Performance Improvement of Bi-Fluid Photovoltaic /Trombe Wall Using Glass Cover and Porous Medium

Omer K. Ahmed[1], Khalaf I. Hamada[2], Abdulrazzaq M. Salih[3], Raid W. Daoud[4]
omerkalil@yahoo.com [1], hamada.khalaf9@gmail.com [2], abdulrazzaq.mohammed@st.tu.edu.iq [3], raid.daoud@gmail.com [4]
Northern Technical University- Hawija Technical Institute, Kirkuk, Iraq[1], Kirkuk Univirsity- College of Engineering, Kirkuk, Iraq [2], Tikrit University- College of Engineering, Tikrit, Iraq[3].

Abstract. This paper aims to improve the performance of a bi-fluid PV/TW system by fixing a glass cover on the front of a solar cell and inserting a porous medium within the air duct. Moreover, the influence of the DC fan and water flow rate through the cooling circuit was investigated. For this purpose, two experimental models of the bi-fluid PV/TW system were built up and tested under various operating conditions. The acquired results revealed that the room and solar cell temperatures were higher for the glazed configuration of the bi-fluid PV/TW system compared to the unglazed configuration. This is a favorable outcome for building conditioning in cold weather; however, it is an undesired consequence in terms of electricity generation. In addition, the presence of the glass cover leads to an increase in thermal efficiency and decreases electrical efficiency due to an increase in the temperature of the solar cell. It is also realized that an increase in water flow rate and using DC fan lead to increase thermal and electrical efficiencies. The maximum values of thermal and electrical efficiencies were 76.76% and 13.69% for the glazed and unglazed models, respectively, with porous medium and DC fan at 300 liters/day of cooling water discharge. While the maximum value of total efficiency was 87.44% for the glazed model, with porous medium and DC fan at 300 liters/day of cooling water discharge.

Keywords: Photovoltaic/Trombe wall, Porous medium, glass cover, Performance, Improvement.

1 Introduction

The use of solar energy takes a great deal of attention in the energy programs of different countries[1]. Rapid depletion of fossil fuels and the combined crisis of pollution and of the steep rise in oil prices has brought about an upsurge of interest in solar energy[2]. On the other hand, the practical applications of solar energy are not free from problems[3]. Solar energy is not available at night or during periods when the local weather conditions obscure the sun. Moreover, solar energy is diffused in nature. It is a time-dependent energy resource. Energy need for a variety of application are also time-dependent, but differently than solar energy[4]. Consequently, if solar energy is to be economically competitive it must be converted into a usable form of energy with maximum effectiveness[5][6]. Over the years ago, several passive and active technologies have been developed to convert solar energy into a useful form. One of the passive techniques, which has been considered

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for building conditioning, is the Trombe wall [7]. This wall consists of a wall of concrete or bricks for heat storage and the wall is coated with black paint to increase absorption of solar radiation. There are layers of glass at 5–10 cm distance from the concrete wall to increase the absorbed solar radiation[8]. The design of the Photovoltaic/ Trombe wall is presented in **Figure 1** [9]. The use of solar energy to generate electricity using solar cells is one of the most important applications now. However, the disadvantage of these cells is the elevated temperature, especially in the hot sunny climate, which leads to a decrease in efficiency[10]. Several studies have been conducted in recent years to develop and improve the performance of the PV/TW system[9][11][12]. Ji et al.[13] studied the effect of the air vent on the performance of the PV/TW system. Sun et al.[14] concluded that the thermal efficiency of PV/TW was influenced by south-south design through numerical simulation. Hu et al.[15] implemented three PV/TW models practically. The work targeted the inclination angle and the airflow rate and proposed certain factors for the PV/Blind TW type. Another similar study was carried out by Su et al.[16], in which the aspect ratio was carefully studied for the Trombe wall. In addition from [17], authors investigated various glazing configurations aimed in reducing the CO_2 emission. The results showed in this work that double glass filled with argon outperformed other structures. In [18] introduced porous medium to improve the performance of a PV/TW system. The results were revealed that the room temperature increases and the temperature of PV cell reduce in presence of porous medium and DC fan. Also, about 13% and 4% increment were recorded in thermal and electrical efficiencies of the system, respectively, in presence of porous medium with DC fan. The optimum thickness of the PV/TW system was recommended to be 0.3-0.4 m for thermal heating under the decrement factor about zero and thermal load leveling of 0.01 as mentioned by Taffesse et al. [19].

