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NUMERICAL AND EXPERIMENTAL INVESTIGATION FOR HYBRID PHOTOVOLTAIC/THERMAL COLLECTOR SYSTEM IN DUHOK CITY

Semyan KHALED[1], Omar ALI[2*]

[1]*Department of Energy Engineering, College of Technical Engineering, Duhok Technical University, Duhok, Iraq*
[2]*Department of Mechanics, College of Engineering, Zakho University, Zakho, Iraq*

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Highlights

The renewable energy (hybrid photovoltaic/ Thermal collector system) is important due to the

- Shortage of electrical power production in Duhok city/ Iraq.
- Increased pollution due to the employment of the fossil fuel to produce the required power.
- Numerical and experimental researches and investigation on the hybrid PV/T system are rare in the Kurdistan region, especially in Duhok.
- The glazed PV/T collector in duhok city for the present work duration is very useful to produce the power.

Abstract. The study deals with the experimental and numerical investigation of the hybrid Photovoltaic-thermal solar collector system in Duhok city during seven months and includes different measurements of temperatures, water mass flow rate, wind velocity, and solar intensity. A one-dimensional mathematical model is used to simulate the transient processes with constant thermo-physical properties and heat transfer coefficients. The energy conservation equations are solved using implicit finite difference method. The numerical and experimental results showed satisfactory agreement with an error (2.36%) between two thermal efficiencies. The results include the estimation of the electrical and thermal energy, thermal, electrical and overall efficiency. The highest overall efficiency of PV/T collector occurs in May 2019 with value (72.01%) and the lowest value in January 2019 is obtained as (63.1%). The cooling method leads to an increase in the electrical efficiency to about 3% as compared with PV solar collector system.

Keywords: solar, radiation, thermal, Photovoltaic, Eco-Energy, numerical, experimental, collector, electrical, efficiency, power, Duhok.

Introduction

The renewable energy sources increase and investment in this area is an essential demand for many reasons such as limited fossil fuel resources and environmental issues. The main issue in the Kurdistan Region of Iraq is the inability to provide energy continuously and it may be solved using renewable energy (Khaled, 2019).

Energy has an effect on human life and the development of many sectors such as transport, education, agriculture, and industry. Solar thermal collector systems are heat exchangers that used to convert the radiation energy from the sun into thermal energy through a transport medium (Alyousifi & Ali, 2020). There are two kinds of the solar collector systems: concentrated and non-concentrated collectors such as flat plate collector (FPC) and evacuated tube collector (ETC) (Ali & Jameel, 2011). The essential features of the traditional FPC collectors are; black metal absorber plate (usually metal), tubes, ducts or passages attached to the back surface of the absorbent plate, insulation material to reduce thermal losses, glasses (one or two) and metal box surrounds all the mentioned components tightly (Duffie & Beckman, 2013).

The solar photovoltaic is used to convert the solar radiation into electricity directly. The PV model electrical efficiency depends on the solar cell temperature and its performance is affected by the temperature rise. The hybrid photovoltaic thermal PV/T system is a combination of the thermal and electricity simultaneously. It is a combination of solar thermal and PV systems/components. The PV/T system can be classified based on heat transfer techniques

*Corresponding author. E-mail: *omar.ali@uoz.edu.krd*

and integration of PV/T systems into PV/T based- air, PV/T based- water, PV/T based on bi-fluid, PV/T based on phase change materials (PCM), PV/T based on Nano-fluids and PV/T based on heat pipe (Sathe & Dhoble, 2017). Kern and Russell (1978) deals with experimental investigation of a hybrid PV/T collector in the Lincoln Laboratory/ US Ministry of Energy. The authors concluded that the hybrid system will succeed by significantly reducing the cost of raw materials. Raghuraman (1981) analyzed the performance of two PV/T systems (air and water) thermally using one-dimensional analysis. The results showed that the overall efficiency of the water-based PV/T system is 9% greater than those of air based. The PV cell has a direct effect on the performance of the solar collector. The author concluded that the thermal losses may be reduced by making the tubes as an integral part of the absorbent plate that increases the costs. Takashima et al. (1994) investigated numerically the air- PV/T collector system to estimate the electrical and thermal energy. The results showed that the integration of the two systems is a major contribution to distribute solar energy technology. Garg, Agarwal, and Joshi (1994) studied experimentally the performance of the PV/T water-based system using silicon PV cells that installed directly on the aluminum absorbent plate. The heat transfer coefficient, overall heat transfer coefficient, and heat loss coefficient of the storage tank are estimated using practical experiment data that compared with the theoretical outcomes and showed good agreement. The results showed that the collector thermal efficiency reached 33.5% and electrical efficiency to 3.25% assuming that the photovoltaic cell temperature is equal to the absorber plate average temperature. Saitoh et al. (2003) conducted a field experiment of two hybrid collector systems in parallel, at a low-energy house of the Hokkaido University, Japan for one year and the winter season is excluded from the experiments based on constant supply temperature of brine (propylene glycol solution) as a carrier medium of the experiment. The experimental results showed that there is an agreement between the conversion efficiency of the PV/T and PV systems; however, the collector efficiency of the PV/T is less than those of solar thermal collector. The PV/T collector efficiencies at 20 °C brine temperature is 40% and it is approximately 50% at 40 °C. The annual energy balance has been evaluated for PV/T collector and proved that PV/T collector has a high degree of feasibility. Alobaid et al. (2018) studied numerically and experimentally the thermal and electrical performance of the PV/T system using different values of inlet water temperature in the climatic condition of Saudi Arabia. The effect of the temperature variation on the outlet temperature of the water and solar cell are investigated. The solar cell temperature is measured separately for each cell. The mathematical model is used to calculate the PV/T system performance. The results showed that the electrical efficiency is 13.7% and the average thermal efficiency is about 65%. Kazem (2019) designed a grid-connected PV/T based on the water under the weather conditions of Oman during three days testing to perform the electrical performance. The PV/T collector system showed better electrical performance as compared with the conventional PV panel during the test with a difference of 6% as average.

Abdullah et al. (2020) is studied numerically the PV/T collector system performance as compared with those of the indoor experimental studies of the hybrid system and PV panel without cooling system under insolation range between 500 and 1000 W/m^2 with different flow rate between 2 and 6 LPM. The numerical and experimental results are showed a good agreement. The highest electrical efficiency is about 11.5% at 500 W/m^2 and 6 LPM; while the maximum thermal efficiency is about 58% at 1000 W/m^2 and 5 LPM. The increase of the mass flow rate and solar radiation cause an increase in the thermal efficiency. The panel temperature is decreased and the electrical efficiency is increased with enhancement of the flow rate.

