

Modeling and Simulation of Hybrid Concentrated Photovoltaic/Thermal System

H. I. Abdelkader, A. Y. Hatata, A. Elansari, M. A. Abo-Elsoud

Abstract— Concentration photovoltaic /thermal (CPV/T) system provides, an effective way to increase the efficiency of traditional PV system. The system is producing both electric and thermal energy and recovering thermal energy at high temperature. This paper presents a model and simulation of CPV/T systems. It uses the MATLAB program to build the CPV/T. It includes modeling of the reflective optics with parabolic mirror concentrator and the triple-junction cells (InGaP/InGaAs/Ge) assembled with a dual axis tracker. Also an active cooling system of the photovoltaic cells is considered. The model adopts a mathematical approach in order to simulate and investigate the cell characterization curves including module electric and thermal efficiencies, thermal and electric energies provided by cell and module, and cooling fluid temperatures. The model works for different time levels (yearly and daily) in terms of direct normal irradiance measured practically and the results were presented.

Index Terms— Modeling of PV, Concentration photovoltaic /thermal (CPV/T), Electrical and thermal efficiency.

1 INTRODUCTION

The development of new energy sources is continuously enhanced because of the critical situation of the chemical industrial fuels such as oil, gas and others. Thus, the renewable energy sources have become more important contributor to the total energy consumed in the world. In fact, the demand for solar energy has increased by 20% to 25% over the past 20 years [1]. It is well known that, PV is the simplest technology to design and install, however it is still one of the most expensive renewable technologies. But its advantage will always lie in the fact it is environmentally friendly and a non-pollutant low maintenance energy source [2].

Amongst the various different photovoltaic technologies, the latest at present is concentrated photovoltaic, commonly known as CPV. The primary advantages of CPV systems are their high efficiencies, the systems use less expensive semi-conducting PV material to achieve a specified electrical output [3]. By concentrating the sun's radiation through magnification, the intensity of solar radiation may be increased by several times or several hundred times of its standard output [4]. This allows for a reduction in the cell area required for producing a given amount of power. The goal is to significantly reduce the cost of electricity generated by replacing expensive PV converter area with less expensive optical material. This approach provides the opportunity to use higher performance PV cells [5]. These characteristics could make CPV to be the most widely used solar energy for large generating plants in the future.

Many researches provide study the modeling of CPV/T [6-11]. Ref [6] presented the design, modeling and performance evaluation of a photovoltaic/thermal-assisted heat pump water heating system. And studied the cooling effect of enhances the PV/T efficiency and effectively improves the coefficient of performance. Ref [7] studied the effect of the collector area covered by PV module on the performance of hybrid PV/T water collector. They considered two configurations in which the collector is partially and fully covered by PV module and compared their results with those of a conventional flat plate collector. Ref [8] studied and designed low CPV and (PV/T) and the tests for a given spring climatic condition of the Tunisian Saharan city Tozeur then developed and validated against the experimental results. Ref [9] considered a PV/T collector of various geometric shape designs, and operating characteristics and discussed the effect of non-uniform flow distribution on the thermal and electrical performance of their solar systems. Ref [10] characterizes experimentally the thermal and electrical performance of a 2m² PVT system. These experiments were done for three different types of solar cells and the optimal design was evaluated. The performance evaluation and response of PV cell parameters of low level of concentration were presented in [11]. Solar cell's parameters influenced by high temperature as a result of increased irradiance was investigated also different types of heat removal arrangement were proposed.

2. Working principle of the CPV/T system

In CPV/T system applications the production of electricity is the main priority, therefore it is necessary to operate the PV modules at low temperature in order to keep PV cell electrical efficiency at a sufficient level. This requirement limits the effective operation range of the PV/T unit. For low temperatures the co-generated heat is available at relatively low temperature that can be achieved by flat plate collectors, usually about 40-60°C. Keeping the temperature low is considered an advantage since the conversion efficiency of PV cells decreases with increasing temperature. However, the collected thermal energy is suitable for domestic water heating or space heating,

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but it is inadequate for applications that require higher temperature applications for PV/T systems [12].