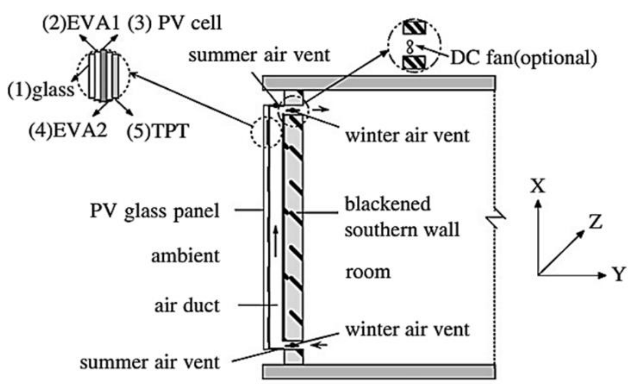


Fig. 1. Basic geometry of PV-Trombe wall including DC fan [12]

An improved design of a photovoltaic/Trombe wall (PV/TW) system was introduced by Ahmed et al. [20]. In this design, a bi-fluid (water and air) was used to cool the solar cell. Prashant et al. [21] presented a mathematical and experimental investigation of a porous medium effect on the performance of glazed double-pass air solar heater. The results confirmed the thermal efficiency of the system increased by 10-12 % in the system with a porous medium than the system without a porous medium. Also, Ahmed et al. [22] presented a practical study on operation performance of the porous medium for PV/solar collector. Ahmed and Bawa [23] used reflective mirrors to improve the performance of hybrid PV/T solar collectors operating under Iraqi airspace. The results of this article confirmed the increase in the total daily efficiency of the system to reach the highest value of 81.03 % when using reflective mirrors.

In present work, an improvement of the bi-fluid PV/TW system by using both the glass cover and porous medium was investigated. Moreover, the influence of the cooling water flow rate on the system performance with and without DC fan was studied. System performance was evaluated in terms of thermal and electrical characteristics.

2 Methodology

The Middle East region, especially Iraq, is characterized by hot weather with high solar radiation and long periods of sunshine. Under such circumstances, the temperature of PV cells is increasing which decreases its conversion efficiency. In this context, many studies have been conducted in recent periods to increase the efficiency of PV/thermal systems. The porous medium is one of the most important methods to increase the rate of heat transfer in the thermal system due to large surface area of heat transfer. The present article aims to use the porous medium (glass pellets) to improve and increase the efficiency of the PV/Trombe wall. Also, this article investigates the operational and design factors affecting the performance of a bi-fluid PV/Trombe wall system in hot climates.

3 Experimental Set-up

Testbed was built to reveal the effect of porous medium as well as the climatic conditions on the operational performance of the bi-fluid PV/TW system. The work carried out in Kirkuk, Iraq. Experimental measurements were recorded from 9 am to 7 pm. The tested rooms with height 2m, and 1.25m width were made of insulating panels, which has good thermal insulation. Solar panel was placed on the southern face to achieve optimum solar radiation as shown in **Figure 2**. The specifications of the employed solar cells are given in Table 1.