The Iraq suffered from the electricity lack from about 30 years that have an effect on the life of the Iraqi people. The total energy production of the Iraq depended on fossil fuels because it is one of the largest producers worldwide. The researchers and scholars in Iraq using photovoltaic solar panels are unclear due to an acute shortage of knowledge (Chaichan & Kazem, 2018).

The main issues of the Duhok city are the shortage of electrical power production in Duhok city, and the increased pollution that obtained from the combustion of the fossil fuel to produce the required power. The numerical and experimental studies on the glazed hybrid PV/T system are rare in Kurdistan region, and especially in Duhok city. The glazed system is used during the winter season to increase the thermal energy that may be used in home applications and space heating for the building that required more electrical load consumption. The cooling method with using PV/T collector system lead to a reduction in the panel temperature that causes an increase in the electrical efficiency. The novelty of the present work that there is no experimental or numerical investigation about hybrid PV/T solar collector system in the region.

The present work includes the experimental and numerical investigation of the hybrid PV/T collector of the hybrid PV/T solar flat plate collector manufactured by the researcher and tested under the weather conditions of the Duhok city for a period of time not less than six months. The mathematical model deals with active PV/T hybrid collector covered by single glass under transient conditions with using MATLAB software to solve the mathematical model numerically. The experimental results are presented to verify the numerical solution of the present work. The experimental and numerical results will display the performance of the system and the effect of the panel temperature reduction on the system performance.

1. Theoretical modelling

The flat-plate PV/T hybrid collector is modeled mathematically; Figure 1, the various components are in the transient states. The control volume of the PV/T hybrid collector is analyzed with dividing it into six nodes.

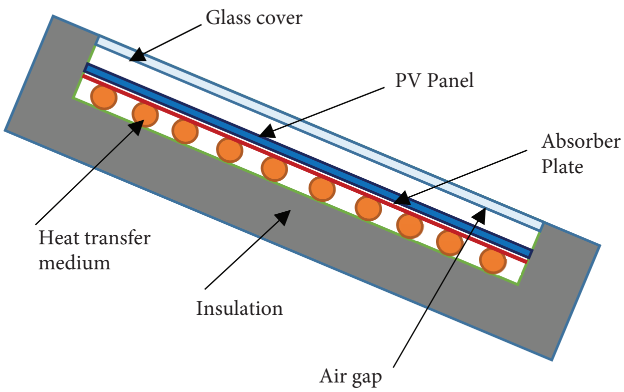

Figure 1. Sketch of the flat-plate PV/T collector model with six nodes

Six nodes are used to apply the energy balance for the components; the general energy balance of one-dimensional heat transfer is given by:

$$\frac{dE}{dt} = \dot{Q}_{in} - \dot{Q}_{out} + \dot{Q}_{gen}. \tag{1}$$

E is the system energy, $\dot{Q}_{in}$ is the energy rate into the system, $\dot{Q}_{out}$ is the energy rate out of the system, $\dot{Q}_{gen}$ the rate of heat generation into the system. The potential energy and kinetic energy are neglected in this case.

$$\rho \cdot V \cdot C_p \cdot \frac{dT}{dt} = \dot{Q}_{in} - \dot{Q}_{out} + \dot{Q}_{gen}. \tag{2}$$

It considered that the hybrid PV/T system have uniform mass flow rate in each tube, the heat transfer is considered as one-dimensional, the insulation and glass have constant properties, the ambient temperature is constant for the collector, the dirt and dust is neglected on the collector, the ambient conditions and sky radiation are time-dependent, and the thermo-physical properties are temperature dependent for the air gap and the fluid.

The glass cover governing equation may be written as:

$$\rho_g \cdot C_g \cdot V_g \cdot \frac{dT_g}{dt} = \Big[h_{g.amb}\left(T_{amb} - T_g\right) + h_{r1}\left(T_{PV} - T_g\right) + h_{c1}\left(T_a - T_g\right) + \alpha G \Big] p\,\Delta z. \tag{3}$$

The governing equation of the air gap may be written as:

$$\rho_a \cdot C_a \cdot V_a \cdot \frac{dT_a}{dt} = \Big[h_{c1}\left(T_g - T_a\right) + h_{g.PV}\left(T_{PV} - T_a\right) \Big] p\,\Delta z. \tag{4}$$

The PV module governing equation can be written as:

$$\rho_{PV} \cdot C_{PV} \cdot V_{PV} \cdot \frac{dT_{PV}}{dt} = \left[G\left(\alpha\tau\right)_{PV} - E_{PV} + \frac{K_{pv}}{\delta_{pv}} \cdot \left(T_{ab} - T_{PV}\right) + h_{r1}\left(T_g - T_{PV}\right) + h_{c1}\left(T_a - T_{PV}\right) \right] p\,\Delta z, \tag{5}$$

E_{PV} is the actual amount of energy that the PV module absorbed (Alobaid et al., 2018).

$$E_{PV} = G \cdot P_c \cdot \eta_{el}, \tag{6}$$

where $P_c = \dfrac{area\ of\ PV\ Cells}{area\ of\ PV\ panel}$. The electrical efficiency, (the electrical performance) is given in different methods (Chow, 2003; Mousavi et al. 2018; Khatiwada & Ghimire, 2015; Chow et al., 2006).

$$\eta_{el} = \eta_{ref} \cdot \left[1 - \beta_{ref}\left(T_{pv} - T_{ref}\right) \right], \tag{7}$$

where β_{ref} is the thermal coefficient of cell efficiency and it equal to 0.0041 (Dubey et al., 2013); T_{ref} – reference temperature (25 °C).

The electrical efficiency may be calculated using

$$\eta_{el} = \frac{V_{oc} \cdot I_{sc} \cdot FF}{G \cdot A_{PV}}, \tag{8}$$

where FF is the Fill factor is defined as

$$FF = \frac{V_m \cdot I_m}{V_{oc} \cdot I_{sc}}. \tag{9}$$

The maximum power may be determined from

$$P_m = V_{oc} \cdot I_{sc} \cdot FF = V_m \cdot I_m. \tag{10}$$

The absorber plate governing equation is written as:

$$\rho_{ab} \cdot C_{ab} \cdot V_{ab} \cdot \frac{dT_{ab}}{dt} = \left[\frac{K_i}{\delta_i}\left(T_i - T_{ab}\right) + \frac{K_{ab}}{\delta_{ab}}\left(T_{PV} - T_{ab}\right) \right] \cdot p\,\Delta z + \pi d_{in} h_f \left(T_f - T_{ab}\right). \tag{11}$$

The governing equation of the insulation may be written as:

$$\rho_i \cdot C_i \cdot V_i \cdot \frac{dT_i}{dt} = \left[\frac{K_i}{\delta_i}\left(T_{ab} - T_i\right) + h_{i\_amb}\left(T_i - T_{amb}\right) \right] \cdot p\,\Delta z. \tag{12}$$

