Performance Evaluation for the Parabolic Photovoltaic/Thermal Hybrid Solar System

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***Abstract*— Concentrated Photovoltaic Thermal (CPVT) or as it known in markets as stand-alone unit for the remote areas to supply the area with electricity and thermal hot water which is used for many years with different applications. In Heliopolis University (HU) for Sustainable Development; two modules have been tested, thermally and electrically. The module of triple junction photovoltaic is the one which has the ability to work under high temperature. When the concentrated heat was focused on the electric module, the cooling is must to drop the temperature from 120 °C to 45 modules, the cooling is essential to drop the temperature from 120 °C. The production of the heat has directed to cool the cell; which plays an important role to use the thermal heat in different applications. The performance of the two modules has been investigated and the whole system has been described in details. At the end; the research proposed different types of the thermal modules when it was noted that the useful power produced by the thermal was much power than the electric power produced by the photovoltaic PV. The system moves about two tracking axes and operated to test modules thermal PV. The receiving modules placed on the focus line displays with ten concave mirrors five up and five down. The triple junction photovoltaic cells technology has applied with water flow channels to cool the PV cells from back. The inlet water varied from 25C to 35C. By sensing the module temperature by the thermocouple, a solar pump is operated for circulating water in the system cycle. Temperature limit is set to 72C, above which the pump operates. Within that time temperature goes below the limit and thus the operating temperature of PV can be maintained with in specified limits to secure the life time of the modules. The outlet electrical power has connected to the grid by single phase invertor. The direct normal irradiation (DNI) is measured by solar sensors mounted on a solar tracker. Experimental results are used to evaluate the optimum application in Egypt from the thermal and electrical power obtained from the system. Therefore, concentrated photovoltaic thermal CPVT is a promising technology for smart Cities.**

I. INTRODUCTION

The researchers attempted to enhance the performance of the photovoltaic which started from 8% performance reached to 20% with different types and manufactures [1], the system of the photovoltaic usually affected by many parameters which reduce to power output and drop the current-volt (IV) curve of the maximum power point of the PV[2]. Dust, temperature, tilting angle and orientations are parameters have significant consequences on the performance of the PV [3]-[4].

The type of the thermal modules was playing an importing role to increase the performance of the thermal system which were either flat plate collectors or evacuated tube collectors [5], [6]. With reference to the previous work, the annual absorbed by our land approximated to be 3.85 million EJ [7], the collectors also were varied from parabolic trough (PTC), or linear Fresnel reflectors and concentrator of photovoltaic thermal CPVT. These types contributed to enhance the usage of the solar power into heat and electricity[8]. The beginning of the work for concentrator of photovoltaic thermal CPVT type of collectors started in Sandia the national Labs in 2007 [9]. Science that, several approaches and designs with number of experiments and investigations to improve the performance of the PV and thermal unit in the concentrator of photovoltaic thermal CPVT some of the experiments reached 66% of the system [10] and maximum media fluid to 200C [11]. The cost benefits in Egypt was not in the scope of research for small applications yet but it should be further work of our team and applied on the system exist in our university. Meanwhile cost of electricity in the application of the concentrated solar power was 2.37 $ per watt in [12] and the total production of thermal and electricity cost 8.7$ per watt in [13]. The thermal conductivity and the basics of the thermodynamics become the essential researches to enhance the performance of the concentrator of photovoltaic thermal CPVT. Also the concentration ratio is one of the main factors for the concentrator of photovoltaic thermal CPVT collectors. The use of triple junction photovoltaic performance for the system of CPVT is expected to reach 30% from its conversion ratio between the solar power to the output electrical power according to the experiments studies in [14]-[15]. Among the alternatives of the concentrator of photovoltaic thermal CPVT units and collectors, Fresnel lens reflectors ranked as the most suitable type to be used in concentrator of photovoltaic thermal CPVT for advantages of the size, the weight and cost in the previous work [16]. It reaches 26% of its theoretical efficiency with production of 30KW. Hybrid the thermal and photovoltaic has overcome the challenge of expensive PV for high performance and the number of the cells has reduced. The previous work of the researchers, a dynamic simulation model for the performance of the heating and cooling of the solar power has studied applied on LiBr-HO absorption

