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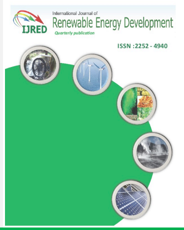

Research Article

Optimization of PV/T Solar Water Collector based on Fuzzy Logic Control

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ABSTRACT. Hybrid solar collector (PV/T) is designed to produce electricity, hot water, or hot air at the same time as they operate solar cells and solar heaters in one system. This system is designed to increase the electrical efficiency of solar cells by absorbing heat from these cells. The fuzzy logic (FL) is a tool usually used to optimize the operation of the systems. In this paper, the FL is to monitor and correct the main system parameters to remain optimization efficiency at a better level. Three affected variables were studied: Effect of reflective mirrors, the effect of the glass cover, and the effect of the lower reflector angle on the performance of the PV / T hybrid solar system. These three parameters are traveled to be inputs for the FL, and the PV temperature in addition to system efficiency is the output for it. The effect of solar radiation was found to have a great effect on the efficiency of the hybrid solar collector. The thermal efficiency was 82% for the given value of the PV and mirrors, while the efficiency down to 50 for another angle. By using the artificial intelligent the system behavior depends on its output, which called feedback close loop control, at a real-time process that optimizes the system efficiency and its output.

Keywords: Fuzzy logic, PV/T, Optimization.

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1. Introduction

Solar energy is the most important energies that man can exploit; because it is renewable energy and is not exhaustible and does not result in gases or by-products harmful to the environment compared to other sources of energy (Ahmed, 2016; Ahmed, 2017; Mohammadnezami *et al.*, 2015), and researchers have done a lot of research in this area and suggested many ways to develop and exploit this energy, like the reflective mirrors (Shahdost *et al.*, 2019) to collect solar light and other ways to absorb solar energy, such solar cells that enable us to obtain electricity directly from the sun (Ahmed and Mohammed, 2017a).

Hybrid solar collectors (PV/Thermal collectors) are assemblies that supply electricity, hot water, or hot air at the same time. It integrates the two systems, solar cells with solar heaters (Omer & Zala, 2018). This system is mainly designed to increase the electrical efficiency of solar cells by absorbing heat from these cells (Ahmed & Zala, 2017). The hybrid solar collectors operate on the same mechanism as the thermal collectors with the replacement of absorbing panels with the solar cell. It consists of the same components of the solar thermal collector and their parts: Solar cell, the aluminum plate, and the pipeline through which the cooling fluid passes in the case of water cooling, glass cover, and sometimes without glass cover and insulator). Several types of research and studies have been carried out to develop and improve the efficiency of these electrical and thermal systems. Many researchers have studied the improvement of the performance of hybrid solar collectors used for heating water (Ahmed and Bawa, 2019).

Chow (2003) studied the performance of the solar PV / T collector used to heat the water in a natural circulation system under variable conditions. The researcher found that using the cooling water system reduces the temperature of the solar cell. Zondag *et al.*, (2003) studied the effect of the glass cover on the performance of the hybrid solar collector. The researcher concluded that the electrical efficiency of the hybrid collector covered by the glass was 7.2%, while the hybrid collector without glass cover was 7.6%. Ozgoren *et al.*, (2013) investigated the effect of using water to cool the solar cell to improve its efficiency by using a mono-crystalline solar cell and a thermal absorption plate type (shell and tube). The optimal flow of water flow was (0.03 kg / s) for the system used. Jin *et al.*, (2013) presented a practical studied of the hybrid solar collector (PV/T) to heat the water and used a special design of the copper tubes and concluded that the electrical efficiency increases with increased solar radiation and increased water flow.

Baccoli *et al.*, (2015) presented the mathematical model of a flat solar collector connected to an external reflector at the bottom edge of the collector and determined the optimal slope of the collector and the reflector for each month. The research concluded that it

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achieves the best performance when the slope of both the collector and the reflector is tilted backward in winter and forward in the summer. Ghadiri *et al.*, (2015) used Fe_3O_4-water nanoparticles and concentrations ranging from 1% to 3% to improve the performance of the hybrid solar collector. The researchers found that the total efficiency of the hybrid solar collector when using Nanofluid increased by 3%. Tabet *et al.*, (2014) studied the effect of double mirrors on the performance of the hybrid solar collector used to heat the air in Algeria. The researchers presented a mathematical model to show the effect of mirrors on the performance of the hybrid collector. The study showed that overall efficiency improves with dual mirrors. Kostic & Pavlovic, (2015) studied the effect of four mirrors installed on the top, bottom, right, and left of a solar cell on the amount of solar radiation reaching it. The researcher used an analytical model to determine the optimal slope of the reflectors relative to the horizontal surface of the cell.