Consider the variation in total energy with time and the whole heat transferred into the fluid control volume.

$$\rho_f \cdot C_f \cdot A_f \cdot \frac{dT_f}{dt} = \left[\pi d_{in} h_f \left(T_{ab} - T_f\right) + \dot{m}_f\, C_f \frac{\partial T_f}{\partial z} \right]. \tag{13}$$

The first law of thermodynamics within the control volume of the storage tank is applied to develop the energy conservation of the storage tank as shown below:

$$\frac{dE_{cv}}{dt} = \left[\dot{Q} - \dot{W} + \dot{m}_{in}\left(h_{in} + \frac{V_{in}^2}{2} + g z_{in} \right) - \dot{m}_{out}\left(h_{out} + \frac{V_{out}^2}{2} + g z_{out} \right) \right]. \tag{14}$$

The storage tank equation can be written as:

$$\dot{m}C_v \frac{dT_{\tan k}}{dt} = \left[\dot{m}_{tot} C_P \left(T_f - T_{\tan k} \right) - h_{\tan k-amb} A_{s\ \tan k} \left(T_{\tan k} - T_{amb} \right) \right]. \quad (15)$$

The radiation heat transfer between the glass cover and the PV module:

$$h_{r1\ .j} = \frac{\sigma \left(T_{pv\ .j}^2 + T_{g\ .j}^2 \right) \left(T_{pv\ .j} + T_{g\ .j} \right)}{\left(\frac{1}{\varepsilon_{pv}} \right) + \left(\frac{1}{\varepsilon_g} \right) - 1}, \quad (16)$$

where σ – Stefan-Boltzmann constant, h – heat transfer coefficient, r – radiation, ε – the emissivity.

The convection heat transfer inside the inclined air gap is:

$$h_{c1\ .j} = \frac{Nu_{q\ .j} K_{q\ .j}}{\delta_a},$$

where $Nu_{q\ .\ j}$ is the Nusselt number and it can be calculated using the formula given by (Hollands et al., 1976).

$$Nu_{a\ .j} = 1 + 1.44 \left[1 - \frac{1708 \left[\sin(1.8\beta) \right]^{1.6}}{Ra_j \cos(\beta)} \right]^+ \cdot$$

$$\left(1 - \frac{1708}{Ra_j \cos\cos(\beta)} \right) + \left[\left(\frac{Ra_j \cos\cos(\beta)}{5830} \right)^{\frac{1}{3}} - 1 \right]^+, \quad (17)$$

where the sign "+" in the above formula it should be considered only the positive values otherwise, it replaced to zero. β is the incline angle of the collector, Ra is the Rayleigh number, and it can be estimated using the following Equation:

$$Ra = \frac{g \cdot \beta' \cdot \Delta T \cdot L^3}{\alpha' \cdot \nu}. \quad (18)$$

The heat transfer coefficient on the external surface of the glass cover can be calculated by:

$$h_{g\_am\ \cdot j} = \frac{\sigma \varepsilon_g (T_{g\ \cdot\ j}^4 - T_{sky}^4)}{T_{g\ \cdot\ j} - T_{amb}} + h_{c2}, \quad (19)$$

where T_{sky} is the sky temperature and it can be calculated by C. Swinbank formula (Saleh, 2012):

$$T_{sky} = 0.0552 \cdot \left(T_{amb} \right)^{1.5}. \quad (20)$$

The convection heat transfer on the external surface of the insulation and the cover (Duffie & Beckman, 2013) is:

$$h_{c2} = \frac{Nu_{amb} \cdot K_{amb}}{\delta}, \quad (21)$$

where:

$$Nu_{amb} = 0.86\, Re_{amb}^{0.5}\, Pr_{amb}^{\frac{1}{3}}; \quad (22)$$

$$\delta = \frac{4ab}{\sqrt{a^2 + b^2}},$$

where, a is the length of the insulation, b is the width of the insulation, the dimensions of the collector in meter.

The heat transfer coefficient on the external surface of the insulation can be calculated by

$$h_{i\_am.j} = \frac{\sigma \varepsilon_i (T_{i\ .j}^4 - T_{sky}^4)}{T_{i.j} - T_{am}} + h_{c2}. \quad (23)$$

There is another way to calculate h_{c2} by using the h_w which is the convection heat transfer due to wind and can be calculated by J. Watmuff formula (Watmuff & Proctor, 1977):

$$h_w = 2.8 + 3u, \quad (24)$$

where u is the wind velocity, m/s.

The heat transfer coefficient inside the PV/T collector tube can be calculated using:

$$h_{f.j} = \frac{Nu_{f.j} K_{f.j}}{d_{in}}, \quad (25)$$

where the Nusselt number can be calculated using the Heaton formula (Heaton et al., 1964) and proposed by Duffie and Beckman (2013), for laminar flow in tubes (short tubes). For the case of constant heat flux boundary condition:

$$Nu_{f\ .j} = Nu_\infty + \frac{a \left(\mathrm{Re}_{f.j}\ \mathrm{Pr}_{f.j} \left(\frac{d_{in}}{L} \right) \right)^m}{1 + b \left(\mathrm{Re}_{f.j}\ \mathrm{Pr}_{f.j} \left(\frac{d_{in}}{L} \right) \right)^n}; \quad (26)$$

$$1 < Re_{f\ .j}\, Pr_{f\ .j} \frac{d_{in}}{L} \le 1000,$$

where the values a, b, m, n, Nu_∞ are 0.00398, 0.0114, 1.66, 1.12, and 4.4 respectively. Consider the flow is fully developed inside of tubes.

$$\left| \frac{T_{j\ .(k+1)}^{t+\Delta t} - T_{j\ .(k)}^{t+\Delta t}}{T_{j\ .(k+1)}^{t+\Delta t}} \right| \le \vartheta, \quad (27)$$

where T is the estimated temperature, ϑ equal to (10^{-4}) it is the acceptable tolerance through the iteration process.

Finally, k is the counter of iteration for every time step (e.g. 1, 2, 3, ...).

The implicit finite difference method is used to solve the differential Equations (3)–(13). The MATLAB software version R2017b is used to model the mathematical formulation.

2. Experimental setup

Hybrid PV/T system is designed, fabricated and installed at the roof of the Duhok Technical College of Engineering building as shown in Figure 2, under meteorological conditions at Latitude (36°51′41.0″N), Longitude (42°58′40.5″E). The duration time of the test is between November 2018 and May 2019.