2.1 Concentrating photovoltaic types

Concentrating photovoltaic (CPV) is used to describe systems that combine photovoltaic (PV) cells with an optical component that concentrates light. The optical components, which are also called optical concentrators, are designed to harvest sunlight from a wide area and focus it directly onto a small area covered by PV cells. This increases the intensity of the light reaching the PV cells, which in turn increases the amount of power the cells can produce.

Concentrating photovoltaic CPV systems consist primarily of an optical concentrating element which could be a Fresnel lens, parabolic troughs dishes, V-trough mirrors, luminescent glass, refractive prism or a compound parabolic concentrator. Other elements of the system include solar cells and a heat dissipation system [13]. The CPV/T systems depend on the type of sunlight focus and they classified according to the concentration factor. In low concentration plants, the concentration factor is less than 10 (suns) while it is between 10 -100 (suns) in case of medium concentration plants, while it is between 100 -1000 (suns) for high concentration plant [7].

2.2 Cooling systems

Various cooling techniques have been proposed for cooling of solar PV cells under high concentration. These techniques aim to attain low and uniform cell temperature using simple designs, including passive cooling or active cooling [14]. Passive cooling techniques are employed with linear concentrators like the trough system where the concentration ratio is low, around 20 suns [11]. Also the heat is dissipated by natural cooling and natural convection [15], while in the case of high concentration ratio and high temperature, heat is removed from the back of solar cell by a water cooling system. However, at concentration levels of 10 and above, air cooling is not sufficient, thus there is a need for a forced cooling system that uses water, for example [11].

3. System Descriptions

The CPV/T system used in this study consists of multi junction (InGaP/InGaAs/Ge) cell and optical device which is parabolic concentrators which has high concentration ratio and temperature so it uses active cooling system, which is consisting of water pipes. The CPV/T module is connected electrically with load and the thermal energy is used for demonstrated application as shown in Fig 1.

4. Parabolic Concentrator

In CPV systems the solar radiation is concentrated by means of optical devices that allow decreasing the solar cells area proportionally to the concentration factor [7]. The active cell area is the region of the cell that is designed to be illuminated. Unlike in most non-concentrating systems, the entire cell need not be illuminated by the primary lens. The non-illuminated edge of the cell is often provided with bus bars for electrical connection, and this need not result in an efficiency loss as would be the case in a flat-plate module.

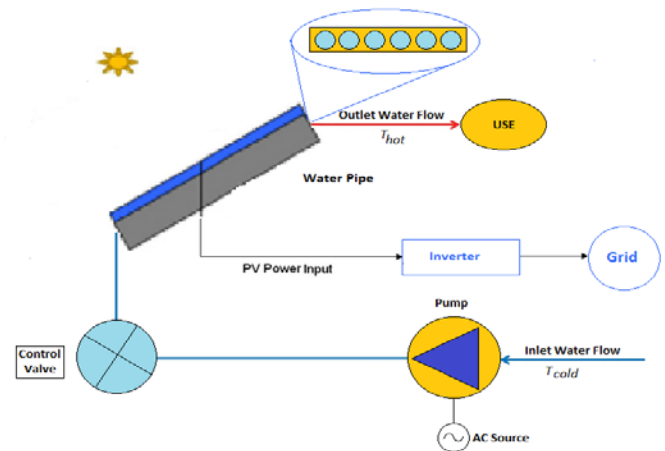


Fig.1 Block diagram of CPV/T system

Parabolas have the property that, if they are made of material that reflects light, then light which enters a parabola travelling parallel to its axis of symmetry is reflected to its focus; regardless of where on the parabola the reflection occurs [5]. A basic concentrator configuration is the reflective parabolic concentrator shown in Fig. 2. The two-dimensional cross section is shown, which could represent the cross section of either a two-dimensional linear parabolic trough or the cross section of a three-dimensional parabolic of revolution [5]

The equation relating the x and y components of the parabolic surface is [5,16]

$$y = \frac{1}{4}Fx^2 \tag{1}$$

Where F is the focal length of the parabola. It can be shown that all rays coming from straight up will pass through the focus; D is the diameter or width of the parabola. For a two-dimensional parabolic trough, the concentration ratio is given by equation below [5,16].