Chiller for both types of concentrated solar power and evacuated tubes and the results were simulated on Matlab and agreed with the pervious studied using Trasys software [17]. In Tunisian research team, the researchers tested two water mass flow rates and 3D CFD model interpreting and predicted the temperature for the different components in this hybrid system [18]. Much more studies of the different collectors and parameters with their effect of the coefficient of performance of the concentrator of photovoltaic thermal CPVT is discussed in details in [19]. Also in India, the researchers studied the performance of the fully use of the solar efficiency as heat and electricity and have concluded their work with using the water as the fluid to cool the PV cell[20]. Modeling of both the thermal and electrical modules has applied using COMSOL Multiphysics environmental software and PSIM environmental software to enhance the performance of the system[21]. Another modeling has presented in Tunisia for the texture application and improve the total efficiency including the losses of heat [22], and another application for supermarket [23]. Also for small scale as domestic use [24]. For the large scale systems, compound parabolic concentrated system has been used in steady and unsteady state conditions, the output were 55% and 1,730,039 KJ [25]. To compare the most existing low concentration systems with linear focus, which use silicon crystalline cells, it was reported in the review paper [26]. In the present system, the module installed is called triple junction solar cells. This type is depended on efficiency on the operating temperature and can work with good efficiency even with high temperature which could reach 120°C, as shown for example by [27] . This allows heat production at medium temperature during the experiment with active cooling. In Iran, the system of CPV/T has be determined for a house consists of 5 persons to supply electrical and thermal power and the results give the following percentages for the house's needs 61.7%-83% of thermal and 24.5% to 43.9% of electrical [28]. And for the technology of compound parabolic concentrator (CPC) with using the flat plate collector receiver, the overall efficiency was 26.5% but the results indicate that further research is needed in that system of concentrated power [29].

The experiment of a system of concentrated photovoltaic/thermal prototype has set at Heliopolis University (HU) for Sustainable Development in Egypt as hot arid region. The system has been tested and the results has recorded with its remarks and conclusion. Consequently, concentrated photo voltaic CPVT is a encouraging technology for future Smart Cities which is based on the clean renewable energies.

Nomenclature

CPVT *Concentrated photovoltaic/thermal*
PV *Photovoltaic*
A_m *projected area of the mirrors* (m^2)
cp *specific heat of the water* ($J\ kg^{-1}\ K^{-1}$)
DNI *Direct Normal Irradiance* ($W\ m^{-2}$)
$\dot{m}_W$ water mass flow rate ($kg\ s^{-1}$)
I current generated by the photovoltaic cells (A)
HE heat exchanger
I_L light current (A)
E voltage (V)
P_{el} electrical power (W)
q_{th} useful heat flow rate (W)
t time (s)
I_0 diode reverse saturation current (A)
T temperature (°C)
T_m^* reduced temperature difference ($K\ m^2\ W^{-1}$)
$\dot{V}$ Volumetric flow (m^3)

Greek symbols

η_{el} electrical efficiency (-)
η global efficiency (-)
ρ density ($kg\ m^{-3}$)
η_{th} thermal efficiency (-)

The rest of the Article is organized as follow: Section II discusses the Concentrated Photovoltaic Thermal Prototype. While Section III presents Experimental set up. Meanwhile, Section IV explains Handling of Data. Additionally, Section V demonstrates Experimental Results. Furthermore, Section VI validates the Comparison of Thermal and Electrical Model. Finally; Section VII concludes the article.