(a) Glazed model (b) Un-glazed model

Fig. 2. Photographic images of laboratory models

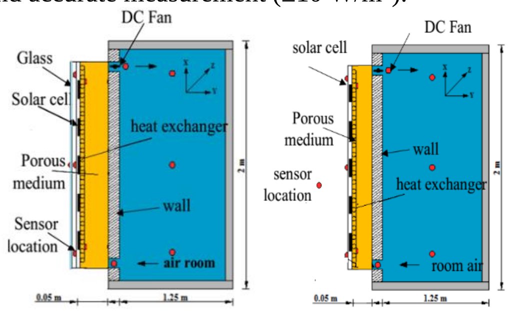
The present work investigates two formations of PV/TW model. Glass cover of 6 mm thick is applied on the first one at the front side as shown in Fig.3-a. The glass cover was installed at 3 cm away from the solar cell. The white silicon was used to mount the glass cover, which ensures a completely isolated Trombe-wall, and prevents the outside air from entering inside. The glass cover protects the solar cell from weather conditions such as rain and dust. A serpentine heat exchanger was attached to the backplate of the solar cell, which was followed by an air duct than a massive wall. The second configuration is similar to the first configuration without a glass cover on the front side as shown in Fig.3-b. Several modifications and setting were applied for cooling oil and DC fan. Low-cost DC fans work at low voltage were chosen for air circulation. For each PV/TW system, two DC fans were used to pull the air to the duct. The porous structure and its position is presented in Fig. 3. The porous medium is glass balls characterized by 15.98 mm diameter and of 0.78 W/m. K thermal conductivity [24]. The porosity of the porous medium was equal to 0.437. The dimensions of the air duct in both models are 2 m height, 0.68 m width, and 0.05 m thickness.

Table 1. Required data for experimental models

Parameters	**Values**	**Parameters**	**Values**
Room Height (m)	2	Maximum Power at STC (W)	150
Room width (m)	1.25	Maximum Power voltage (V)	17.9
Room depth (m)	1.25	Maximum Power Current (A)	8.38
Glass length (m)	1.48	Open Circuit Voltage (V)	22.4
Air duct width (m)	0.05	Short Circuit Current (A)	8.81
Length of water pipe (m)	11.34	Operating Temperature (^{o}C)	25
Number of cycles of water pipe	21	Operating Radiation (W/m^2)	1000
Diameter of the inner water pipe (m)	0.004	Tolerance	± 3%
Diameter of the outer water pipe (m)	0.005	Cell Type	Polycrystalline
Distance between tube rolls (m)	0.046	Standard Packaging	20 pcs

Thickness of the glass cover (m)	0.006	Size m^3	1.48 × 0.68 × 0.035

The heat exchanger was implemented into the rear of solar cell on a plate of Aluminum. Copper pipes with a diameter of 5 mm and a length of 11.34 m were utilized to shape a serpentine configuration of the heat exchanger. Twelve thermometers were used to measure temperatures at designated locations for each test room as shown in **Figure 3** (a and b). Various thermometers (six in total) were employed to get the suitable readings all over the system model. Each thermometer has its own digital LCD for monitoring and reading. These thermometers are characterized by an accuracy level of ±1°C. To measure the intensity of the solar radiation falling on the surface of the PV/TW system, the solar meter (model SM206) was employed. This device is characterized by its low weight, convenient and accurate measurement (±10 W/m^2).



(a) With glass cover (b) Without glass cover

Fig. 3. The details of the test set-up

The generated voltage and current by solar cells were measured using a digital multi-meter device has an accuracy of ± 0.5%. Three DC lamps (21-watt, 24-volt) were representing the load of the solar model. These lamps were chosen to suit the output voltage from the solar cell; however, two DC fans were also used as load. **Figure 4**. The volumetric method was applied to achieve the WF through the cooling circuit of a solar cell. A graduated container and stopwatch were used to measure the WFR. The flow rate was measured every 30 minutes during experimental tests to ensure that there is no fluctuation in water flow. Three flow rates of water (100, 200, and 300) L/day were considered.