$$C = \frac{\cos\theta_{r,max} \cdot \sin\theta_{r,max}}{\sin\theta_{i,max}} \tag{2}$$

Where $\theta_{i,max}$ is the maximum incident angles and $\theta_{r,max}$ is the maximum reflection angles on the edge (rim angle), that the maximum concentration for a parabola at $\theta_{r,max}$ equal 45° at $f=0.6$, where f is called the f-number of the parabola [5,16].

Noting that the total receiver size, S required to capture all rays up to incident angles of $\pm \theta_{inr, max}$ [5,16].

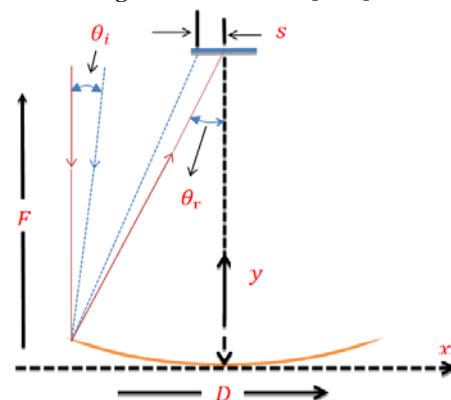


Fig. 2 Basic parabola concentrator

5. Temperature Effect

It is assumed that temperature increase has negligible effect on short circuit current, while open circuit voltage is influenced significantly. The new solar cell temperature as a result of increased irradiation is expressed according to the following equation below [11].

$$T_c = T_{amp} + \left(\frac{NOCT - 20^\circ C}{800} \right) \quad (3)$$

Where:

T_{amp} : is the ambient temperature.

G : Solar irradiation in W/m^2 .

NOCT: is the nominal operating cell temperature which is the cell temperature under standard operating conditions: ambient temperature of $20^\circ C$, solar irradiation of 0.8 kW/m^2 , and wind speed of 1m/s [17].

Variation in cell temperature occurs due to changes in the ambient temperature as well as changes in the irradiation [3]. In fact the temperature affects all of the parameters in the solar Cell's characteristic, but temperature effect on two parameters, namely open circuit voltage V_{oc} and short circuit current I_{sc} far more significantly than the others [11]. As the PV cell temperature increases above $25^\circ C$, the module V_{mp} decreases by approximately 0.5% per degree C [3].

$$V_{oc} = V_{ref} + K_v(T_c - 25) \quad (4)$$

$$I_{sc} = I_{ref} + K_i(T_c - 25) \quad (5)$$

6. Modeling of CPV/T system

The CPV/T system produces both electrical and thermal energy, and each type of energy product is calculated by a separate equations.

6.1 Electrical Energy

A) Cell electrical power (P_c)

For using a concentration system, the electrical power produced by a single cell can be calculated from the equation below [7]:

$$P_c = \eta_c \cdot \eta_{opt} \cdot A_c \cdot C \cdot G_{ind} \cdot f \quad (6)$$

Where G_{ind} is the direct irradiance per hour, A_c is the area in m^2 , and f is the non-ideal tracking system factor and equal 0.9 [7]. η_c and η_{opt} are the cell efficiency and the optical efficiency. The optical efficiency is depending on the type of mirror used and its state of cleanliness. A clean mirror made of low-iron glass with a silver back-coat should provide a reflectivity of $90\text{--}94\%$ [18]. We will use a concentration ratio of a few hundred and optical efficiency η_{opt} equal to 0.85 typical values for parabolic concentrators [19]. The cell efficiency varies with concentration C and cell temperature TC according to the equation (10):

$$\eta_c = 0.298 + 0.0142 \cdot \ln(C) + (-0.000715 + 0.0000697 \ln(C))(T_c - 25) \quad (7)$$

B) Actual electrical power ($P_{c,a}$)

The actual electric power delivered by cell ($P_{c,a}$) is given by the equation below [20]:

$$P_{c,a} = K_t \cdot P_c \quad (8)$$

Where, K_t is the correction coefficient for temperature when the standard temperature is set to $25^\circ C$ and can be calculated by equation below [20].

$$K_t = 1 + a(T_c - 25) \quad (9)$$

Where a is the normalized temperature coefficient and depend on cell type and manufacturer; analyzing many data sheets a value equal to -0.16% has been selected [7]. ($T_c - 25$) is the difference between the cell temperature and the rated temperature ($25^\circ C$).