II. CONCENTRATED PHOTOVOLTAIC THERMAL PROTOTYPE

The total efficiency of the system will be calculated as the submission of the thermal and electrical efficiency separately as shown in Equation 1:

$$\eta_o = \eta_{th} + \eta_e \quad (1)$$

During the experiment, the efficiency of the photovoltaic module has be tested according to the total power of the sun to the power produced by the cell and has reached to 0.14

The value of the electric power and thermal power is differs according to the form of energy. Since the electric energy is converted from thermal energy so in order to correct that value and the energy saving of the CPVT, it should define the term of the primary energy saving as the following order:

$$E_f = \frac{\eta_e}{\eta_{power}} + \eta_{th} \quad (2)$$

When η_e the electric power generation efficiency for the photovoltaic ; and η_{power} is the electric power generation efficiency for the designed value and η_{th} is the heat collection efficiency of the concentrator of photovoltaic thermal CPVT and deferent shapes of modules has been investigated to reach the maximum thermal power [30]

The new prototype of linear photovoltaic concentrator is shown in Fig.1. Ten parabolic trough mirrors concentrate the solar radiation onto a linear receiver 6.2 m long, where a photovoltaic-thermal module is placed (at Heliopolis University (HU)). The aperture area of the present system is 17.5 m^2 and the geometrical concentration ratio is nearly 144. The system moves about two-axes (azimuthal and Elevation motions), to have the solar beam perpendicular to the surface plane.

The tracking of the sun is governed by a solar algorithm and by a pyranometer sensor when achieving the best receiver alignment.

In Fig. 2, the photovoltaic-thermal module is presented. A secondary optics device which is type of composed of flat aluminums mirrors, has been designed for reducing optical losses. The module is produced with GaInP/GaAs/Ge triple junction solar cells soldered on a ceramic substrate.by using active cooling system including an aluminum roll-bond in thermal contact heat exchanger and a closed loop for pumping water as the coolant. The roll-bond plate is applied to the back side and drowned into an elastomeric material. The PV cells have shape of square with side length equal to 10 mm and are electrically connected by number of 22 cells in package. The PV package has designed with high photovoltaic efficiency of 34.6% at 25°C cell temperature, 1000 W m^{-2} DNI, 1.5 air mass and 500X solar concentration ratio, as delivered by the manufacturer.

Fig.1. Concentrated Photovoltaic Thermal (CPVT) prototype during tests at HU, Egypt

III. EXPERIMENTAL SET UP

A scheme of the hydraulic loop built up at Heliopolis University for Sustainable Development to test the solar concentrator is reported in Fig.3. The system is described as: the water coming from the active cooling system of the photovoltaic cells enters the storage 1, then passes through a plate of heat sink. Then the water enters the storage 2, which contains number of electrical heaters for the temperature control. The operating mass flow rate is between 720 and 660 lt/hr. hence, it is possible to set the electric power to obtain a desired and constant temperature of the liquid at the inlet of the test section. From storage 2, pump is used before entering the heat exchanger of the module. PT100 platinum resistance thermometers is used to measure inlet and outlet water temperatures in the test section and the ambient air temperature.

The electrical terminals of the module are connected to a rheostat and a power analyzer that measures the current of the circuit, the voltage across the resistive load and the electrical power supplied by the photovoltaic cells. The sliding contact of the rheostat is set in order to make the PV module work close to the maximum power point during run the experiment. The type of the two solar sensors are equipped with a measuring system of solar irradiance.

The first is the standard pyranometer for the measurement of horizontal global irradiance, and the second is standard pyranometer shaded with a band for the measurement of the

Fig.2. Photovoltaic Thermal module

horizontal diffuse irradiance and a pyrheliometer mounted on a sun tracker for measuring the Direct Normal Irradiance (DNI).

IV. HANDLING OF DATA

To characterize the thermal performance of the concentrated photovoltaic thermal CPVT prototype, the inlet and outlet temperatures of the working fluid, the mass flow rate, and the ambient air temperature together with DNI, global and diffuse horizontal irradiance are measured. It was noticed that by taking the DNI's values every 10″ by a pyreliometer, the values were different than the data by JRC PVGIS by varieties from 40% to 8%. At the morning 08:00 am, the difference could reach 40% then decrease unregularly till reaches 8% at 01.00 pm