This article includes a practical study to improve and compare the performance of the hybrid solar collector used to heat water by constructing two practical models of hybrid solar collectors and studying the design and operational variables to demonstrate the optimal performance of these systems in the Middle East. The study focuses on increasing the efficiency of the solar cell by increasing the concentration of solar radiation using external mirrors. In addition to study the effect of the glass cover on the performance of the hybrid solar collector. The FL was used in this study to increase the power efficiency and cooling system of the collector(Zamen *et al.*, 2019).

2. Materials and Methods

The study was conducted in the city of Kirkuk (latitude 35.46° and longitude 44.39°). Water was used as a means of acquiring heat from the solar cell. It was passed inside a heat exchanger installed on the back of the solar cell and built two practical models to compare the thermal and electrical performance of the hybrid solar collector. Each model consists of the main parts: The base of the hybrid collector (the iron carrier), the wooden structure, solar cells, reflective mirrors, and measuring devices. The first model consists of a mono-crystalline solar cell, which is described in Table 1 inside the wooden structure and placed the solar cell inside a wooden structure, isolated from the back and sides with solid glass wool. A small heat exchanger is shown in Fig. 1 behind the solar cell, fix the glass cover above the solar cell 2.5 cm away. Use a bottom mirror with dimensions (length 120 cm, width 50 cm) set at the top of the solar collector as shown in Fig. 1. The iron holder was designed for this lower mirror. This holder is mounted on the iron stand of the solar collector. It can be moved at different angles of the solar thermal collector and the same dimensions of the lower mirror and reflectivity of these mirrors estimated at 0.95. The sides of the mirrors enclose a frame of aluminum to keep it and ensure that it is not broken. The second model is a solar cell without cooling (does not contain heat exchanger below) and does not contain solar mirrors installed on it. The objective of building an asymmetrical model is to achieve an accurate comparison of the effect of design and operational variables that affect the performance of the hybrid solar collector to reach reliable reliability for this comparison. Several types of measuring instruments were used to measure temperature, voltages, currents, solar radiation, etc.), several thermocouples were established to measure temperature in different areas of experimental origin. In the first model, one was installed on the surface of the water input pipe The second on the surface of the water exit pipe of the hybrid collector and another fixed on the front surface of the solar cell and the same on the back surface of the solar cell and two of them were installed on the aluminum plate located below the heat exchanger and was installed another at the middle of the glass cover, The second model of the solar cell (non-cooled) without cooling has been installed two of them on the front face of the solar cell and the distance between them (60 cm) and proved, in the same way, the previous one.These parameters were fixed in the hardware implementation and the FL is used for control issues. Three inputs were determined which is the PV/T angle, a mirror (upper angle), and a lower reflector angle. Tow outputs are monitored for the system efficiency optimization, PV/T temperature, and electrical power generation, see Fig. 2. Use the solar intensity meter (Solar meter SM206) to measure the intensity of solar radiation accurately (± 10 W/m²), the wind speed was measured accurately (± 0.1%) and the instrument (MT-1280) to measure the voltages and currents accurately (± 0.5 The use of four 21-watt (DC) lamps as a load for the solar cell and a flow meter to measure water flow when entering the heat exchanger behind the solar cell Fig. 3 represents a diagram of the device used.

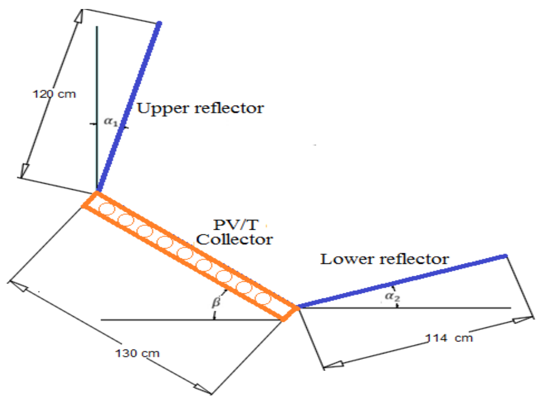

Fig. 1 Dimensions and angles of the mirrors used in the experiment

Table 1
Specifications of solar cells used

Quantity	Unit	Quantity	Unit
Short circuit current	7.51 A	Maximum power (P_{max})	W 100
Cell dimensions	(1200x540x30) mm	V_{max}	18.6 V
Cell operating temperature	25 °C	I_{max}	5.4 A
	Circuit voltages	21.3 V	