C) Ideal module electric power (P_{mod})

Additional module losses are caused by some unavoidable spaces among the cells by front contacts that shade the cell active area, and by current mismatch due to differences in the output of cells connected in series. The electric power produced by the module can be obtained by equation below:

$$P_{mod} = P_{c,a} \cdot N_c \cdot \eta_{mod} \quad (10)$$

Where η_{mod} is the efficiency of module and fixed to 0.9 and N_c is the cell number.

D) Actual module electric power ($P_{mod,a}$)

The inverter performs the conversion of the produced DC to AC, and synchronizes the output of the PV system to the grid frequency [19]. If cell linked in series the actual electric power is given by the equation below [7]:

$$P_{mod,a} = (P_{mod} - P_{par}) \cdot \eta_{inv} \quad (11)$$

Where η_{inv} is the inverter efficiency depends on its size and other parameters; we use a typical value of η_{inv} equal to 0.9 and P_{par} is the module losses given by the equation below [19]:

$$P_{par} = G_{par} \cdot G_{ind} \cdot A_c \cdot C \cdot N_c \quad (12)$$

Where G_{par} is the losses factor depending on the radiation, and equal to 0.0023 [7].

E) Efficiency of the PV module (η_{pv})

The module efficiency under incident flux of 1 kW/m^2 (one sun), accounting for the variation of the cell efficiency with the cell temperature, and concentrating photovoltaic module overall efficiency given by equation below [20]:

$$\eta_{pv} = \eta_c \cdot \eta_{mod} \cdot K_t \quad (11)$$

6.2 Thermal Energy

A) Ideal thermal power delivered by the PV module (Q_{th})

For larger concentrators, the fraction of parasitic power is expected to be smaller. The incident power is the beam irradiation flux multiplied by the overall collector aperture area. The thermal power absorbed by the receiver can be obtained by equation below [7]:

$$Q_{th} = (1 - \eta_{pv}) \cdot \eta_{opt} \cdot C \cdot (G_{ind} \cdot f) \cdot A_c \cdot N_c \quad (12)$$

B) Actual thermal energy transferred to the coolant ($Q_{th,c}$)

Thermal energy is equal to the difference between the theoretical total thermal energy and the radiative and convective losses generally included in the range $1\text{--}3\%$ [7], and given by the equation:

$$Q_{th,c} = Q_{th} - Q_L \quad (13)$$

Where Q_L is the thermal loss which includes a convection coefficient based on a representative wind of 5 m/s [19]. So the heat loss through radiation and natural convection is given by equation [21]:

$$Q_L = [\bar{h}_c \cdot (T_c - T_o) + \epsilon_c \cdot \sigma \cdot (T_c^4 - T_o^4)] \cdot A_c \cdot N_c \quad (14)$$

Where ϵ_c is the cell emissivity and equal to 0.85 and \bar{h}_c equal to $10 \text{ W/m}^2\text{K}$ and σ is Stefan Boltzman constant equal to $5.670373 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4$ [21].