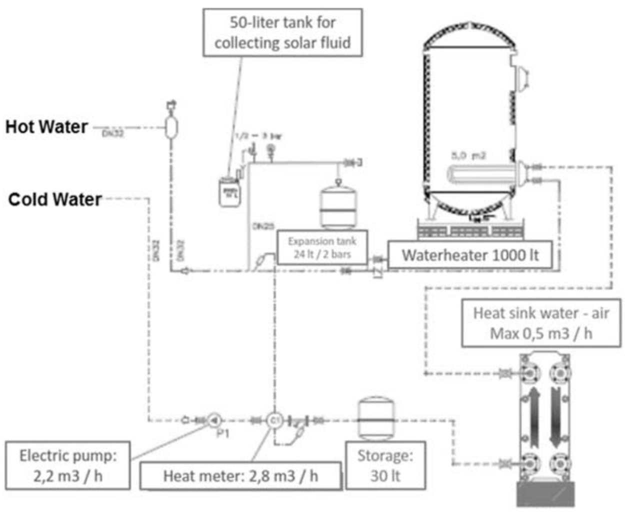

Fig.3. Schematic View Of The Auxiliary Hydraulic Components In-Out The Module

It was noted that there are no appropriate standard procedures for testing and qualifying concentrated photovoltaic-thermal devices with active cooling system as reported by[31]. The steady-state method described in EN 12975-2:2006 for the present experimental tests. Another assumption has been used during the experiment that the direct normal irradiance is considered instead of the global irradiance on the collector plane because it is the actual input energy flux of the studied solar concentrator.

The mass flow rate during the experiment was 260 kg/h, in compliance with the stated fluid flow rate of 0.02 kg/s per square meter of the aperture area. With repeating the measurements at varying inlet water temperature. And for the outlet temperature of each hydraulic circuit integrated in the heat exchanger and at the mixing point.

Test runs have been performed with two condition: in open electric circuit conditions and with electric load and connecting the rheostat and the power analyzer to the electrical terminals of the module. The output power of the single phase inverter has connected to the Egyptian local grid. The power analyzer measures the current generated by the photovoltaic cells and the voltage across the resistive load and the supplied power. To obtain the maximum power point for the electrical power output, the proper position is manually checked several times during each test run and during steady-state test conditions, measurements are collected to produce a set of thermal efficiency data points:

$$\eta_{th} = \frac{q_{th}}{DNI.A_m} = \frac{m_w.c_{p.w.}}{DNI.A_m}(T_{w,out} - T_{w,in}) \quad (3)$$

For the thermal power performance of the concentrator is mainly depends of the heat transfer and the thermal conductivity of the material of each module. The Described of the thermal efficiency is plotted as a function of the reduced temperature difference. The electrical efficiency can be calculated according to Eq. (3) when the rheostat and the power analyzer are electrically connected to the module,:

$$\eta_{el} = \frac{p_{el}}{DNI.A_m} = \frac{E.I}{DNI.A_m} \quad (4)$$

Where, the p_{el} is the power produced by the electrical module, and considering both thermal power presented in the useful heat flow rate and the electric power provided by the concentrated photovoltaic thermal CPVT prototype, the general efficiency of the investigated system can be defined as follows:

$$\eta = \frac{q_{th} + p_{el}}{DNI.A_m} \quad (5)$$

V. Experimental Results and Discussion

Two modules have been tested. The first one is the hybrid electrical thermal output, and the second is thermal only. Thermal insulation of both types of modules will stabilize the thermal power and in case of blackout the heat output will increase. During the test, the invertor switched off due to the local electrical grid instability in frequency. And this lead to increase the thermal power as shown in Fig.4 in case of hybrid module. When the blue curve (the electrical output power) dropped, the thermal output power (the red line) has increased. That means the system of the concentrated photovoltaic should become more efficient in the thermal applications if all the modules convert to only produce heat. And that explain why the system of the parabolic trough widely used in thermal power station than producing electrical and thermal.

