Journal of Engineering Science and Technology
Vol. 16, No. 6 (2021) 4817 - 4832

NUMERICAL STUDY OF COOLING SYSTEM FOR PHOTOVOLTAIC THERMAL COLLECTOR

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Abstract

The present study is to assess the effects of cooling technology using water on photovoltaic thermal collector. Hence, this technology was fulfilled via designing a serpentine copper pipe (Di = 10 mm) to be inserted behind photovoltaic collector (600 mm x 500 mm), to study the performance of photovoltaic with and without cooling system and the effects of increasing water mass flow rate during April, May and June in 2019. MATLAB program was utilized to solve numerical equations. Moreover, the CFD was employed to assess thermal performance of PV panel. The numerical outcome showed the influence of the cooling system clearly decreases photovoltaic surface temperature for all the days studied. As the percentage decreased is about (5.8%) for 24th of April, (5.5%) for 15th of May and (7%) for 13th of June than the condition of without cooling. The effects of increase flow rate from 0.0039 kg/s to 0.0075 kg/s the outlet coolant temperature decreased about (13%). But when the mass flow rate is 0.01 kg/s, the outlet coolant temperature approaching from temperature at 0.0075 kg/s. This indicates that the cooling effect of the photoelectric panel is not effective when this flow rate is exceeded (0.01 kg/s). In addition, the electrical efficiency was increased about (8.4%, 8%, 9.2%) for selective days respectively. The effectiveness of using cooling technology system was improved through reducing photovoltaic thermal collector temperatures and increasing in the electrical efficiency. Matching well was obtained between numerical and previous experimental data.

Keywords: Cooling system, Photovoltaic panel, Serpentine pipe, Thermal collector.

1. Introduction

A photovoltaic-thermal (PVT) is a hybrid device improved by conjoining solar photovoltaic and solar thermal system. It includes of a PV panel with a heat exchanger affixed to the back of the panel. This technique is a combined system which can produce both heat and electricity simultaneously [1]. Hence, great deals of effort have been devoted from the researchers to increase the PVT performance though enhancing the overall efficiency with reducing the payback period of system.

Tonui and Tripanagnostopoulos [2] studied the photovoltaic thermal (PVT) solar collectors with heat gain using air by normal or forced flow. This study utilizes a suspended tinny metallic plate at the mid or fins at the back wall of an air channel as heat transfer improvements in an air-cooled (PVT) solar collector to enhance its total enactment. The sheet in TMS (thin metallic sheet) forms a kind of dual-pass arrangement and doubles the heat gain surface. The FIN system, comprise of fins with rectangular profiles closed to the back wall of the air channel, for practical reasons and oriented parallel to the flow direction. The results proved that the FIN system had greater thermal effectiveness about 30% compared with 28% and 25% for TMS and typical module respectively. Thus, the FIN system is more active in PV heating and cooling than the TMS and REF systems while the TMS is greater in dropping the back wall temperature than the FIN and REF.

Almeida and Oliveira [3] developed a numerical model for two types of flat-plate hybrid PV collector firstly; utilizing monocrystalline silicon (mono-Si) and secondly; amorphous silicon (a-Si) flexible. The results indicated that the upper global effectiveness was provided about 81% for mono Si hybrid collector compared with efficiency of a-Si type (70%). Moreover, the ecological influence of the hybrid collector was contrast with a traditional energy system through assisted the electrical, thermal and total efficiency.

Odeh and Behnia [4] improved the performance of PVT through examine water cooling technique in solar rig experimentally and numerically. The experimental results showed the dissipated heat by convection among coolant and the PV surface increased by 15% in system output is accomplished at highest radiation conditions. While the numerical results of the system were pointed to increase in supplied energy about 5% from the PV unit through warm and dry periods.

Tang et al. [5] carried out the micro heat pipe arrangement to cooling photovoltaic panel using the air- water as a coolant, The liquid inside the system evaporated due to input heat and transfer to the condenser section. The condenser part is cooled via coolant (water or air). So, the heat transfers in the pipe pass from photovoltaic panel to coolant to the temperature of the photovoltaic panel and enhance the photo-electric conversion effectiveness. It was concluded that the temperature of cell can be reduced to efficiently raise the photo-electric conversion effectiveness. The temperature decreased about 4.7 Co and the output power increased about 8.4%, for air-cooling contrasted with normal solar panel, also the temperature decreased about 8 Co and output power increased about 13.9% for water-cooling. Moreover, an experimental study of un-glazed flat-plate PVT system had been established by Huang et al. [6]. So, 240W poly-crystalline silicon PVT collectors with storage tank about 120 litre, pump controller and water pump. The PVT collector was made with copper pipe and copper sheet with welding and adhesive on PV panel posterior side. The results indicated that the system thermal effectiveness can be reached to 35.33% and PV conversion effectiveness can be approximated to 8.77% through the testing time. Consequently, the temperature of the water tank was increased from 26.2 Co to 40.02 Co.

Ibrahim et al. [7] designed and constructed a thermosiphon solar PVT water heating device, which can be utilized for a local purpose. PVT was designed, built and examined used available materials. Solar device provides heat and electricity at the same time. The dissipated heat in the photovoltaic cells, this unused heat, was used by attaching a flow heat exchanger harden to a copper sheet and fixed at the back of the photovoltaic panel to extract the heat from the photovoltaic panel. A hot and cold-water tank was then combined to the system. So, the water flows to the heat exchanger, gets heated and flows into a hot water storage tank through thermosiphon rule. The resulted maximum fluid output temperature, solar radiation, thermal and electrical outputs were (63.2 Co, 957 W/m^2, 509.5 W and 140 W), respectively were obtained on a sunny day.

