Numerical Study of Inspection the Photovoltaic System with Active Cooling

Ghanim Thiab Hasan, Kamil Jadu Ali, Ahmed Hasan Mohammad
Oil and minerals, College of Engineering, Tikrit University, Iraq
ganimdiab@yahoo.com

ABSTRACT -Electricity become a part of human modern life. It has many uses in our daily life and we cannot think of a word without electrical power. Solar source can replace the current fossil fuel or gas for generating the electric power. The aim of this study is to establish a simulation model to investigate the performance of a photovoltaic thermal system (PV/T) by using computational fluid dynamics method (CFD). The model includes a water conduct tube, absorber plate and system for convection heat transfer. The ANSYS FLUENT software has been used for simulation process. The panel electrical output and its efficiency were numerically investigated. In addition, the effect of the absorbed radiation changes on the inlet fluid temperature and absorbing plate on the system performance were investigated. A dynamic analysis of hybrid photovoltaic thermal system with a circulatory pump was given. A detailed mathematical model of the system is presented. The study was conducted for three cases, in the first case, when there is no coolant in the system and in the second case, at a constant fluid flow of the pump, while the third case with optimized operation of the pump. The obtained numerical results by CFD simulators were compared with the experimental results of the documentation. The both results have good agreement. From the obtained results, it can be seen that the system gives a good improvement for the net electrical efficiency of 3.52 % with a low reduction in thermal efficiency of the system by 1.96 % compared to the system when the consistently high flow is used.

Keywords: cooling photovoltaic-thermal systems, circulation pump, Flow optimization.

المستخلص– اصبحت الطاقة الكهرباء جزءا من الحياة البشرية الحديثة من خلال الاستخدامات العديدة في حياتنا اليومية ، بحيث لا يمكن التفكير في عالم بدون الطاقة الكهربائية. يمكن للطاقة الشمسية ان تكون مصدر استبدال للوقود الاحفوري الحالي أو الغاز لتوليد الطاقة الكهربائية. ان الهدف من هذا البحث هو إنشاء نموذج محاكاة للتحقيق في أداء النظام الحراري الضوئي (PV/T) باستخدام طريقه ديناميات السوائل الحسابية (CFD). ويشمل النموذج أنبوب جريان المياه ، ولوحه للامتصاص ونظام لنقل الحرارة . وقد تم استخدام برنامج ANSYS لعمليه المحاكاة. وتم التحقيق عدديا في الناتج وكفاءته. بالإضافة إلى ذلك ، تم التحقيق في تأثير التغيرات الإشعاعية الممتصة علي درجه حرارة السائل المدخل واللوحة الممتصة على أداء النظام. وقدم البحث تحليل ديناميكي للنظام الحراري الضوئي الهجين مع مضخة الدوران. كما تم تقديم نموذج رياضي مفصل للنظام. تم اجراء البحث لثلاث حالات ، في الحالة الاولى ، عندما لا يكون هناك مبرد في النظام وفي الحالة الثانية عندما يكون هناك تدفق سوائل ثابت من المضخة ، في حين ان الحالة الثالثة مع التشغيل الأمثل للمضخة. تمت مقارنه النتائج الرقمية التي تم الحصول عليها بواسطة محاكيات CFD مع النتائج التجريبية الموثقة وتبين ان هناك توافق لكلا النتائج . من خلال النتائج التي تم الحصول عليها ، يمكن ان نرى ان النظام يعطي تحسينا جيدا للكفاءة الكهربائية الصافية بنسبة 3.52 ٪ مع انخفاض في الكفاءة الحرارية للنظام بنسبه 1.96 ٪ مقارنه مع النظام عندما يتم استخدام تدفقات عالية باستمرار .

INTRODUCTION

Due to the fact that conventional energy sources (coal, oil, gas, nuclear fuels) are limited and depleting, and the energy sector is considering the main cause of environment pollution, the energy should be obtained from renewable energy sources. The solar energy is an inexhaustible and an absolutely environmentally friendly source of energy [1]. However, when the solar cell is illuminated, the photo cells will affect and on its

ends appears an electromotive force that is connected to the expended energy supply and thus the solar cell becomes a source of electricity [2]. In this way, only a small fraction of the energy of the solar radiation is transformed into electricity, while the majority is transformed into thermal energy, which is a dedicated panel resulting in an increasing in the temperature of the module which will cause a drop in electrical efficiency for about 0.5%/K [3]. Recent studies have claimed that with the appropriate mass flow rate with a low input temperature, it can be achieve a satisfactory improvement of electrical efficiency [4]. Excess thermal energy that removed by the fluid can be used for the preparation of domestic hot water or as hot water in the pools which increases the overall efficiency of the system. Increasing fluid flow requires addition electrical power of the pumps which reduces the net electrical efficiency of the system [5].