The main hybrid PV/T system components are the thermal collector with PV panel. The hybrid collector consists of the following parts: one glass cover with area (0.9344) m^2, photovoltaic module with maximum power of 150-watt contains 36 solar cells manufactured from monocrystalline silicon with an area of 0.0243 m^2 for each cell. The air gap between the glass cover and PV panel is 0.025 m. The metal of absorber plate is copper with the thickness of 0.00075 m, with mechanical fixture on the back side of the PV panel. The arrangement of copper tubes are distributed in parallel and fixed with the plate. The tubes have headers with 0.22 m diameter and risers with 0.12 m diameter and the tubes length is 1.25 m and the two tubes distance is 0.05 m. The foam is used as insulation material with a thickness (0.042 m). The collector is inclined with optimum tilt angle (34.5°) for Duhok

Figure 2. Front view of the PV/T collector

city in Iraq (Holman 2012). The insulated water-storage tank with capacity of 100 litter is used and connected with PV/T solar collector. Twelve K-type thermocouples are used for different components of the PV/T system, Figure 3.

A hot water circulation pump is used to circulate the water through the system using water flowmeter with accuracy ±4%. The solar radiation is measured using pyranometer with range 0–1500 W/m^2 and accuracy of ±0.3%. Also, the wind velocity is measured using RK100-01 anemometer with accuracy ±0.5 m/s. The digital multi-meter (MT-1233D) with accuracy ±1.2% is used. The temperatures, wind velocity, voltage, and solar radiation during the experiments are recorded using a data logger NAPU-I130D with (16-input channels) and an accuracy of ±0.2%.

The definition of the thermal efficiency of the collector is the ratio of the useful heat gain to the incident energy of the solar with same time period as follow:

$$\eta_{th} = \frac{\int \dot{Q}_u \, dt}{A_c \int G \, dt}. \tag{28}$$

The useful heat gain may be calculated using

$$Q_u = A_c F_R \left[G(\tau\alpha)_{pv} - U_L \left(T_{in} - T_a \right) \right]; \tag{29}$$

$$\eta_{th} = \frac{Q_u}{A_c G} = F_R (\tau\alpha)_{pv} - \frac{F_R U_L \left(T_{in} - T_{am} \right)}{G}, \tag{30}$$

where F_R and U_L are the collector removal factor and collector overall heat loss coefficient respectively.

The uncertainty in the experimental results may be determined to analyze the experimental data and calculate the errors. The thermal efficiency in terms of known quantities that the $\eta_{th} = f\,(\dot{m},\ A,\ G,\ T_i,\ T_a)$ (Holman, 2012). Also, the electrical efficiency may be defined as $\eta_{el} = f\left(G,\ I_{sc},\ V_{oc},\ A_c\right)$. The thermal efficiency

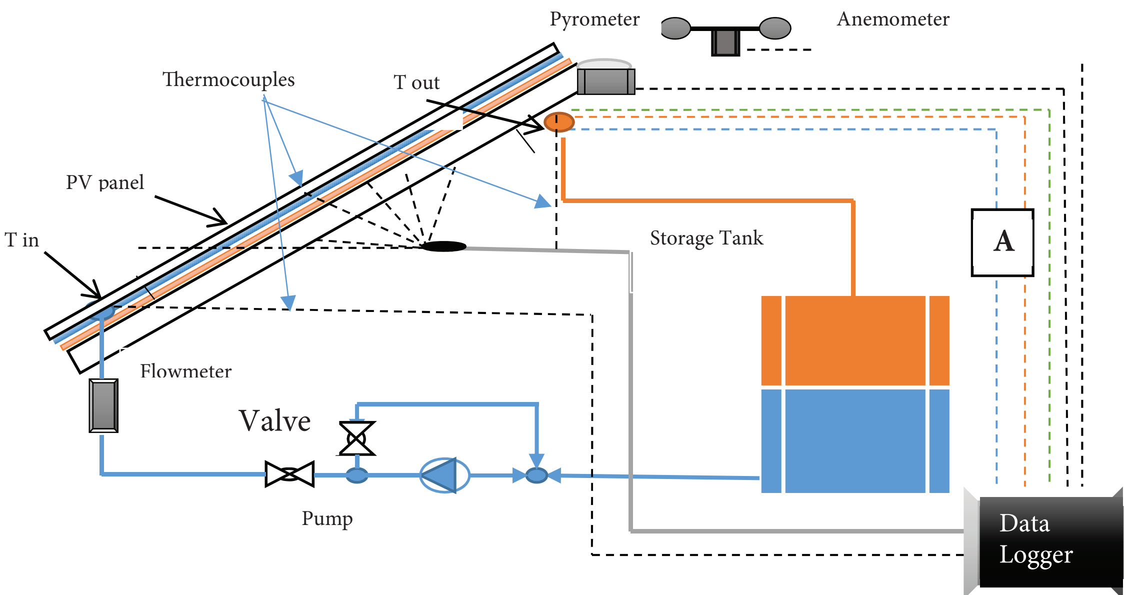

Figure 3. Schematic diagram of the PV/T system

uncertainty $\omega_{\eta_{th}}$ may be estimated using:

$$\omega_{\eta_{th}} = \left\{ \left(\frac{\partial \eta_{th}}{\partial \dot{m}} \omega_{\dot{m}} \right)^2 + \left(\frac{\partial \eta_{th}}{\partial A} \omega_{A_c} \right)^2 + \left(\frac{\partial \eta_{th}}{\partial G} \omega_G \right)^2 + \left(\frac{\partial \eta_{th}}{\partial T_o} \omega_{T_o} \right)^2 + \left(\frac{\partial \eta}{\partial T_i} \omega_{T_i} \right)^2 \right\}^{0.5}. \quad (31)$$

The electrical efficiency uncertainty $\omega_{\eta_{el}}$ is calculated using:

$$\omega_{\eta_{el}} = \left[\left(\frac{\partial \eta_{el}}{\partial I_{sc}} \omega_{Isc} \right)^2 + \left(\frac{\partial \eta_{el}}{\partial V_{oc}} \omega_{Voc} \right)^2 + \left(\frac{\partial \eta_{el}}{\partial A_{pv}} \omega_{Apv} \right)^2 + \left(\frac{\partial \eta_{el}}{\partial G} \omega_G \right)^2 \right]^{0.5}. \quad (32)$$

3. Results and discussions

The experimental tests are obtained in Duhok Technical College of Engineering building under the typical weather conditions of the Duhok city in Iraq. First, the experiment test is selected for comparison between experimental and numerical work in Nov. 2, 2018 because it was a sunny and relatively warm day with a maximum temperature of 29.6 °C, with average wind speed with 1.7 m/sec. The flow rate in the collector is adjusted with 2.5 L/min. The inlet, outlet, absorber, PV panel, glass cover, air gap temperatures, and solar irradiation are measured and recorded every one minute. The measured values of solar radiation and ambient temperature during the experiment are shown in Figure 4. The experiment carried out for period 2 hours from 9:00 to 11:00 am, this time is chosen due to the stability of solar radiation.