Al-Showany [8] examined the influence of weather conditions on efficiency of the photovoltaic (PV) unit. The experiment tests were accompanied by utilizing two similar PV panel of 75 Watt. Water circulation was utilized for cooling of the PV panel and very fine soil used to assess the influence of dust sedimentation and hot weather on the achievement of PV individually. Fill factor (FF) and PV effectiveness affected contrariwise with raising in temperature, moreover cooling process due to increase the generated voltage of PV panel about 11.8%, while the decline in voltage generation by impure panel because of natural pollution sedimentation on the front of the panel during twelve weeks was about 3.8% contrast with pure panel and 13.8% when it was cooled by water.

The main objective of this paper is to examine the influence of serpentine cooling system on the photovoltaic panel through understanding effects of coolant flow rate to enhance the electrical efficiency. Consequently, the working lifetime of the photovoltaic collator will be increased. The overall system performance is calculated based on (sunny day) of the environmental conditions at Baghdad city-Iraq. In addition, to achieve robust mathematical MATLAB program during prediction the amount of heat transfer in PVT compared with FLUENT code and previous experimental results.

2. Mathematical Module

Many relationships and equations are required to achieve the results of this study. The special equations had been described in calculating thermal losses and total efficiency (electrical and thermal effectiveness) in the case of with and without cooling photovoltaic panel. MATLAB program was utilized to solve numerical equations with 140 steps by developing an algorithmic program for analyzing steady, laminar and incompressible flow in a serpentine copper pipe. The thermal losses of the photovoltaic plate were the amount of the thermal losses from the top, bottom, and the other sides. Clearly, the thermal losses from the top are the most influential element in calculating the total amount of losses or energy dissipation to the surrounding. Therefore, the thermal losses from the top (U_t) are a function of several elements and can be calculated from the following formula [9]

$$U_t = \left(\frac{N}{\frac{C}{T_{pm}}\left[\frac{(T_{pm}-T_a)}{(N+f)}\right]^{e}} + \frac{1}{h_w} \right)^{-1} + \frac{\sigma(T_{pm}+T_a)(T_{pm}^2+T_a^2)}{\frac{1}{\varepsilon_{p+0.00591Nh_w}} + \frac{2N+f-1+0.133\epsilon_p}{\epsilon_g} - N} \tag{1}$$

where

$$f = \left(1 + 0.089h_w - 0.1166h_w\varepsilon_p\right)(1 + 0.07866N)$$

$$C = 520(1 - 0.000051B^2)$$

$$e = 0.430\left(1 - 100/T_{pm}\right)$$

The back and edge loss coefficient can be calculated from Eq. (2) and (3) [9].

$$U_b = \frac{k_i}{l_b} \tag{2}$$

$$U_e = \frac{(UA)edge}{A_c} \tag{3}$$

The over loss coefficient U_T is the sum of top, bottom and edge loss coefficients [9].

$$U_T = U_t + U_b + U_e \tag{4}$$

The total effectiveness is represented the sum of electrical and thermal effectiveness can be evaluated by [10].

$$\eta_T = \eta_{th} + \eta_e \tag{5}$$

The thermal efficiency can be calculated by [10].

$$\eta_{th} = F_R(\tau\alpha) - F_R U_T\left(\frac{(T_i - T_a)}{I_t}\right) \tag{6}$$

where F_R, T_i T_a, τa and I_t are respectively, the heat removal factor, temperature of inlet water, ambient temperature, transmission-absorption coefficient and solar radiation [9].

$$F_R = \frac{\dot{m}C_p}{AcU_T}\left[1 - \exp\left(\frac{AcU_T\bar{F}}{\dot{m}C_p}\right)\right] \tag{7}$$

$$\bar{F} = \frac{\frac{1}{U_T}}{W\left[\frac{1}{U_T((D+(W-D)F)} + \frac{1}{cb} + \frac{1}{\pi Dihi}\right]} \tag{8}$$

where W, D, F, $\bar{F}$ and h_i are respectively, tube spacing, tube diameter, fin efficiency, collector effectiveness factor and coefficient of heat transfer inside the tube [9]

$$F = \frac{\tan h\left[M\left(\frac{W-D}{2}\right)\right]}{M\left(\frac{W-D}{2}\right)} \tag{9}$$

$$M = \sqrt{\frac{U_T}{(Kab \times Lab) + (Kpv + Lpv)}} \tag{10}$$

where Kab, Lab, Kpv and Lp are respectively, absorber conductivity, absorber thickness, photovoltaic conductivity, and photovoltaic thickness [10]. The electrical effectiveness is determined by the following formula [11].

$$\eta_e = \eta_r(1 - \gamma(T_{PV} - T_r)) \tag{11}$$

where T_{PV} , T_r , γ and η_r are respectively. photovoltaic temperature, reference temperature, temperature coefficient and reference efficiency. The photovoltaic temperature (cell temperature) in case of without cooling can be calculated by [12]:

$$T_{PV} = 30 + 0.0175(I_t - 150) + 1.14(T_a - 25) \tag{12}$$

In case of cooling photovoltaic panel, the cell temperature can be calculated by heat balance from following formula:

$$T_{PVC} = Q_U * \left[\frac{Lpv}{Kpv\,Ac} + \frac{\ln^{r_2}/r_1}{2\,\pi\,Kpv\,LL} + \frac{1}{h_i 2\pi LL r_1}\right] + T_{point} \tag{13}$$

$$T_{point} = T_a - Q_U[\frac{1}{h_i Ac} + \frac{Lpv}{Kpv\,Ac} + \frac{1}{h_w 2\pi LL r_1} \tag{14}$$

Q_U is the useful heat gain of collector (W/m^2) is determined via [13].

$$Q_U = \dot{m} C_p (T_O - T_{in}) \tag{15}$$

where, T_O is the outlet temperature can be calculated by substitute Eq. (6) and (15) in Eq. (16) [14].

$$\eta_{th} = \frac{Q_U}{I_t} \tag{16}$$

Tables 2 and 3 present the input parameters and characteristics of PV/T collector. Figure 1 shows the flow chart program .