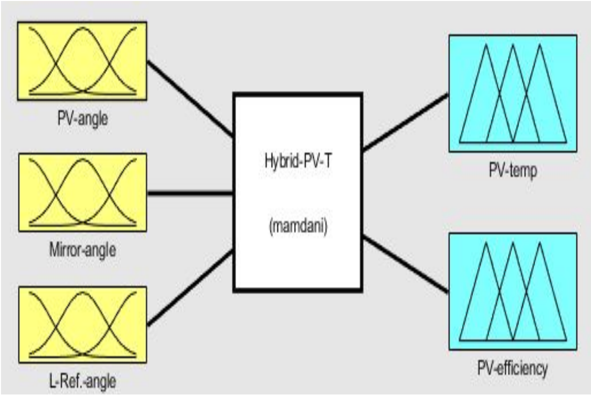

Fig. 2 The FL system architecture.

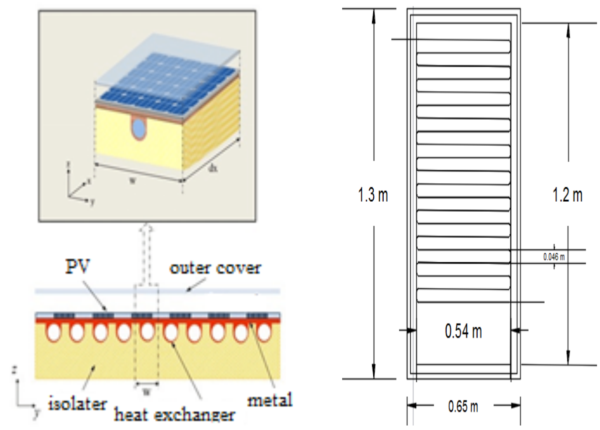

Fig. 3 Diagram of the parts of the solar collector (PV / T collector

It is known that the solar cell produces electricity in the form of DC. When solar energy falls on the solar cell, the positive and negative electrodes outside the cell produce electricity. Its main advantages are that it does not contain moving parts that are subject to breakdown. The energy generated from the cell In this study, according to the following equation (Khatibi *et al.*, 2019; Açıkkalp *et al.*, 2019):

$$P_{pv} = V.I \qquad (1)$$

Where V and I represent the voltage and the current, respectively, which produce by the solar cell, and measured using a device (Digital Scale), which is characterized by high accuracy of the measure of electricity (DC), and the measuring devices must be accurate to calculate the efficiency and electrical power out of the solar cell to be correct And close compared to standard conditions specifications, see Fig. 4.

The design of the hybrid solar collector used consists of a solar cell and a heat exchanger on the other side of the solar cell. The hybrid solar collector is covered with one glass cover. Also, the upper reflector connected to the upper side and the lower reflector connected to the lower side of the hybrid solar collector. The total radiation absorbed by the hybrid system connected to the upper and lower reflectors can be found from the following equation (Duffie and Beckman, (2013):-

$$A_{total=} A_b + A_d + A_g + A_{ref\,r\,1} + A_{ref\,r\,2} \qquad (2)$$

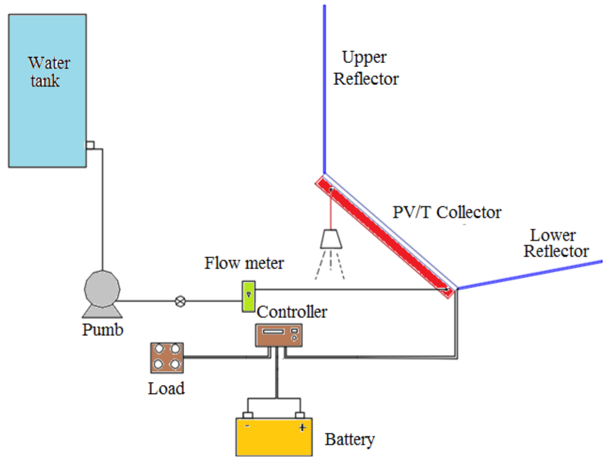

Fig. 4. The diagram of the device used

Each part of the equation is found as follows (Kostic et al., 2010)

$$A_b = I_b R_b\,(\tau\alpha)_b \qquad (3)$$

$$A_d = I_d\left(\frac{1+cos\beta}{2}\right)(\tau\alpha)_d \qquad (4)$$

$$A_g = \rho_g\, I_{\circ}\left(\frac{1-cos\beta}{2}\right)(\tau\alpha)_g \qquad (5)$$

$$A_{ref1} = \rho_{A1}.I_{total}.\sin(z).\sin(\alpha+\alpha_1).(\tau\alpha)_b$$

$$z = \alpha + 2\alpha_1 - \beta \qquad (6)$$

$$A_{ref2} = \rho_{A1}.I_{total}.\sin(x).\sin(\alpha-\alpha_2).(\tau\alpha)_b$$

$$x = \beta + 2\alpha_2 - \alpha \qquad (7)$$

$$\alpha = \sin^{-1}(\cos(\delta).\cos(\varphi).\cos(h)$$

$$+\sin(\delta).\sin(\varphi)) \qquad (8)$$

Where angle α, α_1& α_2 & is shown in Figure (1).