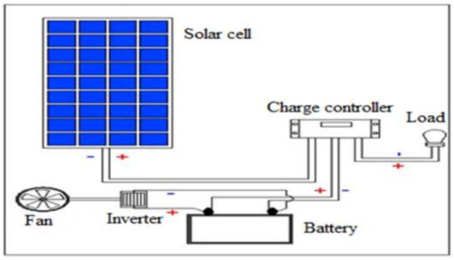


Fig. 4. Details of the solar cell electrical circuit and its accessories

4 Performance calculations

The properties of the working fluid (air and water) are varied due to the influence of the temperature change. Table (2) illustrates the equations governing water properties, which will be relied upon in the present study. The reference[25] was used to determine air properties.

Table 2. Variation of water properties with the temperature

Density (kg/m^3)	ρ_w =1000-0.0178[T-277]$^{1.7}$
Viscosity (kg/ms)	μ_w = 1.788*10^{-3}exp (-1.704 - (1448.5/ T) + (521926.58 / T ^{2}))
Thermal conductivity W/mK	K_w = -8.01 *10^{-6} (T – 273)^2+1.94*10^{-3}(T-273)+0.536
Specific heat (J/kgK)	c_w = 4.1855x10^3[0.966185+0.0002874 ((T-173)/100)$^{5.26}$]

The instantaneous thermal efficiency of the system (without solar cell cooling by water) can be calculated as follows[26]:

$$\eta_{the}=\frac{\dot{m}_{air}Cp_{air}(T_{air,out}-T_{air,in})}{I_{total}\cdot A_{cell}} \tag{1}$$

Where, $\dot{m}_{air}$ is the mass flow rate of the air given as:

$$\dot{m}_{air}=\rho_{air}.A_d.V_{air} \tag{2}$$

V_{air} is the air velocity inside the air duct and evaluated according to the following cases:

- Natural convection, the air moves without a fan, and under the influence of changing the density, the air velocity was calculated from[18]:

$$V_{air}=\sqrt{\frac{0.5.g.\bar{\beta}.H.(T_{fa.out}-T_{fa.in})}{C_{fr}\frac{H}{D_H}+\frac{C_{losin}\cdot A_d^2}{A_{in}^2}+\frac{C_{losout}\cdot A_d^2}{A_{out}^2}}} \tag{3}$$

C_{losout} and C_{losin} are coefficients addressed by [27], C_{fr} is coefficient of friction calculated using [28].

- Forced convection (The air is moved by a fan), the air velocity was calculated from[18]:

$$V_{air}=C_{fan}.I_{total} \tag{4}$$

Whereas C_{fan} is 0.0006 J/m^3 based on [29]. Thermal efficiency is calculated from the following equation:

$$\eta_{the,\ total}=\frac{\dot{m}_{air}Cp_{air}(T_{air,out}-T_{air,in})+\dot{m}_{water}Cp_{water}(T_{water,out}-T_{water,in})}{I_{total}.A_{cell}} \quad (5)$$

The electric power is evaluated from [30]:

$$P_{electrical} = V.I - P_{consumed} \quad (6)$$

The electrical efficiency form the relation [31]:

$$\eta_e = \frac{P_{electrical}}{I_{total}.A_{cell}} \quad (7)$$

The overall efficiency from [32]:

$$\eta_{overall} = \eta_e + \eta_{the,total} \quad (8)$$

The overall heat loss (Q_{loss}) can be calculated from the following set of equations:

$$Q_{loss} = Q_{in} - V.I - Q_{air} - Q_{water} \quad (9)$$

$$Q_{in} = G.A_c \quad (10)$$

$$Q_{air} = \dot{m}_a Cp_{air}(T_{a,out} - T_{a,in}) \quad (11)$$

$$Q_{water} = \dot{m}_w cp_{water}(T_{w,out} - T_{w,in}) \quad (12)$$

5 Results and Discussions

The results of the tests were compared experimentally for different weather cases. Experiments using a porous medium with solar cell cooling by water were carried out at different rates of water flow. The tests were carried out in January 2018 in clear weather at a water flow rate of (100, 200, and 300) Liter/day with and without DC fan. This study dealt with the following cases:

1- Unglazed Bi-fluid Photovoltaic/Trombe wall without a fan and with porous medium under various water discharge (100 liter/day, 200 liter/day, and 300 liter/day).