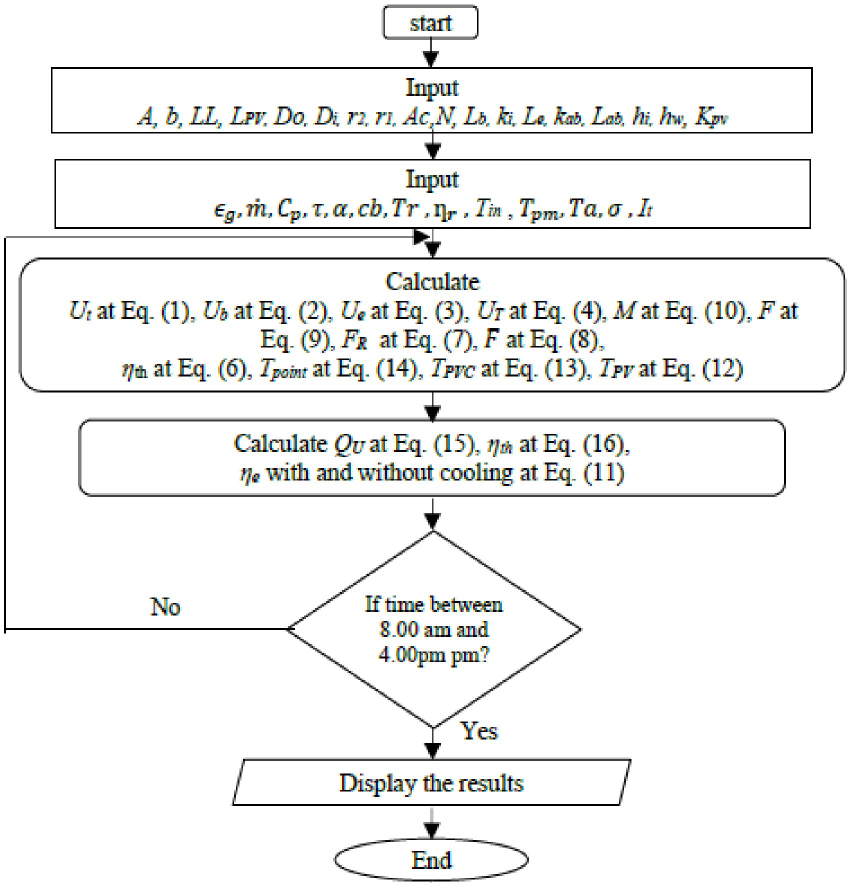

Fig. 1. Flow chart program.

3. Numerical Simulation Model

To computational fluid dynamics (CFD) was utilized in the present study to assess the thermal performance of cooling technique in photovoltaic panel numerically as shown in Figs. 2 and 3. The multi block technique had been chosen for meshing the geometries (two parts): the photovoltaic domain (600 mm x 500 mm x 3 mm) and serpentine cooling pipes domain geometry (Di = 10 mm). Serpentine flow pipe was embedded in photovoltaic geometry to examine cooling method. To achieve high grid CFD software accuracy validation Daud et al. [15] had recommended that: the first grid points near the wall have to be located at $y^{+} \sim 12$ for turbulent flow. While in the present study the flow field is described as laminar flow structure. Consequently, mesh independency strategy has been used to reduce calculation time and operating cost.

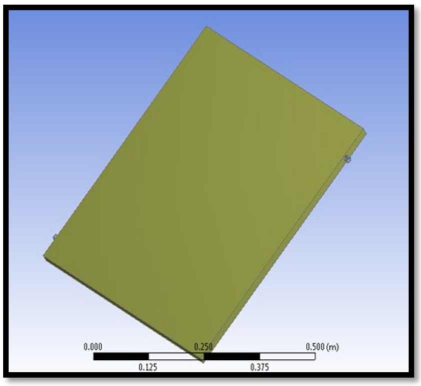

Fig. 2. Geometry of photovoltaic panel.

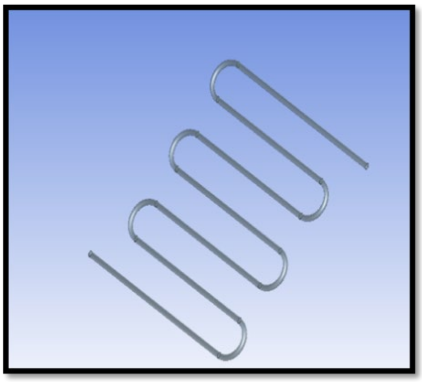

Fig. 3. Geometry of serpentine pipe.

Strategy method tests the grid independency by increasing and repeating the simulation for selected cases. Then there is no significant change in CFD results, the test case had been selected as sufficient resolution. Table 1 presents the mesh dependency results. Five million cells were selective to described fully three dimensional (3D) finite volume methods and understanding the effects of cooling technique.