The numerical work based on the assumptions that the initial water temperature of the storage tank is 29.7 °C, total water flow rate is 2.5 L/min, the ambient temperature from 22.2 to 24.4 °C, the solar radiation from 420 to 500 W/m^2, and the optimum number of nodes along the tube is 12. There is a good agreement between the experimental and numerical results for the inlet temperature as shown in Figure 5. The maximum error is (5.56%) for the inlet temperature due to the variation in the solar radiation and ambient temperature. In the numerical work, the average solar radiation has been used as well as the ambient temperature. Figures 6 show the comparison between the recorded temperature of the outlet water from the PV/T collector on Nov. 2nd and the values utilizing the proposed numerical model. The comparison displays good agreement between the numerical and measured outlet water temperature with maximum error of (2.36%) for outlet temperature. Figure 7 compare the electrical efficiency for different three days of the present work with a system have only PV panel without cooling (Ceylan et al., 2014). The average electrical efficiency is 10.18% for the

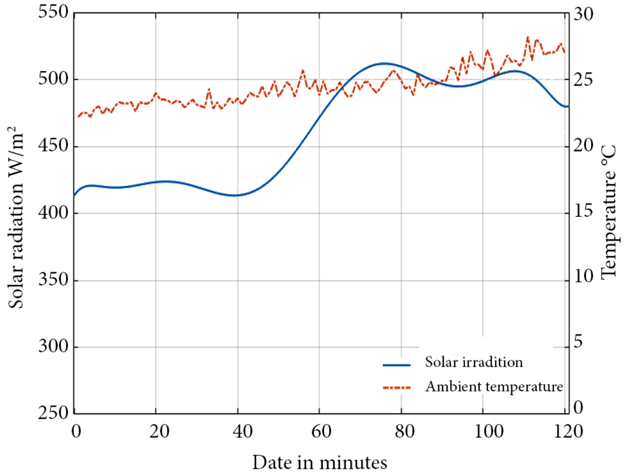

Figure 4. Variation of the recorded solar radiation and Ambient Temperature on Nov 2nd 2018

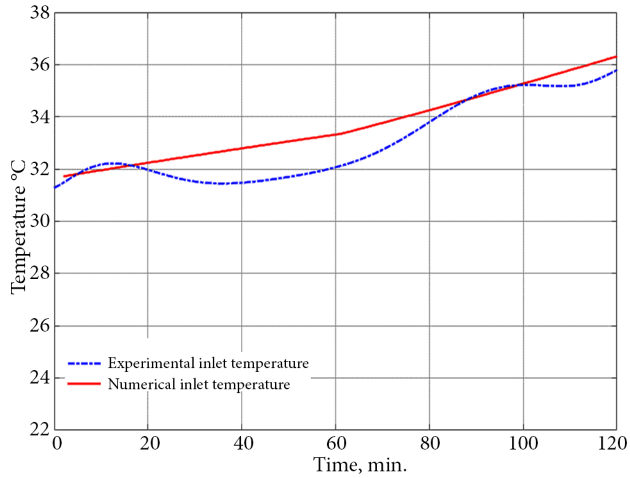

Figure 5. Comparison between numerical and experimental fluid outlet temperatures on Nov. 2018

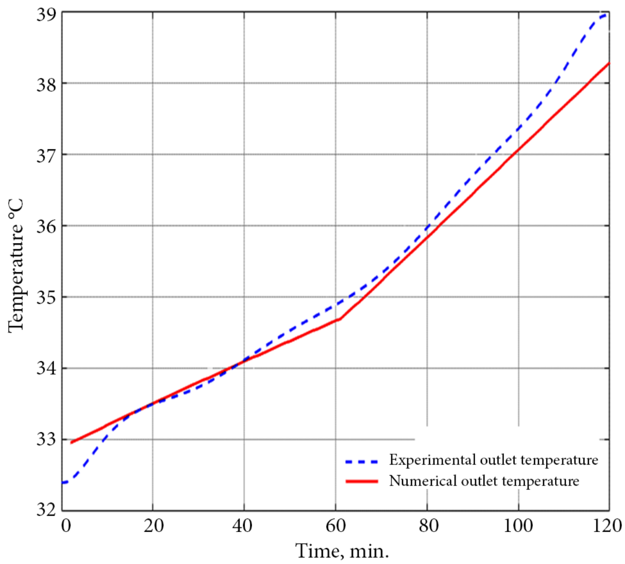

Figure 6. Comparison between numerical and experimental fluid inlet temperatures at the Solar PV/T collector inlet on Nov 2nd 2018

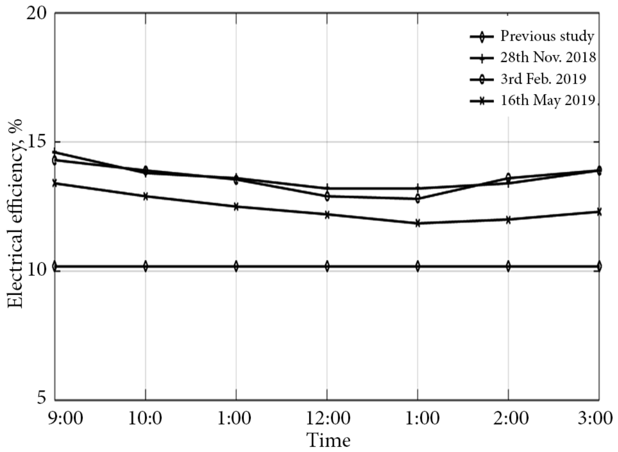

Figure 7. Comparison experimental efficiencies for different three days with previous study

previous study; while the average electrical efficiency for 28th Nov. 2018, 3rd February 2019 and 16th May 2019 are 13.67, 13.56 and 12.45% respectively due to the employment of the water-cooling system. The decrease in the electrical efficiency for 16th May due to the increase of panel temperature.

The experimental tests for random three days from 6 months during the 6-hour period from 9:00 am to 3:00 pm every 15 minutes are recorded and analyzed. The performance of the hybrid PV/T collector is calculated such as useful energy, thermal efficiency and electrical efficiency. Figure 8 represented the behavior of the inlet, outlet, storage tank water, ambient temperature and solar radiation for different three typical days. The trends of the water inlet, outlet and storage tank temperatures are similar for three days that increase with the time, while; different values are obtained with the variation of the time. The temperature values for the date May 16th 2019 are larger than the other days due to the high intensity of the solar radiation and high ambient temperature as compared with other days. The temperatures are continuously increase with the time until 3:00 pm while the solar radiation intensity decreases after 12:00 pm because the system is closed and no load is rejected.