2- Unglazed Bi-fluid Photovoltaic/Trombe wall with fan and with porous medium under various water discharge (100 liter/day, 200 liter/day, and 300 liter/day).

3- Glazed Bi-fluid Photovoltaic/Trombe wall without a fan and porous medium under various water discharge (100 liter/day, 200 liter/day, and 300 liter/day).

4- Glazed Bi-fluid Photovoltaic/Trombe wall with fan and without porous medium under various water discharge (100 liter/day, 200 liter/day, and 300 liter/day).

5.1 Porous effect on unglazed Bi-fluid PV/TW model

The results presented in this subsection focus on the operational of the PV/TW without a glass cover. **Figures 5 and 6** demonstrate the effect of the porous medium and water discharge against the use of DC fan. It is noted that the presence of the porous medium in the air duct significantly reduces the temperature of the solar cell. This is because of the heat rate increased on the rear surface of the solar cell for moving air through the duct. The highest temperature of the cell recorded in Fig. 5 was 65 °C at water discharge 100 liter/day and without a porous medium. While in Fig. 6, the highest temperature was 56 °C for the same operating conditions. In general, cell temperature increased to max value at 1 p.m. and then decreases thereafter due to decreasing solar radiation values and increased thermal losses. Also, the presence of the DC fan reduces the temperature of the solar cell due to increasing airflow through the duct. So, the fan cools the solar cell surface, similar to work in [18][33].

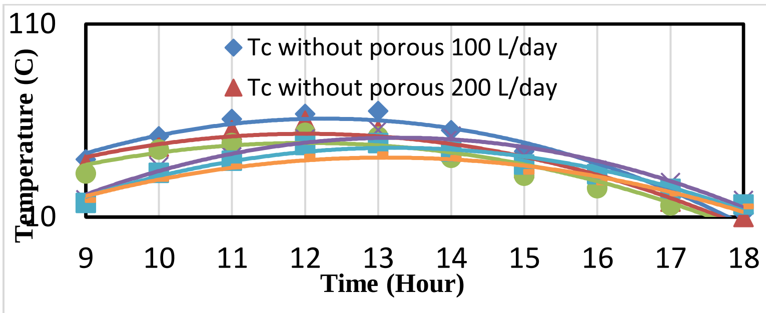


Fig. 5. Porous medium on solar cell temperature for various water flow rate (Without DC fan)

A significant decrease in cell temperature is also observed as the rate of cooling water increases. Where the lowest value of cell temperature was recorded at a flow rate of 300 liters per day and the presence of the porous medium as shown in **Figures 5 and 6**. It is found that the porous and bi-fluid cooling reduce the solar cell temperature significantly and this corresponds to the results of published works [22][34].

Figures 7 and 8 reveal the use of porous medium without/with DC fan. In Figure 7, the highest temperature difference was (19.3 oC) at 100 liters/Day and in the absence of a porous medium. While the lowest difference was (9 °C) at 300 liter/day with the presence of a porous medium. It is also noted that, when comparing **Figures 7 and 8**, the DC fan reduces the difference in water temperature. Where the values of the water temperature differences in presence of DC fan were lower than their values in the absence of DC fan. This reduces the amount of heat transferred to the cooling water as the large portion of heat is conveyed by air circulated by DC fan.