C) Fluid temperature (T_{out})

The variation of thermal energy output relative to the fluid input temperature T_{in} and outlet temperature T_{out} and is given by equation below [7]:

$$\dot{Q}_{th,c} = [\dot{m} \cdot C_p \cdot (T_{out} - T_{in})] \quad (15)$$

Where \dot{m} is the fluid mass flow rate and C_p is the fluid specific heat, for water equal to $4180 \text{ J/Kg}^{\circ}\text{K}^{-1}$. Hence the outlet fluid temperature can be obtained by equation below [7]:

$$T_{out} = T_p - [T_p - T_{in} / e^{(h_c A_c) / (\dot{m} c)}] \quad (16)$$

Where h_c is the convection heat transfer for water equal to $150 \text{ W/m}^2\text{.C}^{\circ}$ and A_c is the heat exchanger areas. In particular, the sun rays focused on the triple-junction cell allow the heating of the absorber plate, the equation that regulates the exchange between the cell and plate [7], is defined as:

$$T_p = T_c - \left[\dot{Q}_{th,c} \cdot \left(\frac{d}{N_c \cdot A_c \cdot k} \right) \right] \quad (17)$$

Where k is the conductive conductance depending on the heat exchanger type and d is heat exchanger thickness.

6.3 Overall efficiency of CPV/T

The overall efficiency of the system can be analyzed by determination of the different losses during the conversion from incident sunlight to the electric and thermal energy produced. The system produces electric and thermal energy and each of them has separate efficiency.

A) Electrical efficiency (η_{ele})

The electric efficiency described by the efficiency of CPV/T to produce the electricity from the sunlight. It can be calculated based on subsystem efficiencies as described:

$$\eta_{ele} = \eta_{opt} \cdot \eta_{pv} \cdot \left(1 - \frac{P_{par}}{P_c} \right) \cdot \eta_{inv} \quad (18)$$

B) Thermal efficiency (η_{Th})

For thermal energy product the conversion efficiency is:

$$\eta_{Th} = \eta_{opt} \cdot (1 - \eta_{pv}) \cdot \left(\frac{Q_{th,c}}{Q_{th}} \right) \quad (19)$$

The overall efficiency of the CPV/T system is the sum of

the two efficiencies:

$$\eta_{CPV/T} = \eta_{ele} + \eta_{Th} \quad (20)$$

7. Simulation of the CPV/T system

The CPV/T is simulated using the MATLAB/SIMULINK. The mathematical model of the CPV/T which is discussed in the previous section is simulated and the proposed Simulink model of the CPV/T is shown in Fig. 3. This model consists of subsystems to determine the variables of the system as illustrated in Fig. 4. The model determines the values of electric and thermal energy and efficiency of the CPV/T system as a function of hourly time.