Based on the hypotheses listed above, energy balance equations have been applied to the hybrid solar collector, which includes the glass cover, the solar cell, the bottom plate, and the fluid used:

Glass cover

$$U_{cell-glass}(T_{cell} - T_{glass}) = U_{glass-Ambient}(T_{glass-}T_{ambient}) \qquad (9)$$

Solar cell

$$A_{total=} = U_t(T_{cell} - T_{ambint}) + h_A(T_{cell-}T_{back\ sheet}) \qquad (10)$$

Back surface

$$h_A(T_{cell} - T_{back\,sheet}) = h_f(T_{back\,sheet} - T_{fluid}) \qquad (11)$$

Fluid flow through heat exchanger tube

$$h_f(T_{back\,sheet} - T_{fluid}) = \dot{m}\, C_P (T_{back\,sheet} - T_{fluid}) \frac{dT_f}{dx} (T_{fluid} - T_{ambint}) \qquad (12)$$

The temperature of the glass cover is calculated from the following equation:

$$T_{glass} = T_{cell} - \frac{U_t(T_{Cell} - T_{Ambient})}{h_{c,cell-glass} + h_{r,cell-glass}} \qquad (13)$$

The temperature of the cell surface can be found from the following equation:

$$T_{cell} = \frac{(\alpha\tau)_{eff} A_{(total)} + U_t T_{Ambient} + h_A T_{back\,sheet}}{U_t + h_A} \qquad (14)$$

Where q_A is the heat transfer coefficient of the aluminium alloy plate:-

$$q_A = \left[\frac{L_{back\,sheet}}{K_{back\,sheet}}\right]^{-1} \qquad (15)$$

$$T_{back\,sheet} = \frac{h_R(\alpha\tau)_{eff} A_{(total)} + U_{tt} T_{Ambient} + h_t T_f}{U_{tt} + h_t} \qquad (16)$$

Both h_R and U_{tt} are represented

$$h_R = \frac{h_A}{U_t + h_A} \qquad (17)$$

$$U_{tt} = \frac{U_t h_A}{U_t + h_A} \qquad (18)$$

The temperature of fluid out of the system is calculated from the following equation ((Bahaidarah *et al.*, (2015):-

$$T_{fm} = T_{fin} + \frac{\frac{q_{useful}}{A_c}}{F_R \times U_c}\left(1 - \frac{F_R}{\acute{F}}\right) \qquad (19)$$

The rate of heat transfer between the front face of the hybrid solar collector is calculated from the following equation:-

$$q_{top\,loss} = U_t A_c (T_{glass} - T_{ambient}) \qquad (20)$$

The amount of useful energy obtained by the fluid passing through the heat exchanger pipe is calculated following equation (Ahmed & Mohammed, (2017b):-

$$q_u = A_C F_R [\alpha_{cell} A - U_c (T_{f,in} - T_a)] \qquad (21)$$

where: (F') coefficient of efficiency of the solar collector, calculated from the following equation (Duffie & Beckman, 2013).

$$\acute{F} = \frac{\frac{1}{U_C}}{(D+2W)\left[\frac{1}{U_C(D+2W\eta_f)} + \frac{1}{(C_P)} + \frac{1}{h_{c,t}(\pi D_t)}\right]} \qquad (22)$$

F_R can be expressed as defined:-

$$F_R = \frac{G\,Cp}{U_c}\left[1 - exp\left(-\frac{U_C F'}{G_c Cp}\right)\right] \qquad (23)$$

G_c is the flow rate of the surface area unit of the hybrid solar collector(Shahdost *et al.*, (2019)):

$$G_c = \frac{\dot{m}}{A_c} \qquad (24)$$

The hybrid solar collector thermal efficiency is calculated according to the following equation (Ahmed, Daoud, and Mahmood, 2019):

$$\eta_{th} = \frac{Q_{useful}}{I_{total} \cdot A_c} \qquad (25)$$

The electrical efficiency of the hybrid solar collector was calculated according to the following equation ((Ahmed & Hussein, (2018):

$$\eta_{electrical} = \frac{I_{max} \cdot V_{max}}{A_{total} \cdot A_c} \qquad (26)$$