Table 1. Mesh dependency results at 10.00 am for 24th of April.

No. of elements	T_{out} (K)
1764544	316.23
2676879	314.00
3214960	312.89
4425847	311.23
5023121	310.5
5976856	310.45

The mathematical model of fluid flow motion equations and the energy equation were solved for 3-Dimansion, steady, viscose and incompressible flow. The velocity-pressure coupling was affected by semi-implicit method for pressurelinked equations developed by Patankar and Spalding [16]. Moreover, second order upwind schemes were selected for all solution schemes and the convergence solution was achieved to 10^{-4}.

Continuity:

$$\nabla(\rho V) = 0 \tag{17}$$

Momentum equation:

$$\frac{\partial}{\partial x_i}\left(\rho U_i U_j\right) = \frac{\partial \rho}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_j}\right) - \overrightarrow{\rho U_\iota U_J}\right] \tag{18}$$

Energy equation:

$$\frac{\partial}{\partial x_j}(\rho U_i T) = \frac{\partial}{\partial x_j}\left[\frac{\mu}{P_r}\frac{\partial T}{\partial x_j} - \overrightarrow{\rho U_\iota t}\right] \tag{19}$$

3.1. Boundary Conditions and Operating Parameters

The initial boundary condition (B.C) details are inserted in the FLUENT code and MATLAB program in cases of thermal collector as main inlet velocity about (0.05 m/s) for 24th of April, 15th of May and 13th of June. In addition to, the inlet temperature had been extracted from experimental data of [17] which is constant with time. In viscous flow models was defined in numerical calculation. Multi block technique was formed in the geometrical model to satisfy the interference between the solid and liquid regions see Fig. 4. so, the conjugate heat transfer was obtained from photovoltaic and cooling pipe to the coolant. MATLAB program are embodying the method of analysis equations of fluid flow motion and energy equation. Therefore, the variation of heat flux is equal to the solar insolation which applied at the upper surface of the photovoltaic panel see Table 2. While zero heat flux was applied to the bottom and side surfaces of the PV panel to affect insulated conditions. A serpentine pipe (absorber) is defined as solid body (copper material). The input properties of photovoltaic panel are as shown in Table 3.

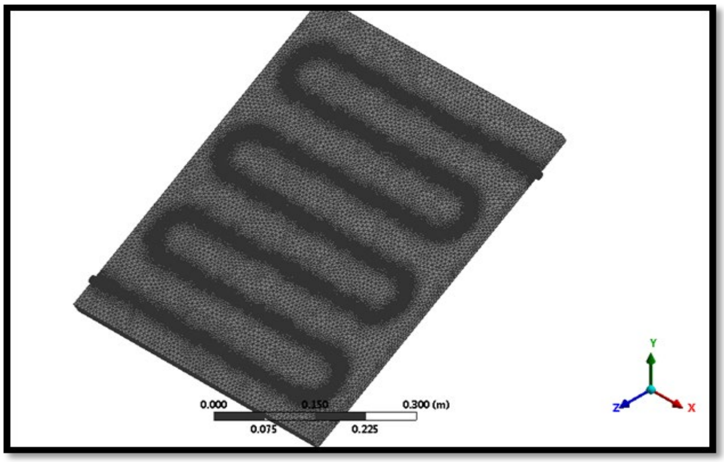

Fig. 4. Volume mesh of photovoltaic panel.

Table 2. Experimental weather condition data input to an algorithmic program [17].

Date	Time	8.00AM	9.00AM	10.0AM	11.0AM	12.00 noon	1.00PM	2.00PM	3.00 PM	4.00 PM
24th April	T_{in} (K)	298	298	298	298	298	298	298	298	298
	T_{pm} (K)	306	310.5	316	320	325	329	326	324	318
	T_a (K)	299	300.3	303	306	308	309	306.8	304	302.4
	I_t W/m^2	343	501	648	753	813	778.5	687	531	363.7
15th May	T_{in} (K)	301	301	301	301	301	301	301	301	301
	T_{pm} (K)	308	314	321	326	330	333	330	326	322
	T_a (K)	300	302.5	305.3	306.3	310	308	309.4	306.4	306.9
	I_t W/m^2	321	475.8	628	701	764	751	660	508	358
13th June	T_{in} (K)	303	303	303	303	303	303	303	303	303
	T_{pm} (K)	308	314	322	325.4	333.12	337.2	332	328	324
	T_a (K)	300	303	308	311.7	313.2	315	311.5	309.7	308.4
	I_t W/m^2	320	519	667	783	839	791	700	580	477

Table 3. The characteristics of PV/T collector.

Parameters	Symbols	Value	Parameters	Symbols	Value
Collector length	A	0.6m	**Thickness of back insulation**	L_b	0.05 m
Collector width	b	0.5m	**Thermal conductivity of insulation**	k_i	0.045 W/(m.K)
Pipe length	LL	4m	**Thickness of edge insulation**	L_e	0.025 m
PV thickness	L_{PV}	0.003m	**Absorber conductivity**	k_{ab}	385 W/(m.K)
Outer pipe diameter	D_O	0.012m	**Absorber thickness**	L_{ab}	0.001 m
Inner pipe diameter	D_i	0.01m	**Coefficient of heat transfer inside tube**	h_i	333 W/(m^2.K)
Outside Tube radius	r_2	0.006m	**Transmittance**	τ	0.88
Inside tube radius	r_1	0.005m	**Absorptance**	α	0.95
Area of collector	Ac	0.3m^2	**Bound of conductance**	cb	∞
Number of glass cover	N	1	**Coefficient of wind heat transfer**	h_w	10 W/(m^{2}K)
Plate emittance	ϵ_p	0.95	**Reference temperature**	T_r	25°C
Glass emittance	ϵ_g	0.88	**Reference efficiency**	η_r	14%
Tilt angle	B	30°	**Specific heat**	C_p	4180
Fluid flow rate	$\dot{m}$	0.0039 kg/s			

4. Results and Discussion

This item will present and discuss the results obtained from the mathematical program and CFD simulation. Theoretical calculations were performed in hot weather conditions for days (for 24th of April, 15th of May and 13th of June) at flow rate of 0.0039 kg/s and 0.0039, 0.0075 and 0.01 kg/s for day 13th of June to show the effect of cooling on the PV panel performance.