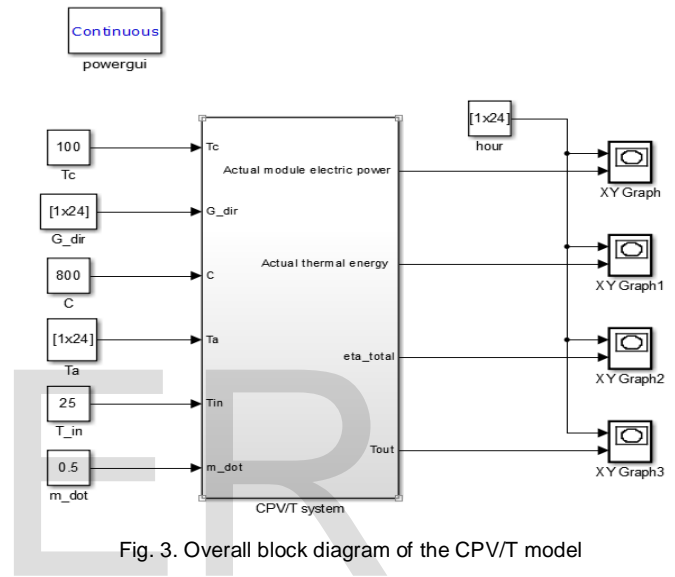


Fig. 3. Overall block diagram of the CPV/T model

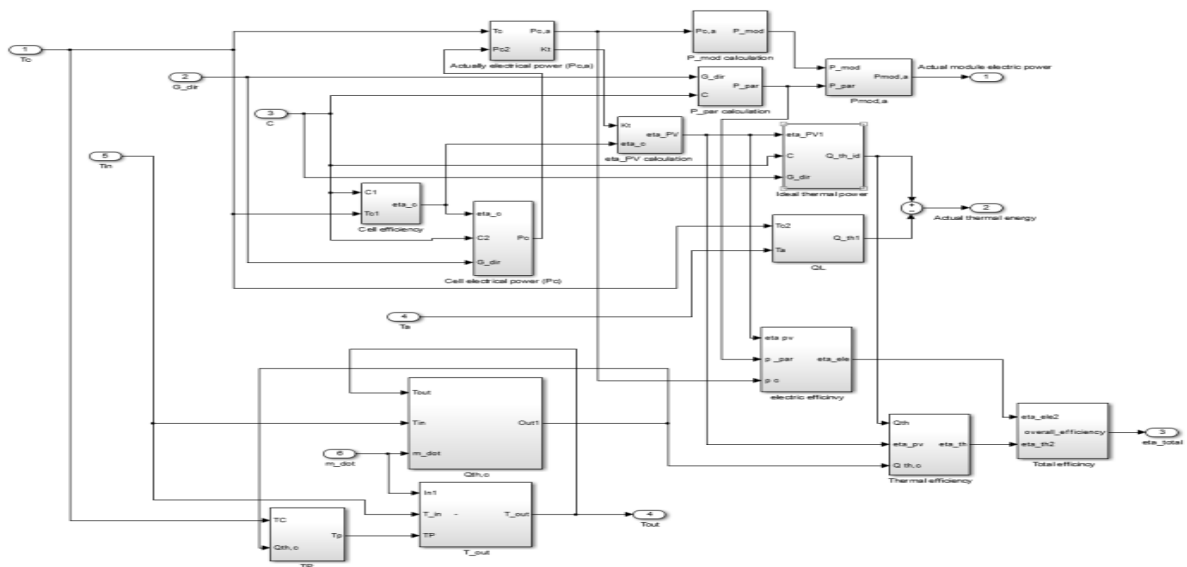


Fig. 4. Subsystems construction of the CPV/T model

8. Results and discussion

8.1 Data description

The proposed model of CPV/T is evaluated using daily direct normal irradiance G_{ind} . This irradiance was measured with a solar power meter device at a selected location AlMarj _ City (Libya, long. 20.8294° E, lat. 32.4739°). The measurements have been performed each 1 h, from 6 h to 19 h and that during successive day, June 10th. Fig. 5 illustrates the hourly G_{ind} .

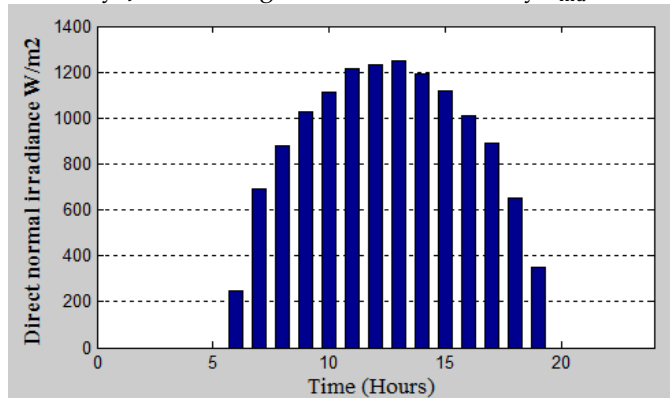


Fig. 5. Direct normal irradiance and Temperature for (Al Marj_City) within 24 hours

The input data of the proposed CPV/T Simulink model are daily irradiance, ambient temperature, size and number of cells, concentration factor and cooling system parameters. These data are illustrated in table 1.

Table. 1 CPV/T system parameters

Parameter	Values
Number of cells N_c	90
Area of cells A_c	$81 \times 10^{-6} \text{ m}^2$
Type of optic	Parabolic concentrators with optical efficiency 0.85
Concentration factor C	1 : 900
Cell temperature T_c	100Co
Trucker system efficiency f	0.9
Temperature coefficient a	-0.0016
Module Efficiency η_{mod}	0.9
losses factor G_{par}	0.023
Inverter efficiency η_{inv}	0.9
Fluid specific heat specific heat C_p	For water $4180 \text{ JKg}^{-1} \text{ K}^{-1}$
Fluid input temperature T_{in}	25 C°
Cell emissivity ϵ_c	0.85
Stefan constant σ	$5.670373 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4$
Convection heat transfer h_c	For water $150 \text{ W/m}^2 \cdot \text{Co}$
Conductive conductance k	For copper 384 W/m.k
Heat exchanger thickness d.	$2 \times 10^{-3} \text{ m}$

8.2 Results of the CPV/T system model

From the simulation data, it is found that, the model presented allows varying the input conditions for different time intervals (hourly), then the CPV/T system according to the site and energy demands.