Whereas, the goal of the hybrid solar collector is to improve the electrical efficiency of the solar cell and to use surplus heat for domestic purposes

4. Results and discussion

4.1. Without control

This section includes the results obtained from the practical experiments and the study, during which several experiments were carried out. The test begins from 9 am to 4 pm and the practical results obtained in different climatic conditions in Iraqi airspace were compared. The hybrid solar collector was tested with external reflectors and the effect of solar radiation and the impact of dust on the performance of the hybrid solar collector were examined. The first model: the traditional solar cell without cooling. Second model: Hybrid solar collector without glass cover with continuous cooling the flow of water used for cooling purposes was about 0.3 L/min with upper reflector only at a 120° angle between the reflector and the hybrid collector.

Fig. 5 shows the change in the temperature of the surface of the solar cell during the day of the two models, wherein both cases the increase in the temperature of the solar cell from the early morning hours to reach the highest levels at noon for the hybrid solar collector with increasing the value of solar radiation, The surface temperature of hybrid solar collector at the highest values of 55 °C, while the maximum solar cell surface temperature of the first model was about 58.5 °C, and this difference due to the effect of continuous cooling by the water of the hybrid solar collector and this is consistent with the results of the previous articles (Rekha & Melvinraj, 2016; Armstrong and Hurley, 2010; Ghasempour *et al.*, 2019).

Fig.6 shows the temperature difference of the water inside and outside of the hybrid solar collector and we notice its rise gradually from 8 am with the increase of the values of solar radiation, where the temperature of the water outside 25.3 °C and increase the temperature of water out gradually until the maximum at 11 pm when it reached 48 °C. The temperature of the outside water increases the thermal energy gained to heat the water and causes the solar cell temperature to drop.

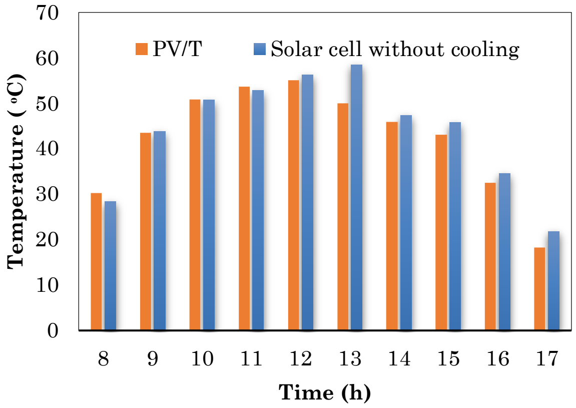

Fig. 5. Comparison of cell surface temperatures for different cases

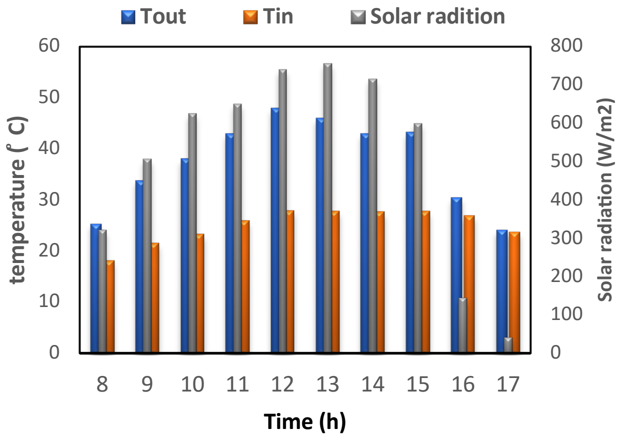

Fig. 6. Comparison of the water temperatures of the hybrid solar collector without glass cover with a top reflector only at 120 ° angle

Fig.7 shows the electrical energy produced by the hybrid solar collector using only the upper reflector and thermal energy of the conventional solar cell. The electric power of the hybrid solar collector is greater than that of the cell without cooling. This is due to the presence of the upper reflector, which contributes to the increasing concentration of solar radiation on the solar cell with scattered clouds in addition to the effect of continuous cooling of the cell by water, which contributed to reducing the temperature of the solar cell and thus increase its productivity (Ghasempour *et al.*, 2019).