For the experiment boundaries, *DNI* between 500 Wm^{-2} and 850 Wm^{-2}, ambient temperature between 15°C and 21°C. In open electric circuit conditions, the water inlet temperature is set at 20°C, 40°C and 45°C. With closed electric load, the simultaneous production of useful heat flow rate and electrical power is investigated by sending water to the test section at inlet temperature of 20°C, 70°C and 80°C. During the test it was noted that high umidity rate stops ultraviolet wavelength of light (< 400 nanometers) and decrease the pointing sensor efficiency.

The graph in Fig.4a) refers to the collected data during a test run displaying an outlet water temperature of around 25°C, with the rheostat and the power analyzer connected to the electrical terminals of the module. The input power, given by the *DNI* multiplied by the projected area of the mirror, the useful heat flow rate and the electrical power gained from the module are plotted against the time of the test day. The outlet water temperature is also plotted. The system without controlled the temperature on certain required value has reported during the test run with electrical production and useful heat recovery and water outlet temperature of around 86°C.

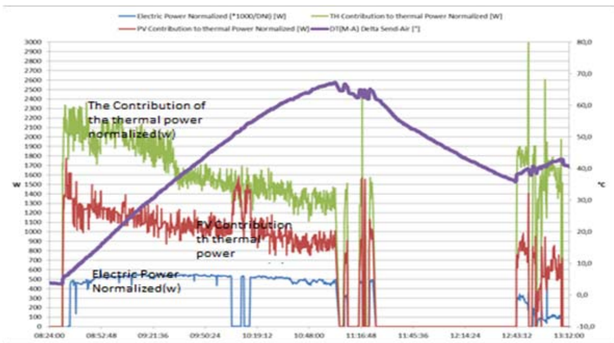

Fig.4. show the performance of the system and the production of electrical and thermal power

VI. Performance of Thermal and Electrical Model

One photovoltaic thermal PV-T module is modeled and combined with thermal module. The thermal module produced 2.365 watt thermal. The system of CPVT produced 604 watts Electrical and 1.622 watts thermal. With total power 4.591 watts total. With two different output temperatures modeled as two different applications. The system reading has plotted with respect to DNI in w/m2. Fig.5 is plotted at output temperature of 45C. This temperature has taken as hot water temperature in buildings. The direct normal irradiation (DNI) was 800w/m2 and produced 700 watt electrical power.

Fig. 5 and 6 illustrated as comparison to set the control system to switch off to sleep mode when the output water temperature reaches 45°C and 75°C respectively. When the temperature increases, the output direct current DC power decrease. In order to describe the performance of the present linear concentrator, thermal efficiency, electrical efficiency and global efficiency, measured during test runs with electric load, have been reported in Fig.6 as a function of the reduced temperature difference , the thermal efficiency obtained in test runs without electrical load is plotted against $T\ m^{*}$. While Fig.6. illustrates the solar cooling in temperature 75□C. In agreement with the previous considerations, the thermal and electrical efficiency decrease when increasing the reduced temperature difference.

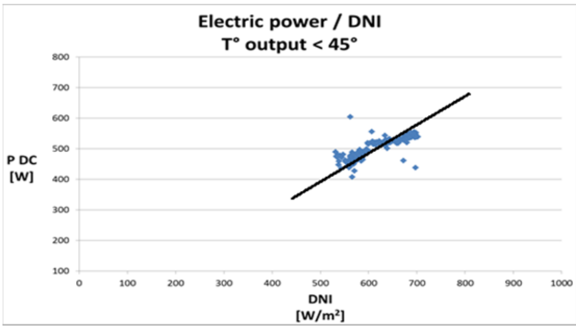

Fig.5. Output power with respect to DNI in w/m^2at 45□C

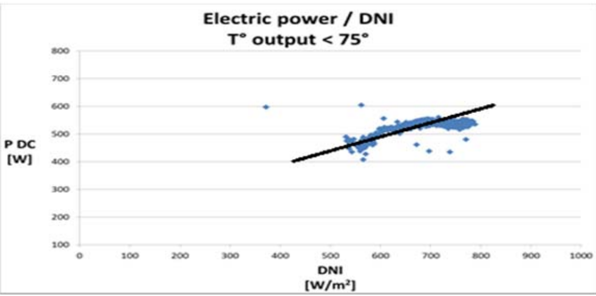

Fig.6. the Output Power with Respect to DNI in W/m^2at 75□C

This means that for a given DNI and ambient air temperature, the thermal and electrical performance of the investigated device decreases when increasing the mean temperature of the working fluid. On the whole, the global efficiency ranges between 0.7 and 0.55 when the reduced temperature difference Tm* varies between 0 and 0.082 Km2/W-1