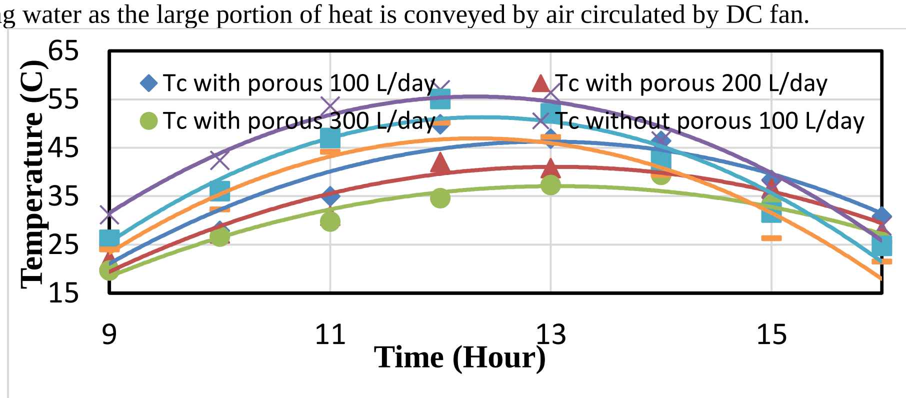


Fig. 6. Porous effects on solar cell temperature for various WFR (With DC fan)

Also, porous decreases the amount of heat transferred to the water. This trend is due to the absorption of part of heat by the glass pellets and converted to heat stored inside the porous medium, which can be utilized at night for heating similar to results in [35][36-38].

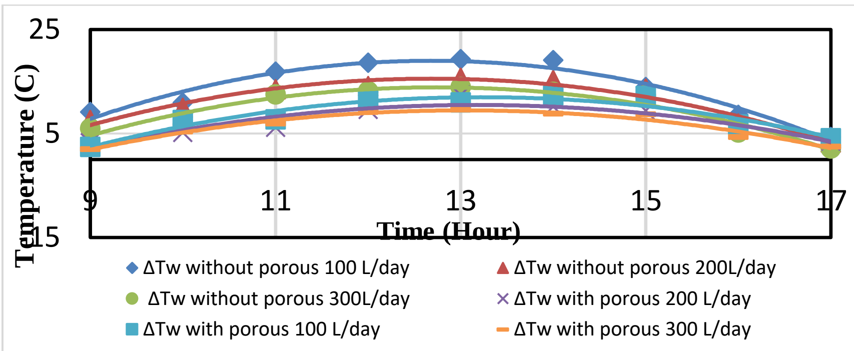


Fig.7. Porous effects on the water temperature difference for various WFR (without DC fan)

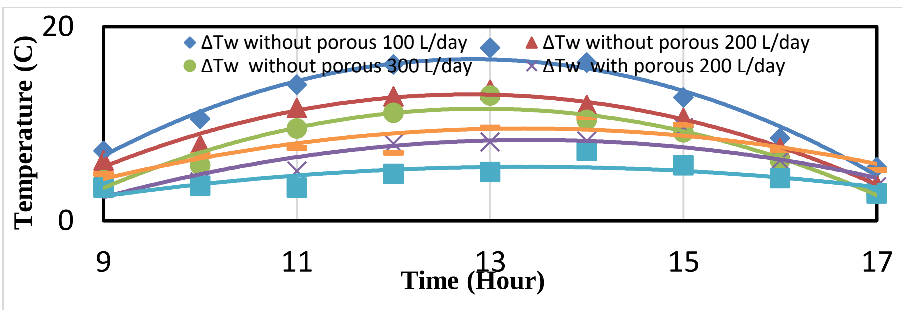


Fig.8. Effect of porous medium on the water temperature difference for various WFR (with DC fan)

Space conditioning by replacing its southern façade by the Trombe wall is the main purpose of using this technology. Therefore, the room temperature is usually used as an indicator to reveal the influence of operational variables on system performance. **Figures 9 and 10** represent room temperature change during the day for various operational situations. In general, it is noted that the change of room temperature follows the change of solar radiation; it rises from morning hours to 1 p.m. and then starts declining after that. As well as, it turns out that the DC fan effect is relatively low on room temperature. The highest recorded room temperatures were 35 °C and 33.5 °C in cases with and without DC fan, respectively, under the same operational conditions. It is also noted that the presence of a porous medium has a positive effect on room temperature. Where the higher room temperatures were recorded in cases with a porous medium due to increased heat transfer rate. Increasing the WFR in the heat exchanger yields to a decrease in room temperature due to the depletion of a large part of the energy to heat water. The results were confirmed by the achieved work in [18].