This paper describes the method of controlling the power of the pump (fluid flow) with the aim of increasing the efficiency of the photovoltaic system. However, the main problem is the energy and economic inefficiencies of unconventional energy sources compared to conventional ones. This is precisely why the dynamic analysis of the system efficiency improvement is given in this paper. We could see how the energy efficiency of the system using hybrid photovoltaic-thermal increases due to the resulting heat energy that can be used in the household, but due to the required power pump electrical efficiency decreases with consistently high flow. For this reason, it is necessary to optimize the system by the only manageable size in the mass flow system by monitoring the change of the dose to the panel and panel temperature in order to obtain the maximum net power output, photovoltaic -thermal panels and system optimization.

Solar irradiation, convection and heat transfer mechanisms are modelled using the CFD method by Selmi et Al. [6]. He was found that the use of forced-flow water has a lower temperature than that of no-flow water. A similar test design has been constructed to consider the validation of the simulated model. There was a high match between the results of the experiments and the simulation results.

Siddiqui et al. [7] has developed a numerical model for comparing a hybrid PV/T system with a PV module. The thermal and electrical sections were combined to provide a multi-physical model. The influence of certain parameters including absorbed radiation, resistance to thermal contact, input temperature and entry velocity were also investigated. It was deduced that the PV/T systems can be used in areas where both solar radiation and ambient temperature are high.

A dynamic simulation was applied by Bhattarai et Al. [8] for comparing the performance of a metal and tube PV/T system through a solar collector. The researchers developed an one-dimensional model by solving energy conservation formulas simultaneously for different sections of a system. Numerical results were in agreement with the data that was measured in the experiment. It has been found that the day to day thermal efficiency of the solar collectors was about 18% higher compared to that of the PV/T system. While the PV/T system's primary energy savings were higher than those of the PV collector.

Cerón et Al. [9] also developed a 3-dimensional model for collectors with flat plates made of metal sheet and pipe. In this study, a number of different heat transfer systems were considered in a stable combined simulation. Numerical results were evaluated with experimental results and standard heat transfer correlations. Moreover, on Nusselt, a number of heat transfers by convection have been calculated for the fluid in the water within the tubes.

Aste et al. [10] reported a novel design of a roller-bond structure PV/T. A simulated model has also been obtained by resolving the related energy balances of the system to assess heat and electrical performance.

An experiment involving a PV/T prototype was installed and observed by Haurant et al. [11] for 18 months. They also provided a simulation model for the PV/T system described in TRNSYS. Simulation software. The results of the simulation and the observed data have been compared. A high agreement was found between the results of the simulation and the results of the experiments.

Photovoltaic thermal system
The photovoltaic thermal system consists of a photovoltaic -thermal panel, which in this study has 24.89 m surface, water tank and circulatory pump. The photovoltaic- panel converts the energy of solar into electricity. The thermal part of the

system represents the absorber plate which has the duty to transfer the resulting heat energy from the panel to the fluid. Heat exchanging occurs in the water tank, where hot water is supplied at the top of the tank, while cold water is brought to the bottom of the tank. Cold water through the circulatory pump sends with the default mass flow to the background of the panel.

Photovoltaic-thermal system was designed in a way that simple photovoltaic solar cells are added directly above the solar absorber. The system consists of glass cover that leaks light to the absorber, photovoltaic cells that convert the energy of the solar dosing into direct electricity and the absorber plate which plays a role of heat transfer from the collector to a tube-passing fluid. The block diagram of photovoltaic -thermal system is shown in Figure 1.
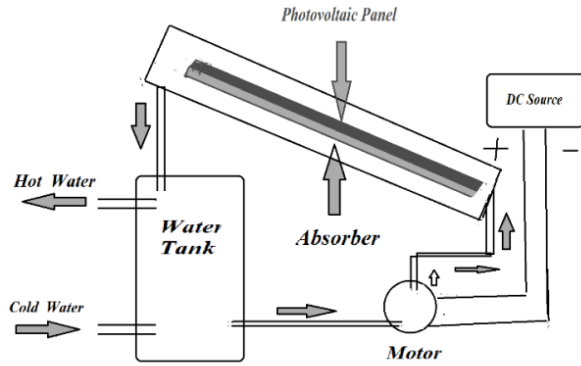
Figure 1: Block diagram of photovoltaic -thermal system.

The pump is part of a photovoltaic -thermal system which has the duty to maintain the desired flow through the background of the Panel. Thus, realizing the resulting thermal energy of the panel and cooling it. To maintain the desired flow, the required electrical power of the pump is given by the following equation [12]:

$$Pp = \frac{Km^3}{2A_C^2 \varphi^2 \eta} \qquad (1)$$

where: K is the total coefficient of loss, m: is mas of flow rate, ρ is fluid density, Ac is: area of the cross-section of the pipe and η is efficiency of the pump.

From equation 1, it can be seen that the only variable is the fluid flow mass, while all other parameters are constant and depend on the physical characteristics of the system and fluid. The required electrical power for the operation of the pump is actually an extremely nonlinear function that cubic increases with increasing the flow fluid mass.