The thermal yield of the PV/T system has been presented in Figure 9 for typical three days. The behavior of the useful energy for all days is similar that the energy increases until it reaches maximum value between 11:30 am and 12:00 pm and decreases to lower value at 3:00 pm and it is proportional with the solar radiation intensity. The larger values are obtained for May 16th 2019 due to high solar radiation. The output useful energy values are varied with different three days, and larger values are obtained for May 16th 2019 due to high solar radiation and ambient temperature. For other days, the output useful heat is lower than it due to lower solar radiation and ambient temperature.

Figure 10 illustrate the electrical yields of the energy and the measured solar radiation for different three days.

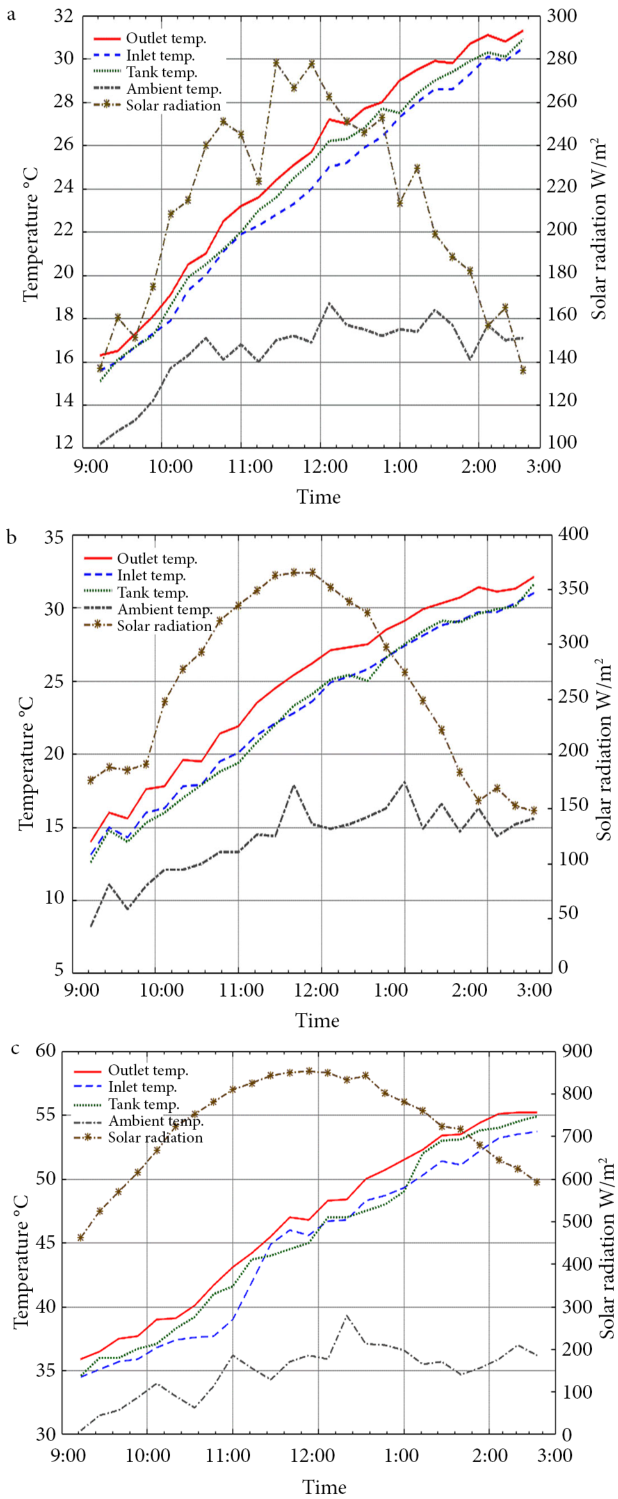

Figure 8. measured outlet, inlet, storage tank, ambient temperature and solar radiation on: a – Nov. 28th 2018, b – Feb. 3rd 2019, c – May 16th 2019

The trends of the electrical energy are similar for all days that the maximum values are obtained at relatively 12:00 pm. The electrical energy decreases until it reaches low value at 3:00 pm. The electrical energy is proportional with the solar radiation. A maximum value is obtained with the day May.16th.2019 due to high solar radiation.

The thermal and electrical efficiency of the PV/T system has been presented in Figure 11 for specified three days. It can be observed that maximum thermal efficiency between 10:30 am and 112:00 pm due to the difference between the inlet water temperature and the ambient temperature over solar radiation. The thermal efficiency increases to maximum value between 10:00–11:00 am then decreases until reaches minimum value at 3:00 pm. The electrical efficiency decreases until 12:30–1:00 pm then increases to larger value. The same behavior is occurred for three days. The maximum thermal efficiency is about 70% and the minimum electrical efficiency is about 12% for day May 16th 2019 due to the high inlet hot water temperature of the collector.

Figure 12 displayed the variation of the panel temperatures for different selected three days. The panel temperature

