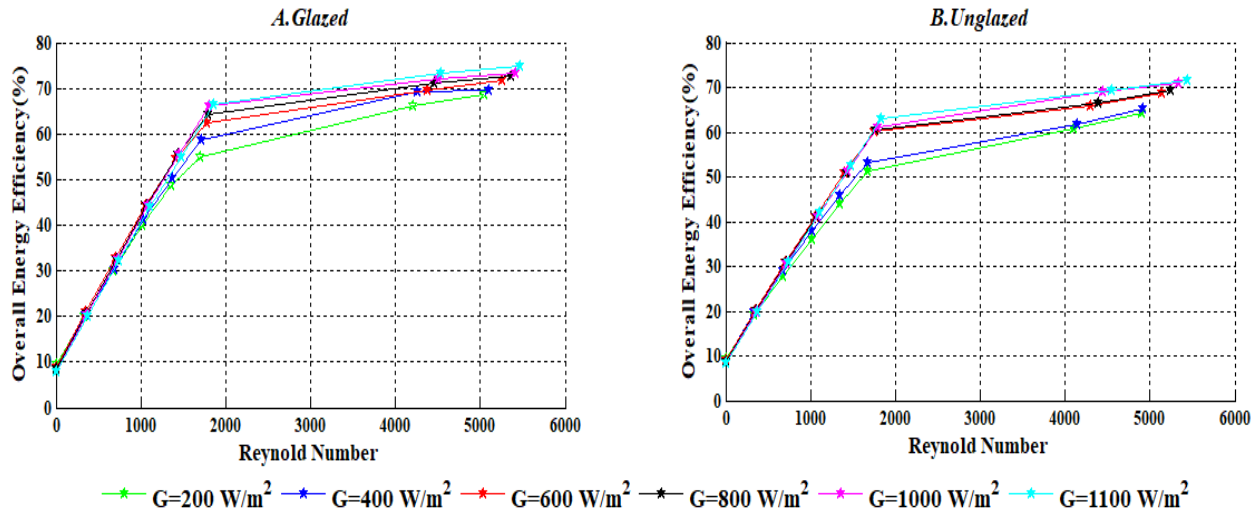


Figure 10. Changes in the overall energy efficiency of PVT hybrid water collector with the Reynold No. under different solar irradiation levels for February.

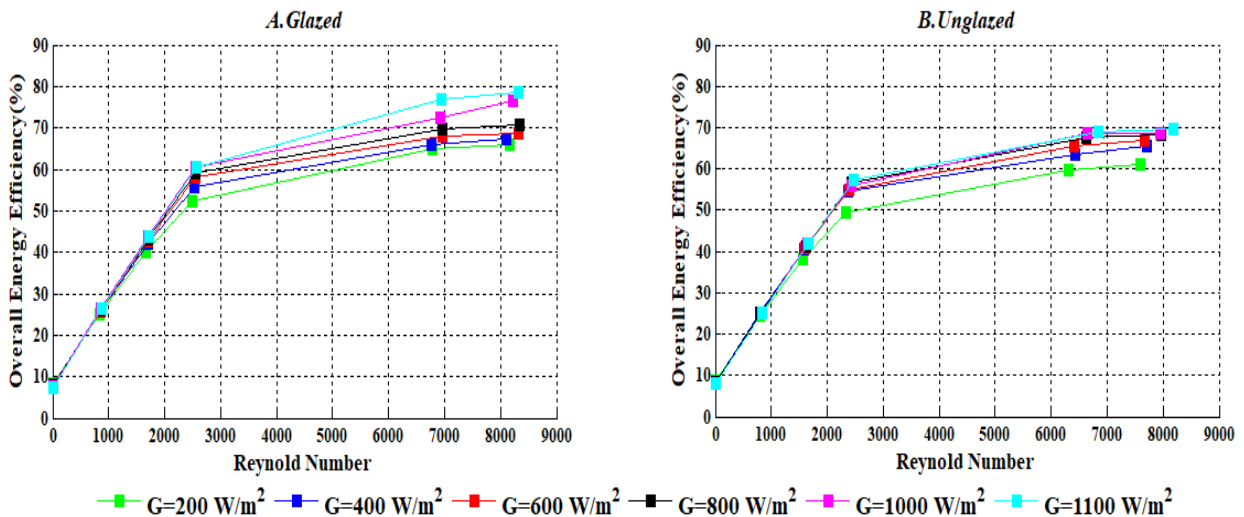


Figure 11. Changes in the overall energy efficiency of PVT hybrid water collector with the Reynold No. under different solar irradiation levels in July.