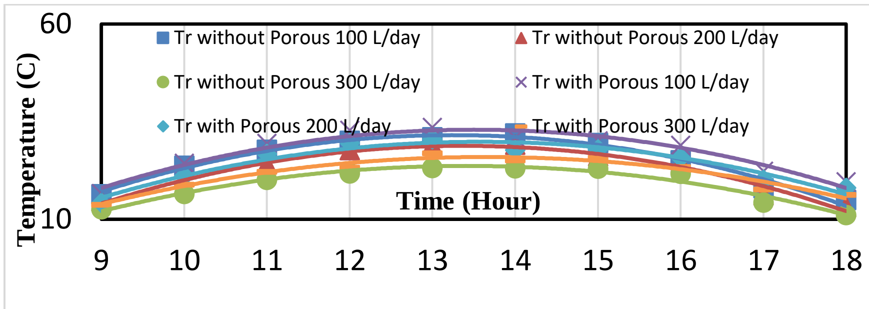


Fig. 9. Applying porous for various WFR (without DC fan)

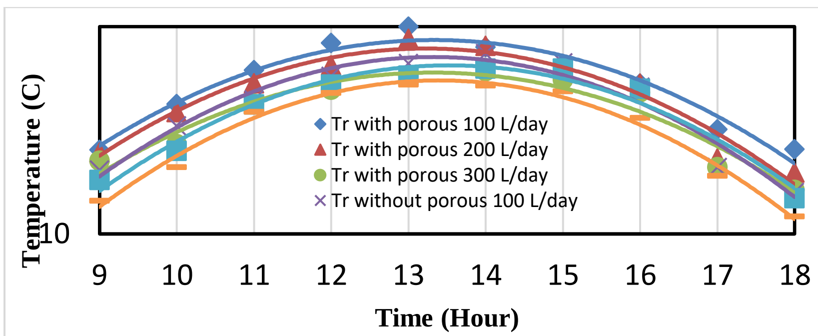


Fig. 10. Applying porous for various WFR (with DC fan)

5.3 Efficiency of the system:

Table 3 presents the efficiency of two models. The max glazed thermal efficiency was 76.76%, with water discharge of 300 liters/day by using DC fan. Whereas 13.69% was achieved for unglazed type. In addition, it is realized that an increase in WFR leads to an increase in thermal and electrical efficiencies, similar achievement to [39].

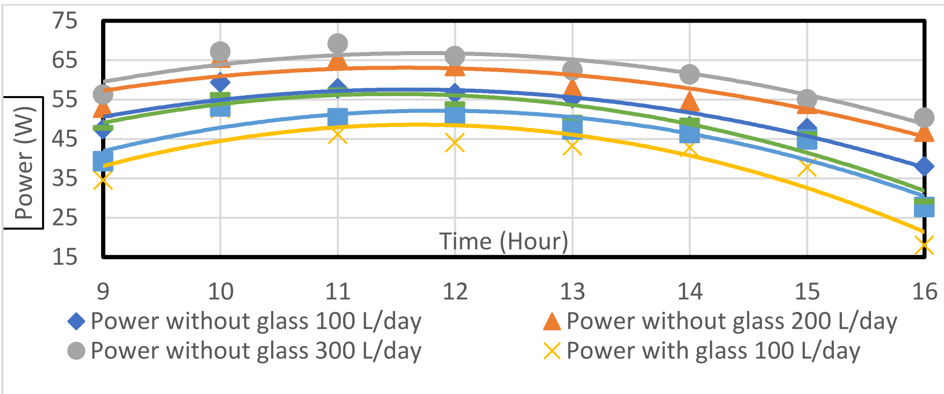


Fig. 20. Effect of glass cover on the EP for various WFR (With DC fan)

Moreover, it revealed that the presence of the glass cover improves the thermal and decreases electrical efficiencies. Therefore, glass cover was approved as a bad choice for electrical applications only [37]. The results also showed that the use of DC fan leads to an increase the thermal and electrical efficiencies of the system. This is due to an increase the rate of heat transfer from a solar cell to the circulated air by DC fan. Furthermore, the unglazed type is found lower than the glazed one due to the increase of thermal losses. Table 4 summarized these variations in which the max glazed efficiency was 87.44% that included a porous medium, cooled by the water flow rate of 300 liters/day, and used DC fan to circulate the air.