Also, it was noted from the same figure the thermal energy of the hybrid solar collector is gradually increasing with the rise of solar radiation, the heat of the atmosphere and the presence of the upper reflector, which increases the useful energy gain to its maximum value at noon was 399 W, while gradually decreasing the evening of the low solar radiation and increasing the density Clouds at 4 pm The maximum electrical energy produced by the hybrid solar collector reaches 54.8 W at noon while 53.46 W corresponds to the cell without cooling for the same hour. Thus, the total useful energy (thermal and electric) of the solar collectors is much larger than the solar cell separately and the behaviour of these results is mentioned in the references (Kaldellis & Kapsali, 2011; Ahmed & Bawa, 2018).

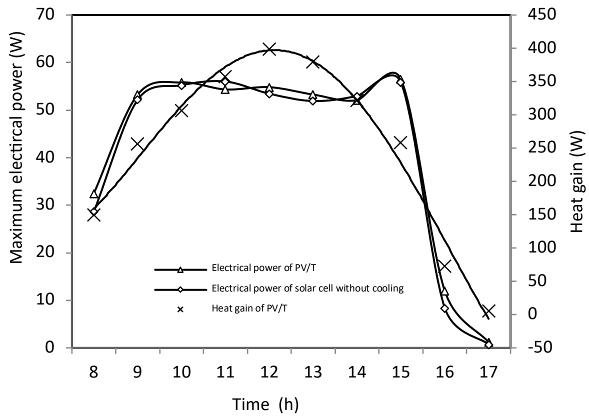

Fig. 7. Change e of electrical power for different cases

Fig. 8 represents the change in the thermal and electrical efficiency of the solar cell and the hybrid solar collector during the day. It is noted from this form of high electrical efficiency in the early morning hours due to the low temperature of the solar cell and the electric efficiency was 15.7% of the cooled cell while the electrical efficiency of the cooled cell was 13.8%.

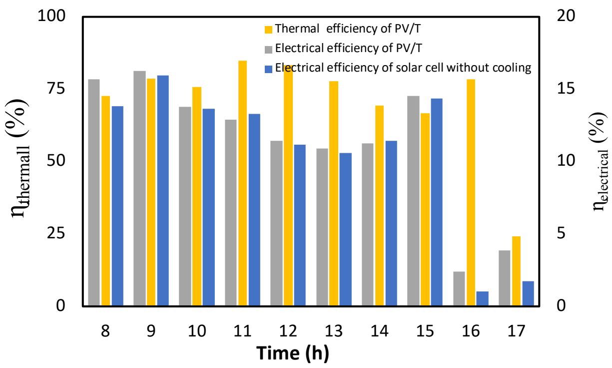

Fig. 8. Change the electrical efficiency of the solar cell for different cases.

It is also noted that the electric efficiency of the cooled cell is higher than the electric efficiency of the cell without cooling. The reason is the presence of the upper reflector, the absence of the glass cover and the cooling effect, which causes the low cell temperature and high efficiency. We note also the low electrical efficiency solar cell in the middle of the day in both cases (cooled cell and the cell without cool) for high-temperature solar cell temperature. The electrical efficiency of solar cells reached 11.4% of the cell-cooled while 11% of the cell without cooling either thermal efficiency daily is up to 71.1% this shows the positive effect of the absence of glass cover on electrical efficiency.

4.2. Fuzzy logic optimization

The responses of the system optimization are fixed during the 3D plots, which represent the output productivity and PV temperature and how they operate. However, the PV efficiency depends on the angles which are low values for the lower reflector and high for the upper one, see Fig. 9. That means the FL detect the weak operation angles and eliminate them from the work. Despite weak efficiency in some cases, but still, the system is self-managed and resolves the unwanted output by replacing the bad angles with those increase both electricity and water heat productivity.

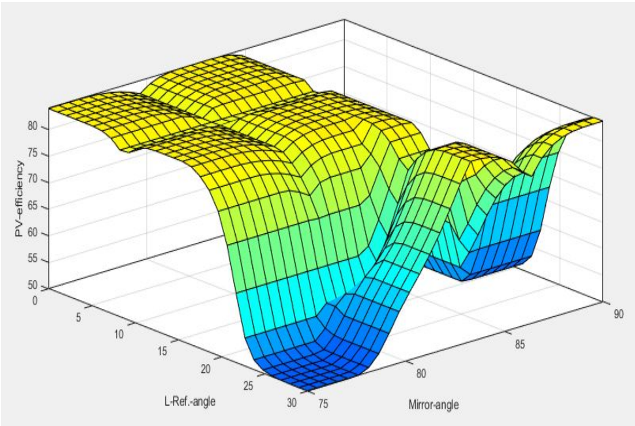

Fig. 9. Effect of the lower and upper mirror on the PV efficiency

The PV temperature had a higher degree at low values of PV angle and upper reflector, see Fig. 10. The real-time process makes the system to select the optimized operation angles for the upper and lower mirrors. The target for the current figure is the PV temperature, which leads to well heat water production in addition to a suitable level of temperature to give the electricity without any effect. All these parameters are managed and controlled by the FL. The operation temperature is around 37 °C for most of the daytime, except at minimum angle for the PV and the upper mirror, which increased, to 45 °C. The working temperature is going to less than 30 °C when the PV angle is at 45°.