Effect of temperature on photovoltaic panel characteristics
Any Changes in the temperature will cause some changes in the characteristics of photovoltaic cells. For study the cell characteristics, it is important to know how the temperature affects the following parameters: Short circuit current I_{ks}, current cell I, open circuit voltage Uok, maximum power Pm and efficacy of cell η. It is common for efficiency to decline around 0.5% for the panel temperature increase of $1\ ^oC$. The reason is that the increase in temperature will cause some reduction in the forbidden belt width, which causes a slight increase in the saturation current, but due to the increase in temperature the kinetic energy of molecules is increasing, which results in decreasing the electric field of the P-N compound. Reducing the electric field causes electrons and cavities to be recombined more quickly, which ultimately represents a reduction in the open circuit voltage.

The temperature change mainly affects the amount of the open circuit voltage. The short circuit current I_{ks} depends on the temperature and can be written as [13]:

$$I_{Ks} = AT^3 \exp(-\frac{qU_{Ok}-E_g}{KT}\pi r^2) \qquad (2)$$

where:
A: collector's surface, T: temperature of the collector, q-Elemental charge (1,602x10 C),
Uok-voltage open circuit, Eg-width of the Forbidden Belt (eV). K-Boltzmann constant (1,3806 x 10 J/K)

Calculation of Total Panel Irradiation
The electrical power of the photovoltaic panel is often determined by the striking solar dosing. The solar dosing on the inclined surface I_{tt} can be expressed as the sum of the following three components [14]:

$$I_{tt} = I_{b,T} + I_{r,T} + I_{d,T} \qquad (3)$$

where: $I_{b,T}$ is the direct sunlight is on the inclined surface, $I_{r,T}$ is the the diffuse solar irradiation on the inclined surface and $I_{d,T}$ is the reflects of the sun's irradiation on the inclined surface.

$$I_{b,T} = I_b \cos\theta \qquad (4)$$

$$I_{d,T} = I_d cos^2 \frac{\beta}{2} \left[1 + F \, sin^3 \frac{\beta}{2} \right] \qquad (5)$$

$$I_{r,T} = \rho \, (I_b cos\Theta z + I_d) \, sin^2 \frac{\beta}{2} \qquad (6)$$

Where: I_b : is the direct (normal) solar maturation, I_d : diffuse horizontal solar maturation, : is the tillage of the collector in relation to the horizontal surface, ρ: albedo soil, F : modulating factor, Θ : is the angle between the direction of the sun and the normal tilted surface, Θz : the zenith angle of the sun, the angle of tilt of the surface β,

$$cos \, \theta = cos \, \theta \, z \, cos\beta + sin \, \theta \, z \, sin\beta \qquad (7)$$

The modulation factor F can be calculated as [14]:

$$F = 1 - \frac{I_d}{I_t} \qquad (8)$$

where: It is the total solar dose on a horizontal surface and is calculated as [14]:

$$I_t = I_b \, cos\Theta \, z + I_d \qquad (9)$$

The angels that determine the optimum panel position is demonstrated in Figure 2.
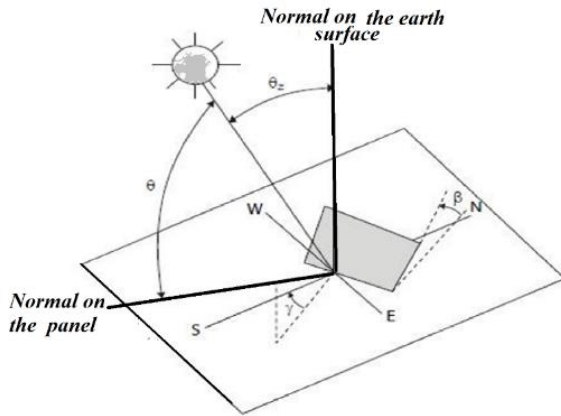

Figure 2: The angels that determine the optimum panel position [15]

Mathematical Calculation of Photovoltaic Thermal System

One of the factors influencing the operation of the photovoltaic panel is the temperature. Part of the sun's irradiance that falls on the system is mostly absorbed by the panels and turns into electricity and surrenders, while the other part becomes the internal energy of the material from which the panel is made and the whole system temperature rises. This heat will transfer to the fluid circulating through the pipes in the absorber. The processes of exchange of heat that occur are convection, conduction, radiation. Taking all these parameters into account we get the equation of the temperature change module as follows [16]:

$$C_{Mod} \frac{dt_{Mod}}{dT} = q_{Lw} + q_{Sw} + q_{Con} - P_{Out} - Q_t \qquad (10)$$

where: C_{mod} is the modules heat capacity, dt_{Mod} : is the module temperature, q_{Lw} : is the power of long-wave radiation, q_{Sw} : is the charge of short-chain radiation, q_{Con} : is the power-conduction heat-convection, P_{out} is derived electrical power panels and Qt is the taken thermal power over fluid.