The daily simulation results represent the input of the hourly simulation that has allowed evaluating the high potential of the CPV/T system in Al Marj_City.

In Figure 6 the electric power and efficiency of a CPV/T module with C equal to 800 referring to Al Marj_City in June are reported related to the reflective optics. A maximum power of 1380 W is measured at about 13. Moreover, the thermal daily power of the CPV/T module obtained from the model has been illustrated in Figure 7.

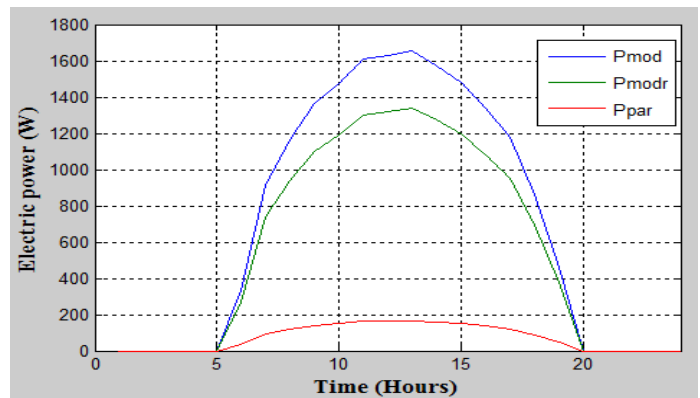


Fig. 6 Electric power of CPV/T module at C= 800 suns and TC=100oC

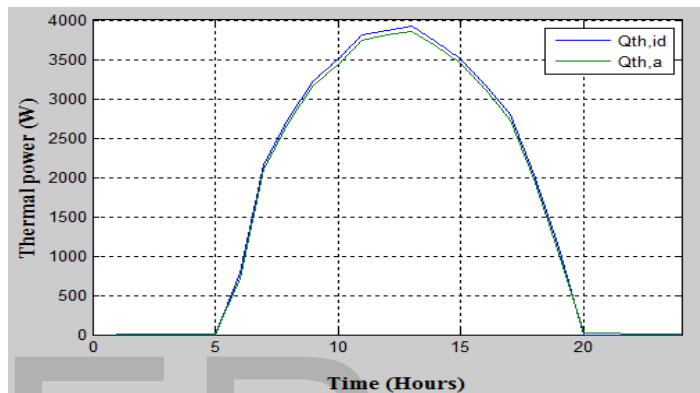


Fig. 7 Thermal power of CPV/T module at C= 800 suns and TC=100oC

Change the concentration factor affect the electric and thermal power produced from the CPV/T system as shown in Fig. 8 and 9. They show the electric and thermal energy produced in Al Marj_City by a single module when the concentration factor varies. The electric and thermal energy production increases when the concentration factor increase, with absolute values higher in Al Marj_City.

In the same working conditions the electric and thermal efficiency of the CPV/T system increased by increase the concentration factor.