Another assumption put one PV-T and four thermal as the focal line of the system is for number of five modules with each length of 0.95 meter. The main application was the hot water with total thermal power of 9460.00 watts in addition to hybrid PV-T with 604 watts electrical. The overall system produced 11886 watts which meets with the system peak power of 15000 watts total.

Working with combined systems, it should keep notified the importance to identify the new problems arising from the integration of the both two separate thermal and Electrical technologies. That will be critical especially when considering the long durability of the system. According to that, some reasons as trackers in concentrator of photovoltaic thermal (CPVT) need their own standard, in a hybrid concentrator of photovoltaic thermal (CPVT) system, adding extra tests are necessary to determine whether these techniques are able to deal with problems such as the failures of the cooling system, or whether there is an adjusting the control system for the case when the thermal storage system tank has reached the maximum design temperature.

The new hybrid system requires new methods to control and protect the photovoltaic raising temperature receiver against cooling system failures, and these failures should be validated and anticipated by appropriate test standards.

VII. Concluding Remarks

Heat transfer fluid (usually thermal oil) runs through the tube to absorb the concentrated sunlight. The increases of the temperature of the fluid then used to heat steam in a standard turbine generator. The process is economical and, for heating the pipe, thermal efficiency ranges from 60-80%. The overall efficiency from collector to grid, i.e. (Electrical Output Power)/(Total Impinging Solar Power) is about 15-25%,. For the system dual axis tracking, the system has installed to track east-west direction which reduce the overall efficiency of the modules than the north-south axis. However the tracking here approaches the theoretical efficiency during fall equinoxes and spring but less accurate of light at other periods during the year. Some errors have noted due to the daily sky tracking greater at sunshine and sunset and less in noon. That was required to calibrate the solar sensors from time to time. In general the whole Concentrated PhotoVoltaic Thermal (CPVT) system introduced almost 55-75% of the theoretical efficiency due to the errors which recorded to be sensor accuracy, the stability of the grid and some other difficulty have noted like the shadows and mirrors clean also the efficiency of the modules. The input power is slightly high during the test and the temperature of the outlet water around 86°C. The heat exchange was a parameter for the heat losses towards the external environment increase with the fluid working temperature and the electrical efficiency diminishes due to the higher working temperature of the triple junction photovoltaic cells. The peculiar properties of the triple junction photovoltaic cells employed in the present concentrator allow the electrical power to remain around 500-1500 W per module even at the higher temperature and that make the electrical efficiency couldn't reach more than 26% comparing to 34% with reference to the manufacturer data sheet. Regard the thermal performance, the small area of the module limits the heat losses and that was advantages because free convection and radiation was ignored during the test calculations.

This trend in thermal performance has been observed also in the test in open electrical circuit conditions. The input power and the useful heat flow rate are reported against the time of the day for two different test in which the water inlet temperature was set equal to 20°C and 40°C, respectively. For the total efficiency of the system, it can be noted that when running the concentrator of photovoltaic thermal (CPVT) system without electrical load and water inlet temperature of 20°C, the thermal production increases by the amount of 50% which led to extend the experiment in the future with only thermal modules. Two modules has been developed to predict the electric and thermal production. The electric efficiency displays a minor penalization with increasing temperature difference. And that will give the possibility to increase the operating temperature (80-90°C) to produce more heat. The measured global efficiency reaches 65%. In conclusion, the hybrid technology which develops between the two existing technologies should benefit from its own technology's standards. The new standards should be based on the existing standards and built around previous experience, and obtain the maximum benefit from industry knowledge. Hence, will lead to improved, reliable technology that benefits from consumer trust through demonstrated manufacturing quality and reliability.

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