3.2 Efficiency for Case III (Thermal, Electrical, and Overall)

3.2.1 Thermal Efficiency η_{thE}



The thermal performance of the PVT hybrid solar collector evaluated for its thermal and PV performance with the derivation of the efficiency parameters based on the Hottel-Whillier equations. The thermal efficiency of the tested PVT is presented in **Fig. 12**. It can be noticed in the Figure that thermal efficiency increased with water flow rate increase for both laminar and turbulent regime while it had low sensitivity to solar radiation. In the turbulent flow regime, thermal efficiency was higher due to its high water flow rate. The thermal efficiency was 68% and 66.4% for glazed and unglazed collectors, respectively, at 1 pm and flow rate 3 L/min.

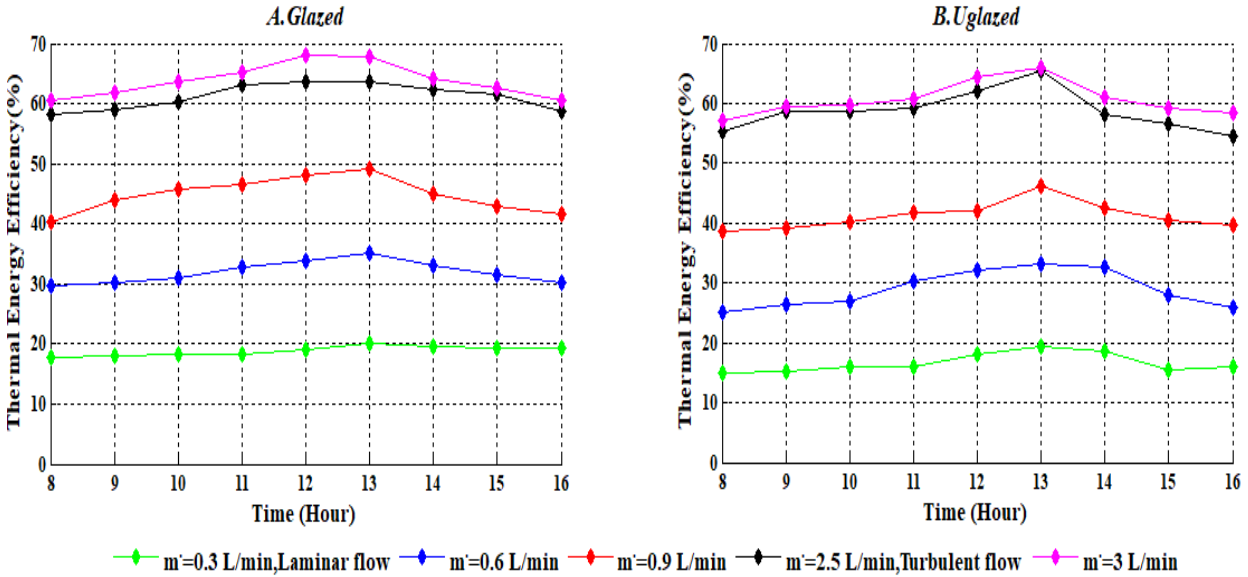


Figure 12. Changes in the thermal energy efficiency of PVT hybrid water collector with time under different water flow rates in March.

3.2.2 Electrical efficiency η_{pvE}

Electrical efficiency varied from 12.7% to 11.4% as solar radiation varied from 8 am to 4 pm at flow rate 3 L/min for the unglazed collector, as presented in **Fig. 13**, and it was almost constant concerning solar radiation. However, in the turbulent regime, somewhat higher sensitivity was noticed for solar radiation. The unglazed collector was better than a glazed collector.