4.1. Thermal performance of PV/T collector

Daily thermal efficiency of PV/T collector for days (for 24th of April, 15th of May and 13th of June) at flow rate 0.0039 kg/s) are 84%, 80% and 81.3% respectively. Figure 5 shows the relationship between the intensity of the solar radiation and the amount of heat gained at the same flow rate of 0.0039 kg/s. In general, the results illustrate that the behavior of the amount of heat acquired is similar to the behavior of the solar radiation intensity for all the days studied, where the amount of heat starts to increase until reaching higher at solar noon and then gradually begins to decrease as it reaches the lowest possible at 4.00 pm. The results illustrate for 24th of April, the amount of heat gain is higher than the others until 10.00 am, but after these times the heat gain for 13th of June is higher than others. This increase in the amount of heat gained indicates an increase in the amount of heat withdrawn from the photovoltaic plate, thus increasing its cooling.

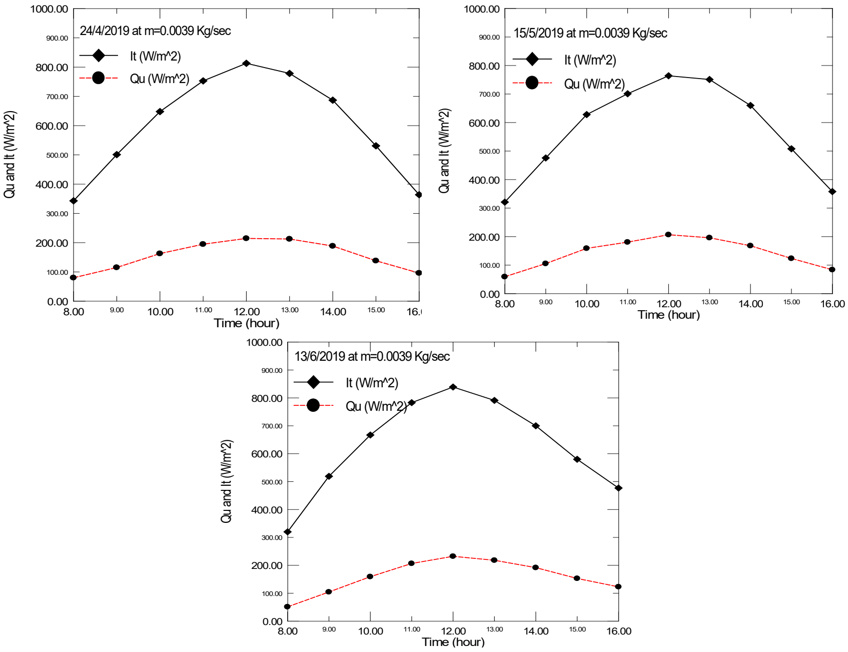

Fig. 5. Relation between useful energy and solar radiation with time.

4.2. Effect of cooling on the photovoltaic temperature

Figure 6 demonstrates the relationship between the temperature of the photovoltaic panel with time in the absence and absence of cooling. The results generally illustrated that the temperature of PV in the case of cooling was less than without cooling for all the days studied. As the percentage decreased of the photovoltaic temperature is about 5.8% for 24th of April, 5.5% for 15th of May and 7% for 13th of June than the condition of without cooling .This due to the effect of coolant (water) to improving the performance of the photovoltaic panels in hot weather conditions.