For the exact budget it is necessary to know each of the specified components of the equation 10, as follows:

Thermal capacity of the module (C_{Mod})

In order to determine the thermal capacity of the module, it is necessary to know the structure of the panel itself. In our case, the panel consists of three layers: the glass cover, the mono crystalline silicon photovoltaic cells and the absorption cover. It is assumed that the temperature of the modules is uniform through all three layers. Each individual layer has its own heat capacity and the heat capacity of the module is defined as the sum of all individual layers and it depends on the type of material of each layer and strain thickness [17]:

$$C_{Mod} = \sum_{K=1}^{m} Ad_K \rho_K C_K \qquad (11)$$

Where A represent the panel surface, d_k is thickness of the individual layer, ρ_k is the density of each layer, C_k is the heat capacity of the individual layer. For our case, the characteristics of each individual layer are given in Table 1. The surface of the panel is 24.9 m².

TABLE 1: CHARACTERISTICS OF EACH INDIVIDUAL LAYER OF THE PHOTOVOLTAIC MODULE [18].

Layer	$\rho_K(kg/m3)$	d_k(m)	$C_K(J/kgK)$	C_{Mod} (j/k)
Monocrystalline	2330	0.0003	677	11780
Absorbing layer	1200	0.0005	1250	18637
Glass cover	300	0.003	500	112027
				143 (kJ/k)

Heat Transfer by Convection (q_{Conv})

Heat transfer by convection is defined by Newtovs ' cooling legislation between the front panel and the surrounding air [19]:

$$q_{Conv} = -h_C A(-T_{Mod} - T_{Amb}) \qquad (12)$$

where: h_C is the transfer factor which represent the combination of natural and forced convection. Where there is no wind, we can disregard the factor of forced convection. The coefficient of natural convection between ambient air and system is defined by the following equation:

$$h_{C,free} = 1.31\sqrt[3]{T_{Mod} - T_{amb}} \qquad (13)$$
$$b_{C,forceed} = 5.6 + 3.8v \qquad (14)$$

where v: is wind speed.

During the average day heat transfer by convection equals the sum of forced and natural convection and is given by the following equation [19]:

$$q_{Conv} = A(h_{C,free} + b_{C,forceed})(T_{Mod} - T_{amb}) \qquad (15)$$

Electrical Output Power from the Panel

The electrical output power obtained from the panel is the function of total panel maturation and panel temperature. It decreases with the increasing in the temperature and increases with the decreasing in temperature. The electrical power obtained from the panel is calculated from the known table that indicates the value of the electrical power at a specific degree of panel temperature. The row vector represents the total power of the module ranges from 1 to 1501 W/m^2, while the column vector represents the temperature of the panel ranges from 30-70 ^{o}c.

The obtained Thermal Power over Fluids

The transmission-absorption product is the product of the absorption factor and the transmission factor. The absorption factor is defined as the ability of the body to absorb the sun's maturation, while the transmission factors as the amount of solar dosing that passes through the panel body [8]. The system has an absorber of the pipe through which streams cold water and drains the thermal energy from the panels, which causes a reduction of the temperature of the panel, and therefore the greater efficiency of the obtained electrical power panel. At the same time, heat energy is obtained which can be used to prepare domestic hot water in the household, which greatly increases the efficiency of the system as a whole. The heat output from the panel Q_u according to the Hottel-Willier's equation is equal to [20]:

$$Q_u = A[L_{tt}(\alpha\tau) - U_L(T_{Mod} - T_{amb}) \qquad (16)$$

Where: U_L is the total heat loss factor, $\alpha\tau$ is the absorption transmission product.

From Equation 16, we can see how the thermal removal factor is extremely nonlinear function. All variables except mass flow are constant and are dependent on the construction of the system itself and the physical characteristics of the fluid. The heat dissipation is very low with increasing flow. So, according to equation 1, the electric power of the pump is cubic increases with increasing flow, whereby we can conclude that the efficiency of the entire system decreases with high fluid flow level.

Simulation Results before Optimizing System Operation

Before we show the results of the simulation, it is necessary to define all the parameters used in the system. Tables 2 and 3 show the main parameters of photovoltaic thermal system with their values.

TABLE 2: MAIN PARAMETERS OF PHOTOVOLTAIC PANEL USED IN THE SYSTEM [18].

Parameters of panel	Value	Parameters of panel	Value
total area (A)	24,895 m2	absorption factor	(α) 0.7
coefficient of total emission factor module (ε)	0.9	Transmission-absorption factor	0.53
heat loss	5 W/m2K	geometric factor	0.92

Other time-changing data required for the simulation (air temperature, surface irradiation, azimuth and zenith angle...) are found in the programming solution of the work in the form of a vector in one-minute resolution. Results presented are panel irradiation on inclined surfaces, panel temperature, electrical efficiency of photovoltaic panel and net electrical efficiency of the system for the hot day in 28 – 06 – 2018 in Tikrit university in Iraq republic.

TABLE 3: MAIN PARAMETERS OF PUMP USED IN THE SYSTEM [21].