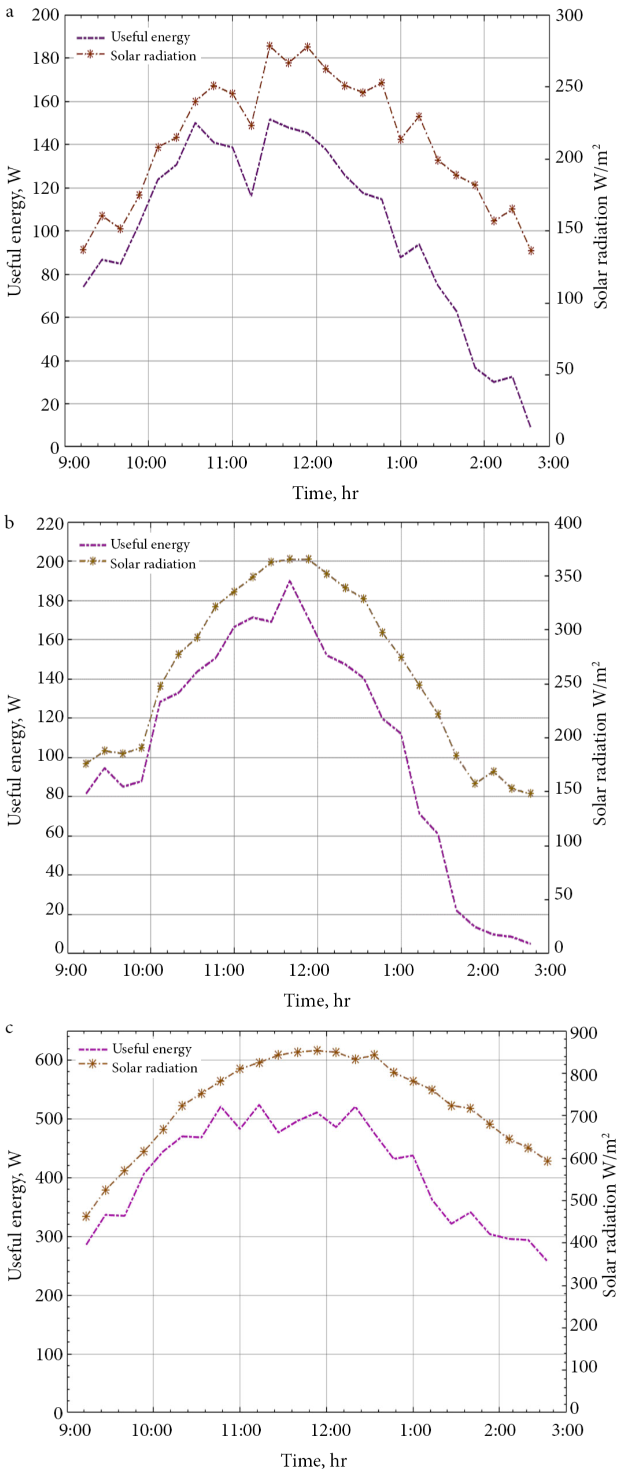

Figure 9. Useful energy variation and recorded solar radiation histories on: a – Nov. 28th 2018, b – Feb. 3rd 2019, c – May 16th 2019

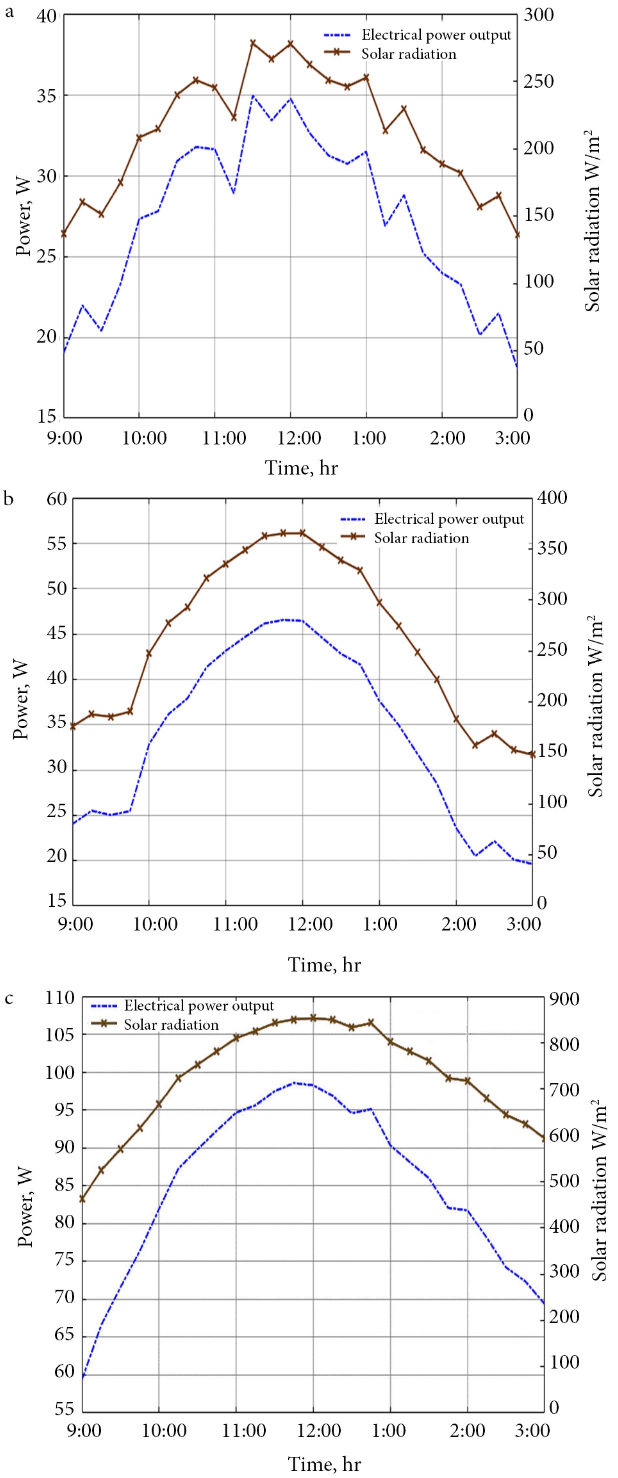

Figure 10. Electrical power output variation and measured solar radiation histories on: a – Nov. 28th 2018, b – Feb. 3rd 2019, c – May 16th 2019

of the 3rd February and 16 May is increased due to the increase in the solar radiation and ambient temperature as shown in Figures 7 and 8. The relatively higher panel temperatures for selected days because the glass cover is used for the collector that increases the PV module temperature.

Figure 13 clearly illustrated the temperature variation of the panel on electrical efficiency for 3rd February day. There is an inverse relationship between the PV module temperature and the electrical efficiency. The phenomena displayed the effect of the panel temperature on the