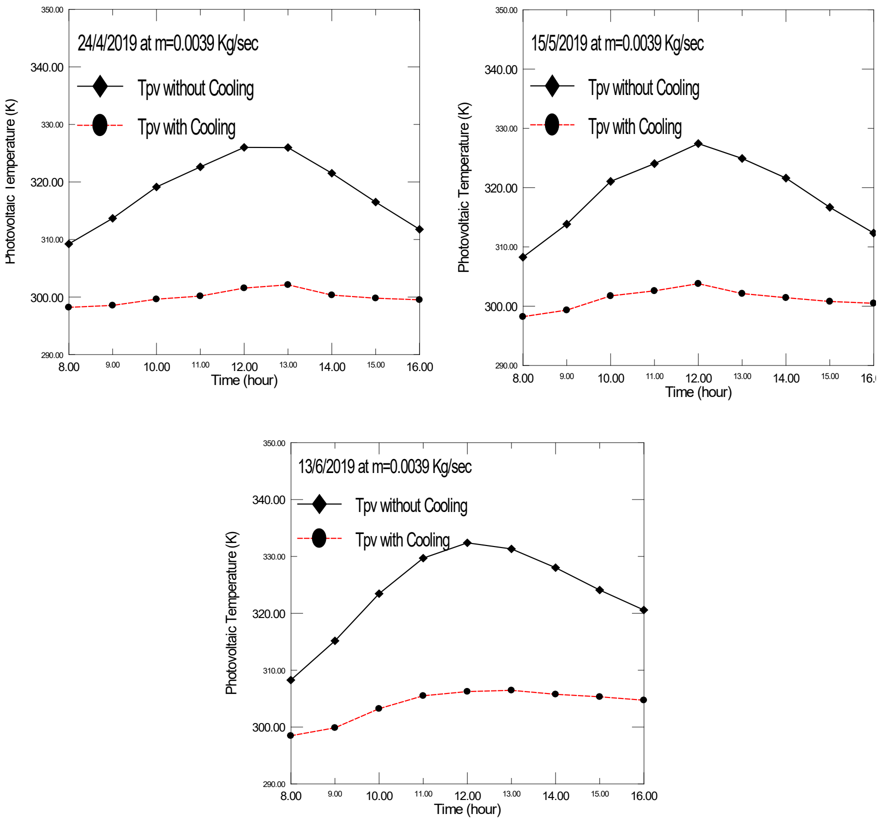

Fig. 6. Photovoltaic temperature with and without cooling.

4.3. The effect of photovoltaic temperature on the electrical efficiency

One of the most important problems with photovoltaic panels is the increase in the panel temperature, which in turn has an impact on its performance. Figures 7, 8 and 9 illustrate the relationship between the photoelectric temperature and the electrical efficiency with and without cooling for all the days studied. The results indicated the percentage of increasing in the value of electrical effectiveness is about 8.4% for 24th of April, 8% for 15th of May and 9.2% for 13th of June than the condition of without cooling. This indicates the role of cooling to improve the performance and efficiency of photovoltaic panels effectively, thus increasing its operating life. In general, the solar cell polarizes the sun rays in the form of thermal photons, which are saturated with energy from the sun light, so the solar cell will be electronically interact with the photons through germanium (Ge) and silicon (Si) elements. The solar cell consists of two layers; the first is rich with electrons (N) and second is rich with gaps (P). Normally, these photons will motivate the electron to penetrate gap layer, and this will generate a DC current. Solar cell performance depends on incoming solar radiation package, increasing manufactured solar cell capacity and normal boundary operating conditions (operating design temperature 20°C). Consequently, any variation in operation design temperature will lead to decrease in solar cell power generation as a result of low motivation in photons and electrons to penetrate each other and thus will reduce internal solar cell stability (decrease in solar cell performance due to high temperature as a result of photon and electron instability. Thus, cooling technology plays an efficient rule in increasing the operating life).

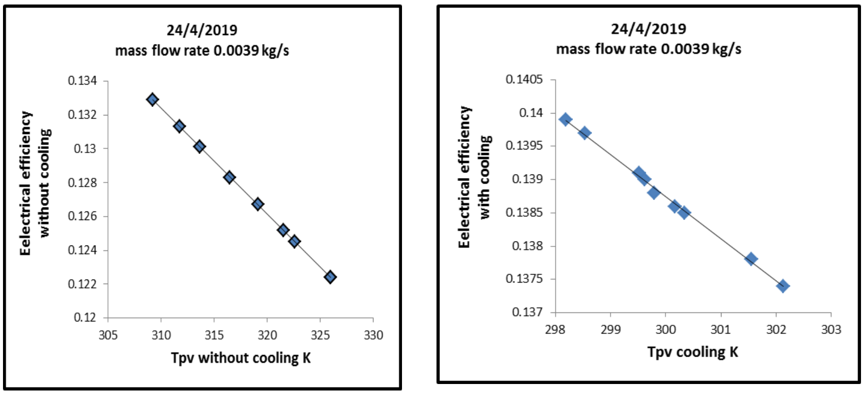

Fig. 7. Effect of cooling on the performance of photovoltaic panel in 24th of April.

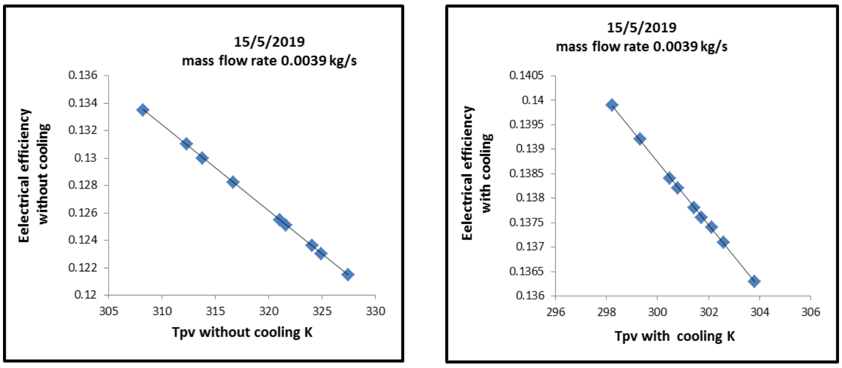

Fig. 8. Effect of cooling on the performance of photovoltaic panel in 15th of May.