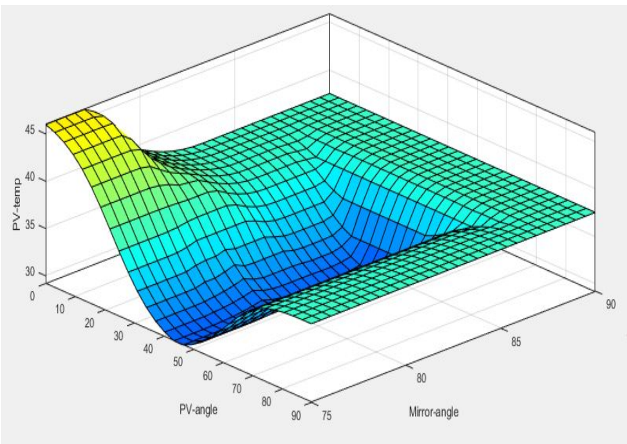

Fig. 10. Effect of PV angle and upper mirror on the PV temperature

The efficiency of the PV/T was in the optimum case when the PV angle values are in a medium as shown in Fig. 11. The FL usually determines the proper solution and selects the better parameters depending on the output at a given moment. So, in this paper, the efficiency goes to the optimum level and the system was in better productivity. The efficiency reached 75 % in this proposed method at PV angle 46° for all values of the upper mirror angles.

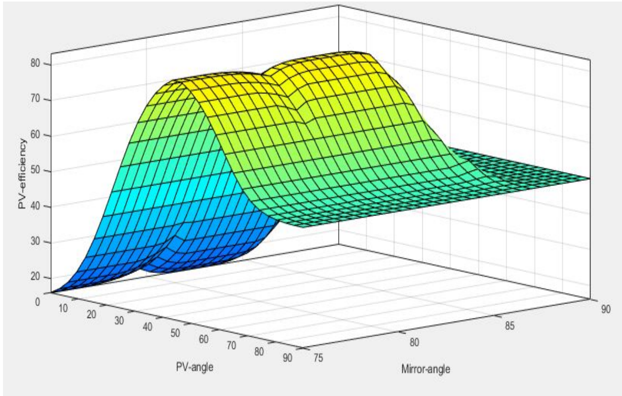

Fig. 11. Effect of PV angle and upper mirror on the PV efficiency

Also, the effective PV angle and lower reflective angle on the efficiency are studied and fixed in Fig.12 clear to see the PV angle has a direct effect on the efficiency rather than lower reflector which has a bit effect on it. Although the higher efficiency which is reached, there are many cases in this model that make the efficiency goes to zero, as shown in this figure, when the PV angle is 0° there is no productivity without any effect for the lower mirror and upper one.

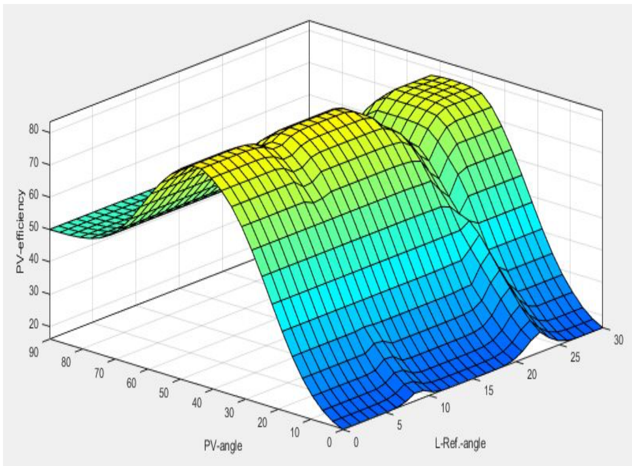

Fig. 12. Effect of the lower reflector and upper mirror on the PV efficiency

The smallest temperature for the PV has been recorded at medium values for the PV angle and the lower reflector has a small effect too. Fig.13 shows the response of the system for different angles for PV and low reflector, so clear to see the temperature decreased for the initial values for the lower reflector then fixed (Ahmed & Daoud, 2018). Secondly, the temperature of the PV becomes the goal of the process, there are many effects on the PV temperature, which has a direct response to the overall efficiency. For the PV angle, 30° until 90° the temperature is between 27-37°C that is very suited for the work, while the temperature goes to maximum range in case of PV angle decreased to closest value.