Table 3. Electrical and thermal efficiencies over time

Type	9 am.	10 am	11 am	12 am	1 pm	2 pm	3 pm	4 pm	Daily Efficiency
η_{th} (without Fan +100 L/day+Porous)	37.74	42.61	53.58	55.69	34.41	45.13	67.88	70.49	50.94
η_{th} (without Fan +200 L/day+Porous)	46.67	48.97	53.12	57.19	54.40	66.48	59.12	67.32	56.65
η_{th} (without Fan +300 L/day+Porous)	41.46	56.98	63.46	67.97	56.16	65.16	68.11	71.55	61.35
η_{ele} (without Fan +100 L/day+Porous)	15.62	13.92	9.57	8.30	9.01	12.31	15.94	14.95	12.45
η_{ele} (without Fan +200 L/day+Porous)	16.82	15.32	9.92	8.72	10.59	12.27	14.20	13.54	12.67
η_{ele} (without Fan +300 L/day+Porous)	17.43	16.61	11.44	10.09	10.49	11.30	12.58	13.38	12.91
η_{th} (with Fan +100 L/day+Porous)	45.49	50.42	54.27	40.23	47.91	58.21	67.63	65.32	53.68
η_{th} (with Fan +200 L/day+Porous)	43.03	52.5	64.11	54.08	56.65	58.08	69.66	73.54	58.95

Table 4. Total efficiency for different cases

Type	Daily Efficiency	Type	Daily Efficiency
η_{total} (without Fan +100 L/day+Porous)	63.39	η_{total} (without Fan + glass + 100 L/day+ Porous)	63.43
η_{total} (without Fan +200 L/day+Porous)	69.32	η_{total}(without Fan + glass + 200 L/day+ Porous)	79.27
η_{total} (without Fan +300 L/day+Porous)	74.26	η_{total} (without Fan + glass + 300 L/day+ Porous)	85.6
η_{total} (with Fan +100 L/day+Porous)	66.25	η_{total} (with Fan + glass + 100 L/day+ Porous)	78.47
η_{total} (with Fan +200 L/day+Porous)	72.1	η_{total}(with Fan + glass + 200 L/day+ Porous)	80.9
η_{total} (with Fan +300 L/day+Porous)	76.75	η_{total} (with Fan + glass + 300 L/day+ Porous)	87.44

6 Conclusions and recommendations

Experimental setups of glazed and unglazed configurations of the bi-fluid PV/TW has been presented with/without porous medium. This also included the study of flow rate of the cooling water with and without DC fan based on weather conditions of Kirkuk city. The presence of a porous medium with bi-fluid cooling (air and water together) in the PV/TW system has reduced solar cell temperature and improves electricity production. A positive effect on the room temperature was recorded by inserting a porous medium due to the increased heat transfer rate. However, the room temperature decreases as the flow rate of cooling water increases due to depleting a share of the energy to heat water. Even though, such a technique will provide extra heat absorbed by the glass pellets, which can be utilized at night for heating, as well as energy gain for domestic heating. On the other hand, the use of DC also increases in the produced electrical energy but also consumed power. It shows that Glazed configuration of the bi-fluid PV/TW system has advantages over the unglazed one in terms of thermal and total efficiencies including to minimizing system heat losses. This is an important and favorable effect for building conditioning in cold weather. Conversely, glazing configuration affects the bi-fluid PV/TW system since temperature increases into the solar cell. However, an increasing flow rate of cooling water reduces the glazing effect because of conveying extra heat to the water stream.

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