Pump parameters	Value	Pump parameters	Value
Coefficient of mechanical losses (K)	15	pipe radius (r)	0.011 m
fluid density	1000	maximum	50W

(ρ)	kg/m3	power	
Thermal Capacity (c)	4186 J / kgK	input temperature in panel	18 oC

Figure 3 illustrates the dependence of the total dosing of panels on the total radiation falls on the titled panel surface, while Figure 4 illustrate the panel temperature dependence of the fluid stream
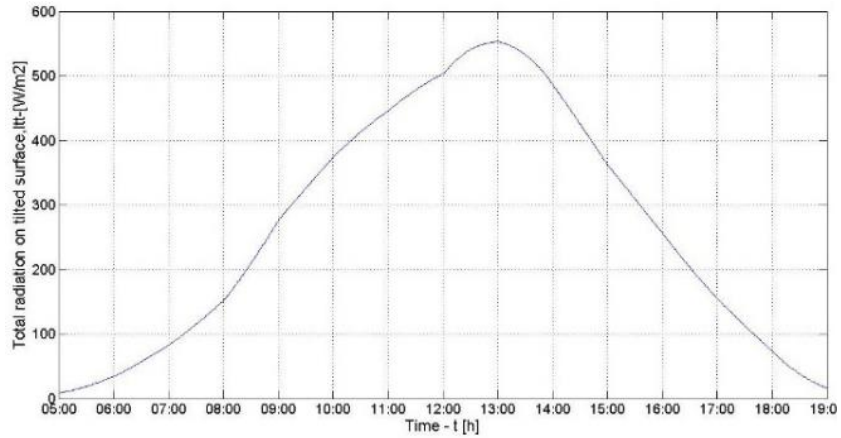

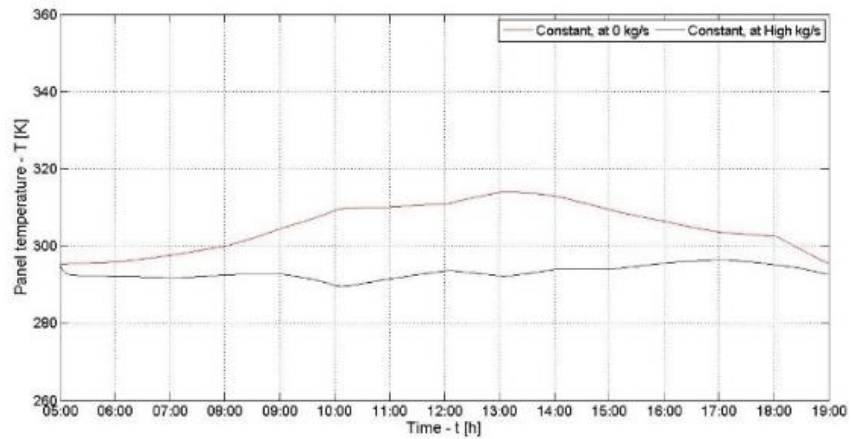Figure 3: The total radiation falls on the titled panel surface.

Figure 4: Photovoltaic heat panel temperature before optimizing the system
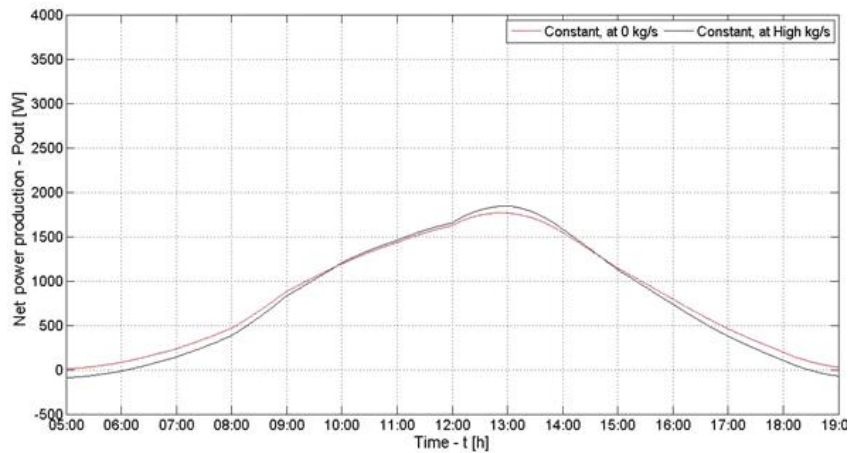