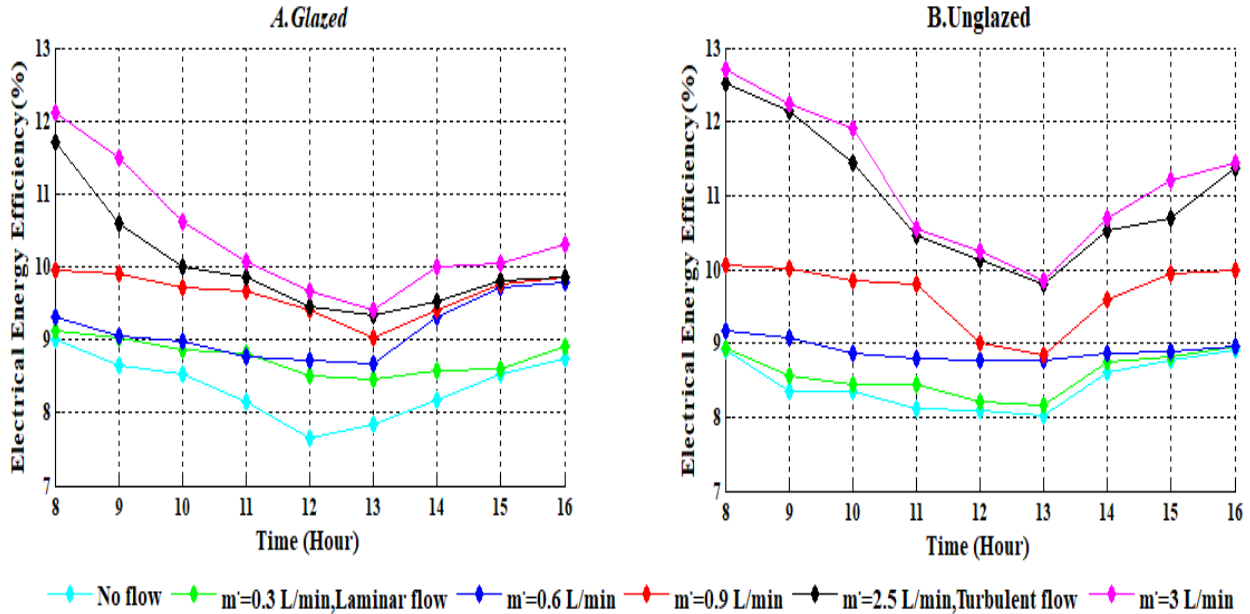


Figure 13. Changes in the electrical energy efficiency of PVT hybrid water collector with time under different water flow rates in March.

3.2.3 Overall efficiency η_{ovE}

Overall efficiency had the same profiles as the thermal energy efficiency profiles, as listed in Fig. 14 with an increment of 13% of electrical efficiency. Consequently, the glazed collector achieved better results than the unglazed one.