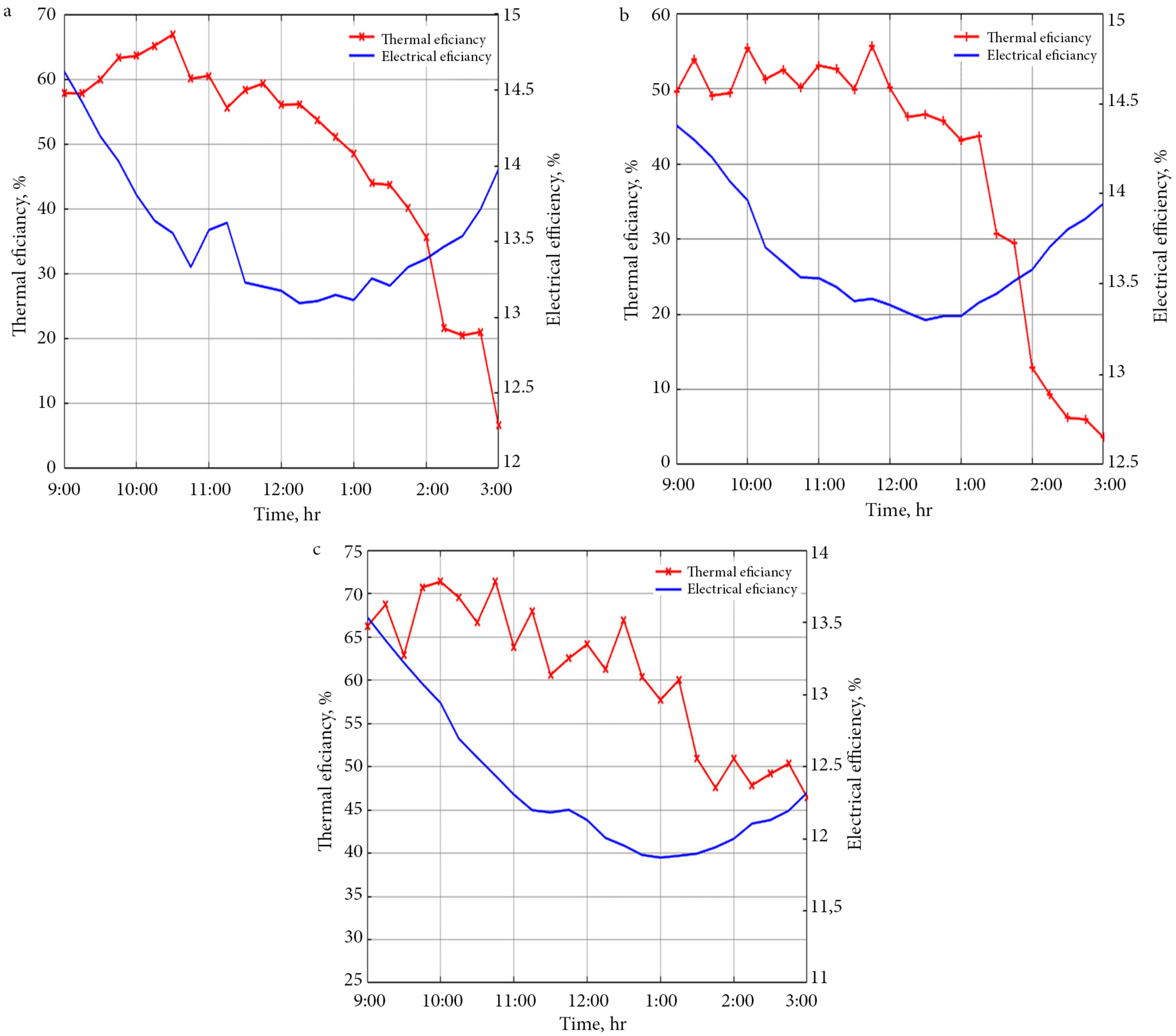

Figure 11. Variation of electrical and thermal efficiency histories on a – Nov. 28th 2018, b – Feb. 3rd 2019, c – May 16th 2019

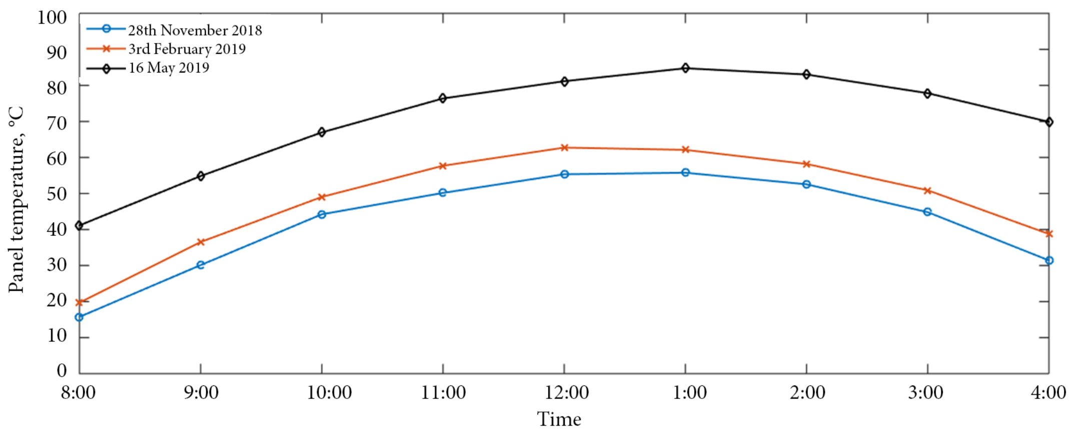

Figure 12. Variation of the panel temperature during selected three days

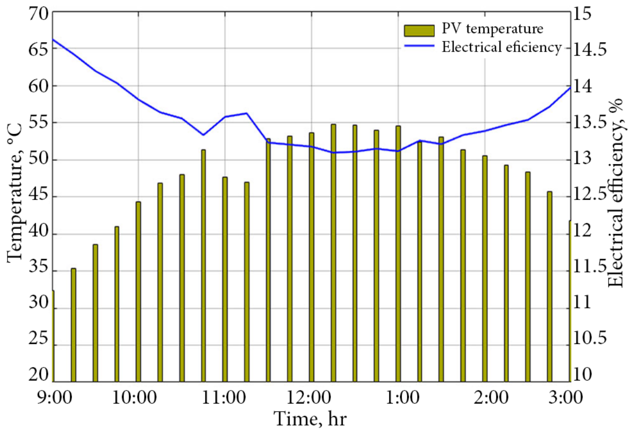

Figure 13. variation between PV cells Temperature and electrical efficiency

electrical power that lead to an effect on the electrical efficiency.

The practical applications of the hybrid PV/T solar collector system is the production of the thermal and electrical energy. The solar energy is one of the renewable energy resources. The renewable energy is the co-friendly environmental energy source because this energy does not emit the CO_2 that causes the global warming potential phenomena that lead to an increase in the ambient temperature and the energy does not have an effect on the environmental due to the pollution. The production of the thermal and electrical energies using fossil fuels lead to CO_2 emission and environmental pollution. The recommendation of the future work is the effect of different water mass flow rates, materials, system configurations and dimensions of the collector on the collector performance and electrical and thermal productions.

Conclusions

The numerical and experimental investigations for a hybrid PV/T solar collector system are obtained in Duhok climate during seven months from November 2018 to May 2019 to examine different weather conditions. The following conclusions are deduced:

The numerical model of the PV/T flat plate collector has been validated by experimental investigation and the results have a good agreement between them with a maximum difference is (2.36%). The results showed the maximum value of the electrical power output and thermal energy gains are in May 16th, 2019 (98.553 W), (523.923 W) respectively and the minimum value are in Nov 28th, 2018, (34.95) W for electric power output and (151.55 W) for thermal energy gain. The enhancement of the panel temperature causes a decrease in the electrical energy. The cooling of the PV panel using PV/T collector system increases the electrical efficiency within 3%. The increasing in inlet water temperature influence on thermal efficiency and decreased it. The overall efficiency range between 63–72%.

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