Figure 5: The net output electrical power of the photovoltaic panel before optimizing the system
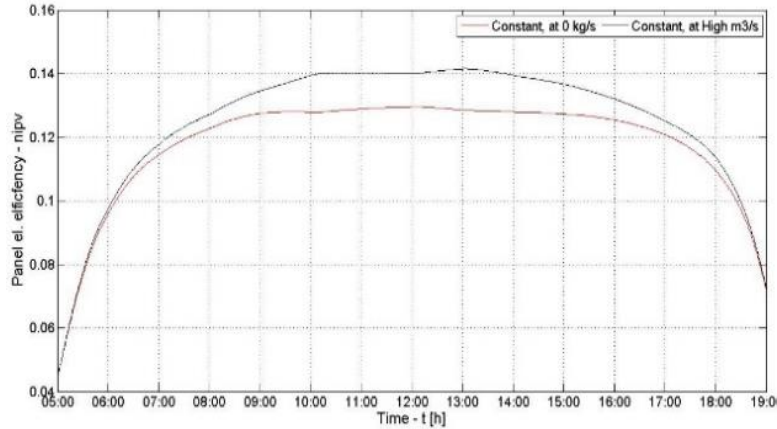
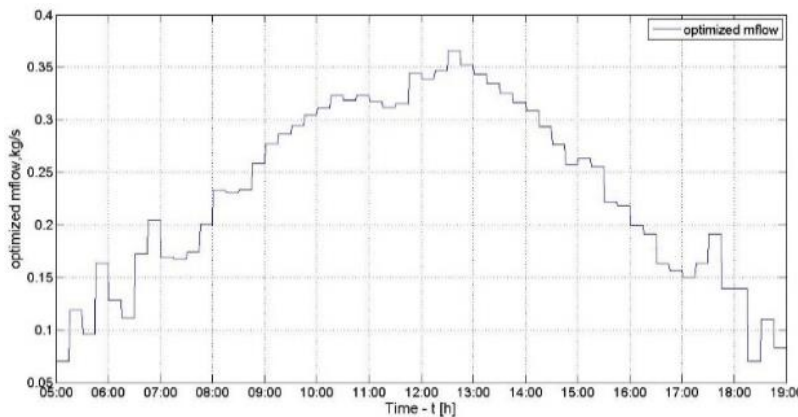Figure 6: The Photovoltaic panel efficiency before optimizing the system.

Figure 7: Optimized fluid flow through the panel in one-minute resolution.

Figure 5 illustrate the dependence of the net power production of panels on the fluid stream, while Figure 6 illustrates the panel efficiency versus the fluid stream.

From the resulting simulations it is clear that the temperature of the panel decreases at a maximum flow for 15 Kelvin for the hottest part of the day (from 10h to 16h). By reducing the temperature of the panel increases the electrical efficiency of the panel itself by 1.5% in the same period of day, which is visible from Figure 6.

For net electrical efficiency, from Figure 5, it can be seen that the system is energy efficient at maximum flow only for the hottest part of the day. When the panel temperature is not above 400C it is energy-efficient and therefore economically cool the panel at maximum constant flow because a small dose will fall on the panel in the morning and early evening. Due to the small dose of the panel, the electrical power obtained on the panels is small, while the embedded electrical power in

the pump remains constant high, resulting in the inefficiency of the system as a whole.

Therefore, it is clear that in the morning and in the evening, the net electrical efficiency is even negative, so, it is necessary to invest electricity from the network in order to achieve the desired operation of the pump. Therefore, it is necessary to optimize the system so that the mass flow of fluid in the system monitors the overall maturation of the panel through the working day.

System Simulation Results after Optimization
By using the finished algorithm, included in the programming solutions of the work, we obtained the optimum flow values in a 15-minute resolution. The optimum flow rate obtained for the in one minute, resolution is shown in the Figure 7. The energy balance of the system is shown in Table 4, for the observed day in case when only a photovoltaic module is used, a hybrid system is used (constantly high flow) and when optimized flow is used.
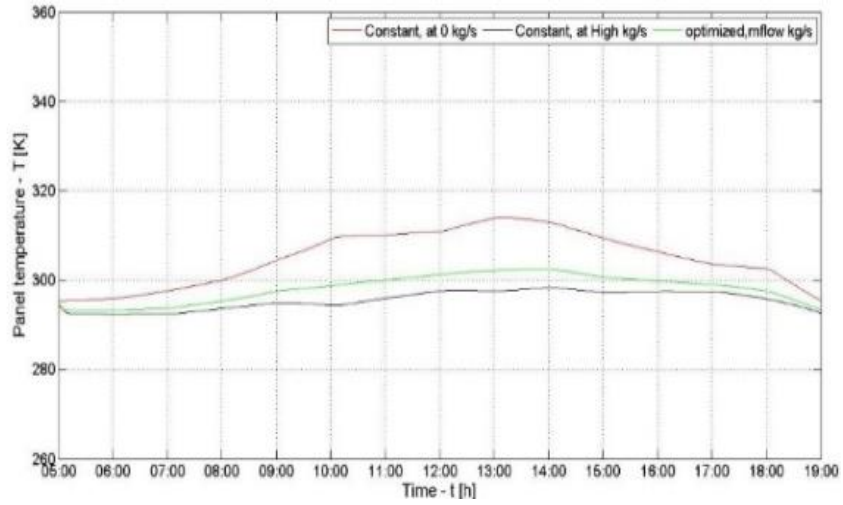
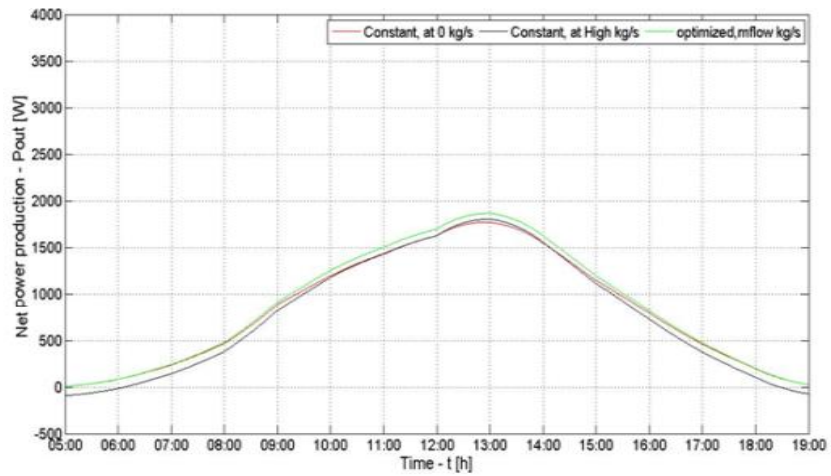Figure 8: Photovoltaic heat panel temperature after optimizing the system