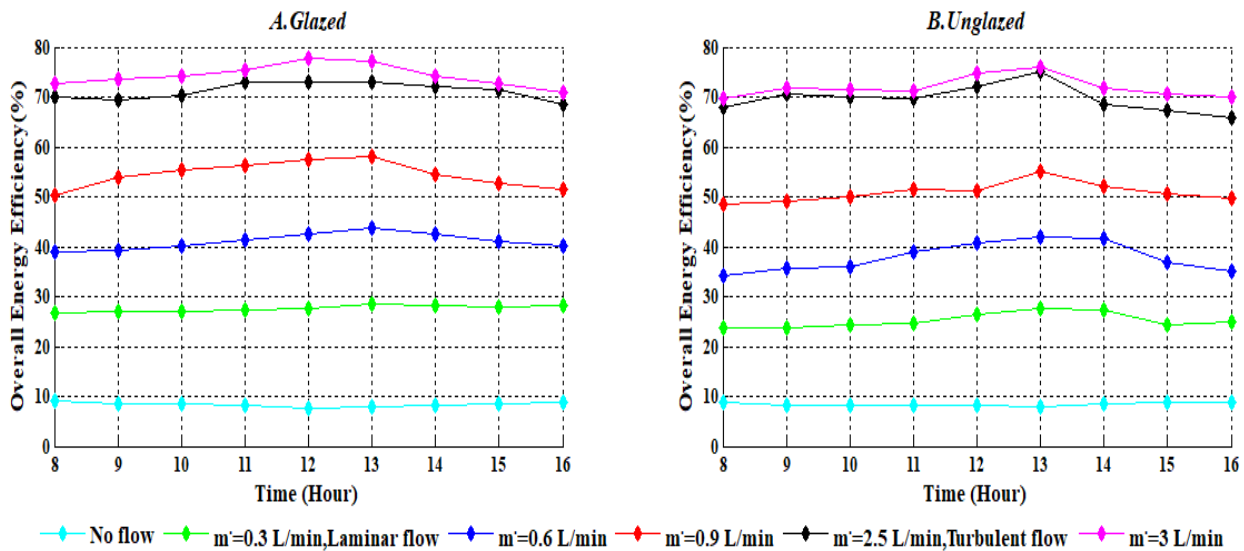


Figure 14. Changes in the overall energy efficiency of PVT hybrid water collector with time under different water flow rates in March.



Comparing to other researchers for the same field, (**Kazem, 2019**) achieved maximum electrical power gain by the PV/T collector around 67 W and average electrical efficiency 6% higher than the electrical efficiency of PV panel. A rectangular absorber shape with a direct flow had been used as the collector for the PV/T collector. On the other hand, investigated the energy performance of three types of PV/T water collector, namely web-flow absorber, direct flow absorber, and spiral flow absorber under 500 W/m^2 – 800 W/m^2 solar irradiation levels and water flow rates from 0.011 kg/s to 0.041 kg/s was accomplished by (**Fudholi, et al., 2014**). The results showed that the spiral flow absorber exhibited the highest performance at a water flow rate of 0.041 kg/s and solar irradiation level of 800 W/m^2 . This absorber produced an overall efficiency of 68.4%, electrical efficiency of 13.8%, and thermal efficiency of 54.6%.

Besides that, analyzing the heating system's energy performance combined with an unglazed PV/T water collector integrated on a building roof of an experimental house was conducted (**Kim and Kim, 2016**). The results showed that the system's thermal and electrical energy efficiency is 30% and 17%, respectively, and the heat load of heating water up to $40 \text{ }^\circ\text{C}$ had been dropped as the collected heat from the roof integrated PV/T was used to pre-heating the water.

Yet, The previous researches for PV/T water collectors vary from each other by different factors like the area of the PV panel used, the weather conditions, the used glass cover or its absence, and the results analysis type. Despite that, the results obtained from the current research seem promising and significant in using manufactured PVT hybrid collectors in terms of electrical, thermal, and overall energy gain. This led to innovating a new module with acceptable efficiency that can contribute to combining solar with thermal energies with new and modern information. On the other hand, investigating the behavior of such a system under Baghdad climate for different weather seasons had been successfully conducted. Other researchers can use the current research findings as a keystone for more studies and developments for these types of systems.

4 CONCLUSIONS

After analyzing the measured data from the current system, the findings indicated that the thermal and electrical gain of PVT hybrid collectors increased by the increase of solar irradiation. The average rise in PVT hybrid collectors' thermal energy efficiency with a glass cover for three cases was 5% compared with the unglazed PVT hybrid collector. Maximum total efficiencies of 79 % and 69.5 % for glazed and unglazed collectors recorded higher values of flow rate and solar irradiation for July. While for March, maximum thermal and electrical efficiencies were recorded at experimenting with 1 pm. It is also clear from the current work that the designed electrical and controlling system that integrated with the PVT system to measure, collect, and save the data was a practical approach. This system helped reduce human effort and minimize the required time of operating the system and monitoring it.

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