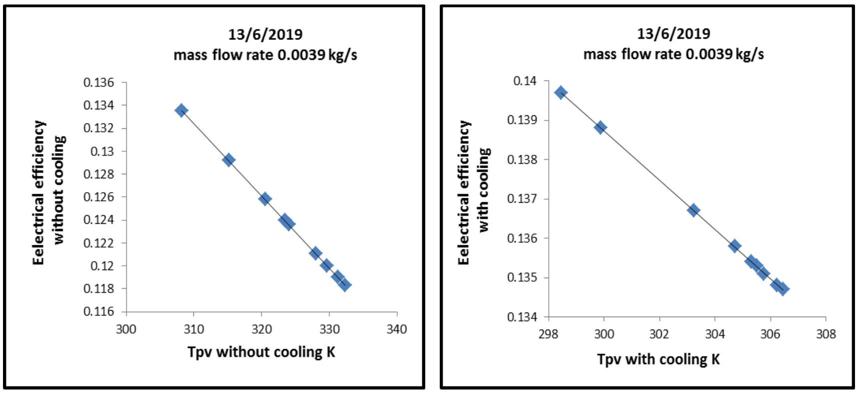

Fig. 9. Effect of cooling performance on photovoltaic panel in 13th of June.

4.4. Effect the water mass flow rate on water temperature

Figure 10 Show comparison the current numerical results with other works to validate the results and good agreements was obtained. Moreover, Fig. 11 represented comparison outlet water temperature for CFD simulation and numerical program for all selective days. The data of outer water temperature obtained from CFD Simulation is higher than numerical program data at mass flow rate of 0.0039 kg/s.

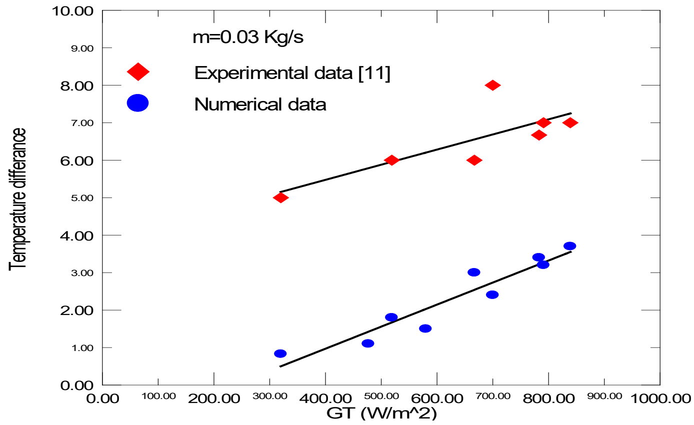

Fig. 10. Comparison with other work.

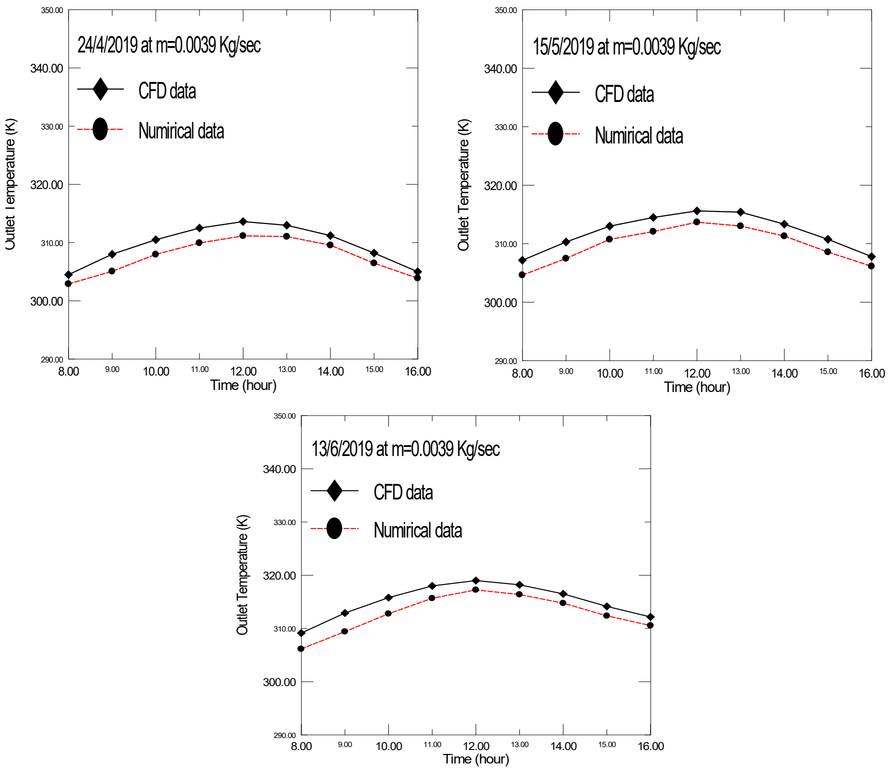

Fig. 11. Outlet water temperature.

Figure 12 shows the influence of increase of flow rates on outlet water temperature. Clearly, the temperature distribution of outlet water temperature increases gradually until reaching higher at solar noon and then gradually begins to decrease as it reaches the lowest possible at 4.00 pm. This, effect is due to increase or decrease the amount of heat gain of PV collector. The results show that when increase flow rate from 0.0039 kg/s to 0.0075 kg/s the outlet water temperature decreased about 13%. But when the flow rate is 0.01 kg/s, the outlet water temperature approaching from temperature at 0.0075 kg/s. This indicates that the cooling effect of the photoelectric panel is not effective when this flow rate is exceeded 0.01 kg/s. Therefore, we observe no change in the photovoltaic water temperature when the water flow rate increased from 0.0075 to at 0.01 kg as revealed in Fig. 13.

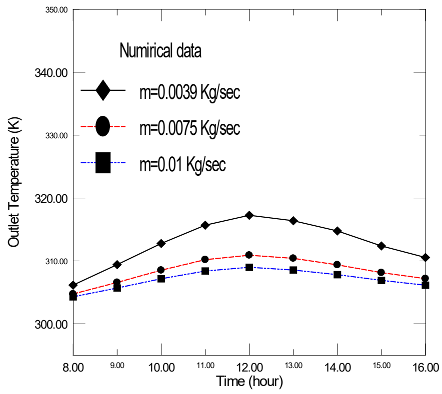

Fig. 12. Outlet water temperature 24th of April.