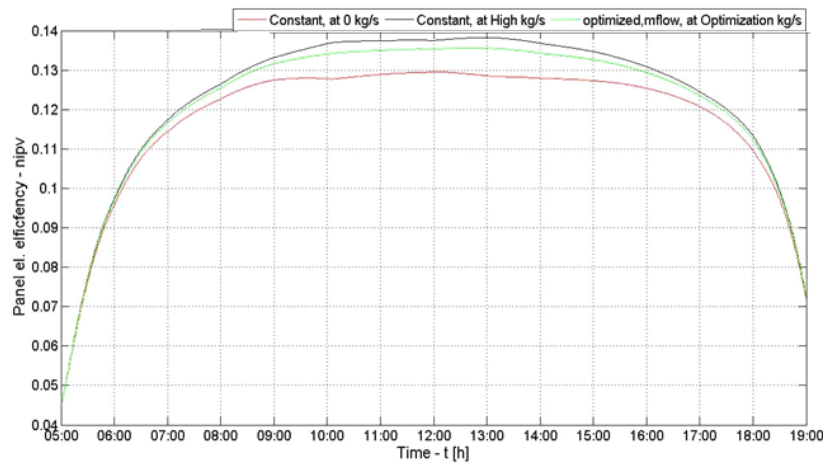Figure 9: The net output electrical power of the photovoltaic panel after optimizing the system.

Figure 10: Photovoltaic panel efficiency after optimizing the system.

TABLE 4: THE ENERGY BALANCE OF THE SYSTEM.

Module type	Average net electrical efficiency of the system, [%]	Average thermal efficiency of the system, [%]	Total efficiency, [%]	Resulting heat energy, [kWh]
PV Module	12.03	0.00	12.21	0.00
PV/T – module at consistently high flow	8.17	61.85	71.85	59.45
PV/T – Optimized flow module	13.14	60.51	73.42	56.41

Discussion

The optimizing algorithm is realized as shown in Figure 7, the optimized flow monitors the change of the total dose to the panel, and therefore changes the temperature of the panels through the day.

As a result, the resulting flow has a form of parabola, which is expected since the smallest flow is necessary in the morning and in the evening when the panel temperature is minimal and minimum cooling is required, while in the afternoon it is the largest since it is the temperature of the panel itself is highest. The result is a significant improvement of the net obtained panel power and overall efficiency of the system, as illustrated by the Figures 8 and 9.

Based on the obtained optimized fluid flow through the panel, we get the results of simulations showing the panel temperature, the net power output of the photovoltaic -thermal system, the electrical usefulness of the overall electrical usefulness of the system is when the flow rate is zero, at a maximum flow and optimized flow.

The objective of the optimized algorithm is to get the net power output of the system as large as possible. For the observed system it should be valid that the function which represents the difference in the power supply on the panel and the required electrical power in the pump must have a maximum value. Since the only manageable variable in the system of mass fluid flow is necessary to implement the optimized algorithm by that variable.

Mass flow management would be achieved with the management of the pumped electrical power at the pump in a 15-minute resolution. From the obtained simulation results, you can see that there is a significant improvement in the electrical efficiency of the entire system and the obtained net power system. There are no more efficiency losses for the period of the day when a small dose is on the panel since it is then a small flow through the system.

In the evening and morning hours the mass flow is about 0.1 kg/s which requires that the electrical power required for the operation of the pump is only a few wats, for the flow of 0.1 kg/s. The required pump power is about 1.52 W. In the hottest part of the day when the maximum panel temperature is required is also the most intensive panel cooling, the mass flow in that period of the day rises up to 0.4 kg/s for which the pump power is required for about 40.9 W.

We can conclude that by optimizing the algorithm, we can get the desired system governance i.e. the mass flow is accompanied by changes in variables that affect the resulting electrical power of the panel, the overall dose and panel temperature. That is why there is a much better system governance in the period of the day when a small dose is compared to consistently high flow and quality behavior for the hottest part of the day compared to the not cooled system. The energy balance for the observed day is shown in the conclusion.