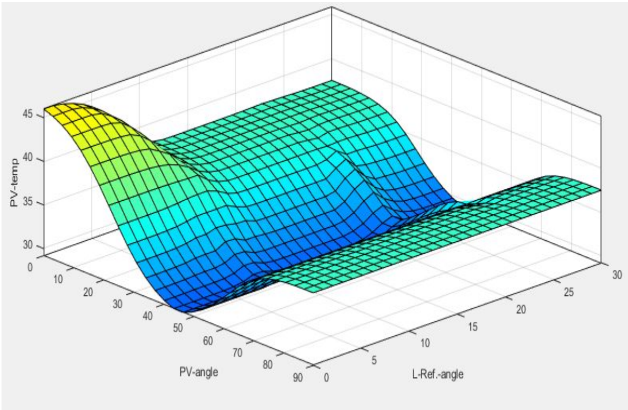

Fig. 13. Effect of lower reflector and PV angle on the PV temperature

The last response for the FL is the lower and upper reflector on the PV temperature and both of them affect. Both angles values affected the PV temperature at a large scale and Fig. 14 shows the response. Simple to see that there are no effects on the temperature while the angle of the mirror is less than 85° and after that, the temperature is goes to high.

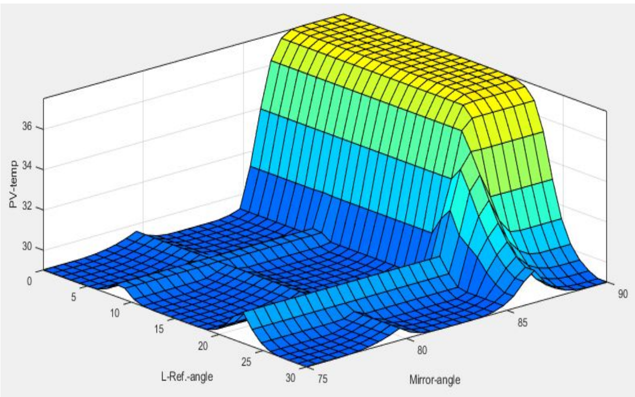

Fig. 14. Effect of the lower and upper mirror on the PV temperature

5. Conclusions

Through the results, we can conclude the following:

- The most important point in this study is the efficiency improvement, so the ratio becomes 84% after 66% in the previous work.
- The electrical efficiency of the hybrid solar collector increases with the increase of the concentration of solar radiation by reflective mirrors, especially with the increased flow of fluid without the presence of glass cover to increase the effect of cooling.
- Smart tuning the system parameter by using FL makes the system more suitable and operates in the optimum situation.
- The presence of external reflectors both lower and upper has a greater impact than the presence of only one reflector on the performance of the hybrid solar collector.
- The presence of dust has a negative impact on the performance of the solar collector hybrid and external reflectors.

Nomenclatures:

A	:	Solar radiation absorbed by a solar cell panel (W / m²).
A_b	:	Direct radiation on the solar cell surface
A_c	:	Hybrid solar collector area(m²)
Ad	:	Radiation spread in the sky
A_g	:	Radiation reflected on Earth.
$A_{ref,r1}$	:	Radiation reflected from the upper reflector to the solar cell with the tilt angle of the upper reflector α_1
$A_{ref,r2}$	:	Radiation reflected from the lower reflector to the solar cell surface with the tilt angle of the lower reflector α_2.
A_dA_{total}	:	Total radiation absorbed by the solar cell (total).
I_b	:	Direct radiation falling vertically on the surface.
I_d	:	Radiation spread in the sky
I_o	:	Solar radiation falling on a horizontal surface.
I_{total}	:	Total Solar Radiation
R_b	:	Percentage of direct radiation on a slant surface to direct solar radiation Horizontal surface.
((1 + cosß)/2)	:	Hybrid composite vision factor into the sky
((1 + cosß)/2)	:	Hybrid solar collector vision factor to the ground.
$(\tau\alpha)_b$	:	the sum of the reflectivity of the absorption of direct radiation.
$(\tau\alpha)_d$	:	The resultant reflectivity of diffuse radiation
ρ_g	:	Ground reflectivity was used in this equation= 0.2
$(\tau\alpha)_g$	:	Absorption and Reflectivity Reflected from the Earth
ρ_{A1}	:	Mirror reflectivity

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