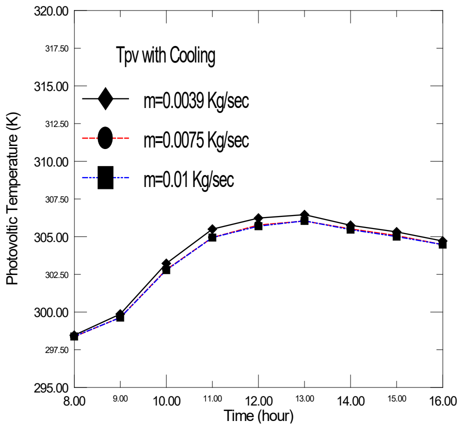

Fig. 13. Photovoltaic temperature at different mass flow rate in 13th of June.

5. Numerical Simulation

The CFD numerical results are presented and analysed to study the effects of cooling techniques on heat transfer specification and photovoltaic thermal device performance. Figure 14 shows the temperature distribution of photovoltaic panel temperature for 24th of April at flow rate 0.0039 kg/s. Figure 15 illustrates the temperature distribution of serpentine pipe at solar noon. The results show that the temperature increased towards the direction of flow. This is due to absorb more heat from PV panel towards the direction of flow and finally cooling the photovoltaic panel.

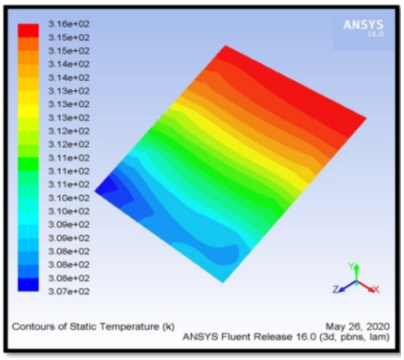

Fig. 14. Photovoltaic panel temperature.

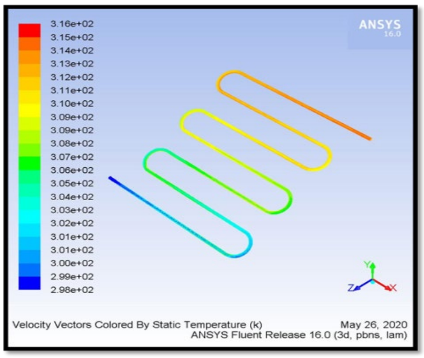

Fig. 15. Temperature distribution of serpentine pipe.

6. Conclusions

The effects of serpentine cooling system on the photovoltaic panel have been accomplished to improve the electrical effectiveness. Consequently, the overall system performance was calculated on (sunny day) of the environmental conditions at Baghdad city- Iraq. Some concluded observations in the present study are given below.

- The performance curves in this study showed the cooling of PV panel is acceptable of as compare with conventional one.
- The results showed the percentage reduction in photovoltaic temperatures is about 7% than the case of without cooling at the same weather conditions.
- It has been found that the electrical efficiency is increase in case of cooling photovoltaic panel than conventional one. which increasing its operating life.
- Robust of mathematical MATLAB program to predicting the outlet water temperature in PVT was achieved through comparing with FLUENT code and previous experimental results and good agreement was obtained.

Nomenclatures

A	Collector length, m
B	Tilt angle, degree
Ac	Collector area, m^2
b	Collector width, m
cb	Bound of conductance, W/(m. K)
C_p	Specific heat, J·kg^{-1}·K^{-1}
D_O	Outside tube diameter, m
D_i	Inside tube diameter, m
F	Fin efficiency
$\bar{F}$	Collector effectiveness factor
F_R	The heat removal factor
h_i	Coefficient of heat transfer inside tube, W/(m^2. K)

h_w	Coefficient of wind heat transfer, W/(m^2. K)
I_t	Hourly solar radiation, W/m^2
k_{ab}	Absorber conductivity, W/(m. K)
k_i	Thermal conductivity of insulation, W/(m. K)
Kpv	Photovoltaic conductivity, W/(m. K)
L_{ab}	Absorber thickness, m
L_b ,L_e	Thickness of insulation (back, edge), m
LL	Pipe length, m
Lp	Photovoltaic thickness, m
$\dot{m}$	Fluid flow rate, kg/s
N	Number of glass cover
T_a	Ambient temperature, K
T_i	Inlet water temperature, K
y^+	Nearest grid cell to the wall
T_{pm}	Mean plate temperature, K
T_{PV}	Photovoltaic temperature, K
T_r	Reference temperature, K
Q_U	Useful energy, W/m^2
U_b	Bottom loss coefficient, W/(m^2. K)
U_e	Edge loss coefficient, W/(m^2. K)
U_T	The over loss coefficient, W/(m^2. K)
U_t	Top loss coefficient, W/(m^2. K)
W	Tube spacing, m
Greek symbols	
η_T	Total efficiency
$\eta_{e.}$	Electrical efficiency
η_r	Reference
ϵ_g	Emittance of glass
ϵ_p	Emittance of plate
α	Absorptance
τ	Transmittance
Abbreviations	
3D	Three dimensions
CFD	Computational fluid dynamics
PVT	Photovoltaic thermal collector
REF	A single-pass air channel attached behind the module
TMS	A double-pass configuration and heat extraction surface

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