Conclusion

The objective of this study is to investigate the feasibility of a water-based Photovoltaic-thermal system by using a mathematical module. An experiment is being made on this paper to numerically analyze the fluid-cooled Photovoltaic-thermal system by using the computational fluid dynamics method CFD. In this research, a model of a simple Photovoltaic-thermal system consisting of a water pipe and an absorbing plate has been simulated to generate the complete heat analysis module. In order to obtain numerical results, the combined thermal transfer analytical method has been applied. The impacts of the

temperature variation of the incoming water and the absorbed sunlight are considered. Both the temperature distribution across the absorber plate and the outlet water temperature are estimated in temperature curves. From the obtained results, it can be seen that the system gives a significant improvement of the net electrical efficiency of 3.52 % with a slight reduction in the thermal efficiency of the system by 1.96 % compared to the system when we use consistently high flow. While compared to the photovoltaic module itself we have an improvement in net electrical efficiency of 0.35 %. The obtained results by CFD simulators were compared with the experimental results of the documentation. The numerical simulation results agree with the results of the experimental measurements in the documentation.

REFERENCES

[1] Hu J, Chen W, Yang D, Zhao B, Song H, Ge B (2016);. Energy performance of ETFE cushion roof integrated photovoltaic/thermal system on hot and cold days. 173:40–51.

[2] Yau YH, Lim KS (2016). Energy analysis of green office buildings in the tropics photovoltaic system. ;126:177–93.

[3] Wang Y, Zhou S, Hou H (2015). Cost and CO2 reductions of solar photovoltaic power generation in China: perspectives for 2020. ;39:370–80.

[4] Correia SFH, Lima PP, Andre PS, Ferreira MRS, Carlos LAD. High-efficiency luminescent solar concentrators for flexible wave guiding photovoltaics. Mater Sol Cells ;138:51–7.

[5] da Silva RM (2010), Fernandes JLM. Hybrid photovoltaic/thermal (PV/T) solar systems simulation with Simulink / MATLAB ;84:1985–96.

[6] Elbreki AM, Alghoul MA, Al-Shamani AN, Ammar AA, Yegani B, Alsanossi , Aboghrara M, Rusaln MH, Sopian K(2016). The role of climatic-design-operational parameters on combined PV/T collector performance: a critical review. ;57:602–47.

[7] Kumar K, Sharma SD, Jain L(2017). Standalone Photovoltaic (PV) module outdoor testing facility for UAE Climate. Submitted to CSEM-UAE Innovation Centre LLC.

[8] Sahay A, Sethi VK, Tiwari AC, Pandey M(2014). A review of solar photovoltaic panel cooling systems with special reference to Ground Coupled Central Panel Cooling System (GC-CPCS). ;42:306–12.

[9] Royne A, Dey CJ, Mills DR(2013). Cooling of photovoltaic cells under concentrated illumination: a critical review. Sol Energy Mater Sol Cells ;86:451–83.

[10] Jordehi AR(2016). Parameter estimation of solar photovoltaic (PV) cells. Renew Sustain Energy ;61:354–71.

[11] Tse K.-K., Chow T.-T. and Su Y. (2016) Performance evaluation and economic analysis of a full-scale water-based photovoltaic/thermal (PV/T) system in an office building, 122, 42–52.

[12] Tan WC, Chong KK, Tan MH. (2017) Performance study of water-cooled multiple channel heat sinks in the application of ultra-high concentrator photovoltaic system. Sol Energy :314–27;

[13] da Cunha JP, Eames P. (2016) Thermal energy storage for low and medium temperature applications using phase change materials ;177:227–38.

[14] Liu L, Su D, Tang Y, Fang G. (2016) Thermal conductivity enhancement of phase change materials for thermal energy storage: a review. ;62:305–17.

[15] Su D, Jia Y, Alva G, Liu L, Fang G. (2017) Comparative analyses on dynamic performances of photovoltaic–thermal solar collectors integrated with phase change materials ;131:79–89.

[16] Wang T, Wang S, Luo R, Zhu C, Akiyama T, Zhang Z. (2016) Microencapsulation of phase change materials with binary cores and calcium carbonate shell for thermal energy storage. ;171:113–9.

[17] Hachem F, Abdulhay B, Ramadan M, El Hage H, El Rab MG, Khaled M. (2017) Improving the performance of photovoltaic cells using pure and combined phase change materials – experiments and transient energy balance ;107:567–75.

[18] Zhu L, Raman AP, Fan S. (2015) Radiative cooling of solar absorbers using a visibly transparent photonic crystal thermal black body. In: Proceedings of the national academy of sciences. p. 12282–87.

[19] Vishwanathan B, Reinders AHME, de Boer DKG, Desmet L, Ras AJM, Zahn FH, Debije MG. (2015) A comparison of performance of flat and bent photovoltaic luminescent solar concentrators :112:120–7.

[20] Correia SFH, Lima PP, Andre PS, Ferreira MRS, Carlos LAD. (2015) High-efficiency luminescent solar concentrators for flexible wave guiding photovoltaics. Sol Energy Mater Sol Cells ;138:51–7.

[21] Popovici CG, Hudisteanu SV, Mateescu TD, Chereches NC. (2016) Efficiency improvement of photovoltaic panels by using air cooled heat sinks. Energy Procedia ;85:425–32.