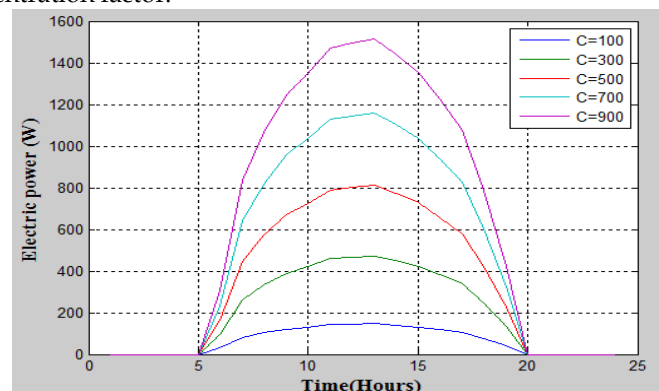


Fig. 8 Electric power at different concentration factor and TC=100oC

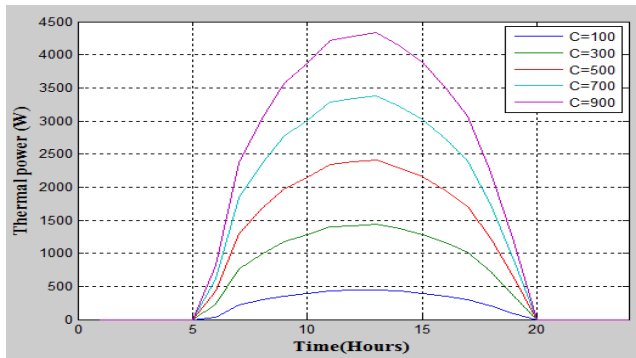


Fig. 9 Thermal power at different concentration factor and $TC=100^{\circ}C$

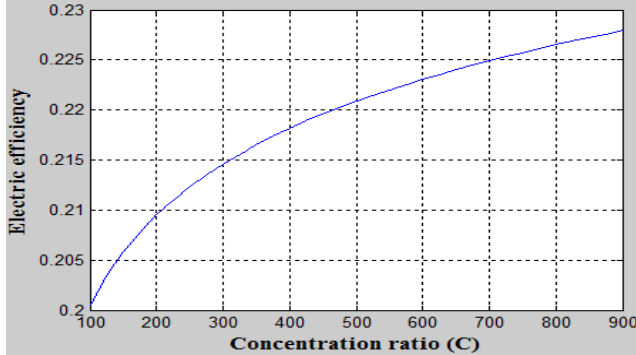


Fig. 10 Thermal efficiency as a function of the concentration factor and $TC=100^{\circ}C$

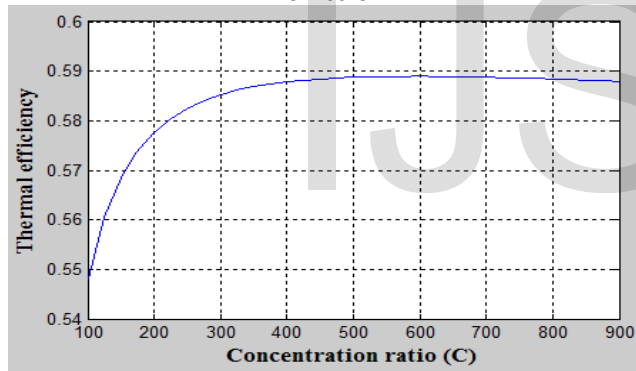


Fig. 11 Thermal efficiency as a function of the concentration factor and $TC=100^{\circ}C$

Increasing the concentration factor C the output fluid temperature will increase as shown in Fig. 11 at constant water mass flow $\dot{m} = 0.015$. By increasing concentration factor C the water mass flow was increased as shown in Fig. 12 at constant output fluid temperature $T_{out} = 80C$.

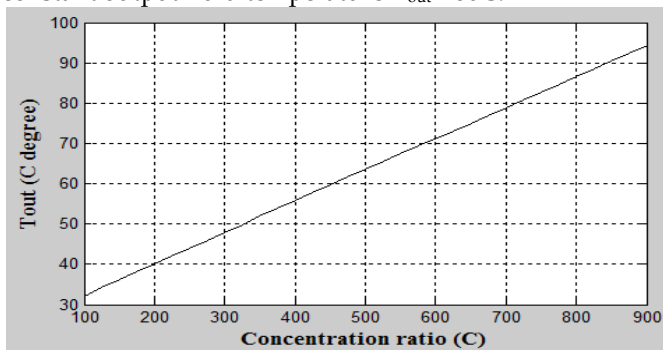


Fig. 11 The output fluid temperature as a function of the concentration

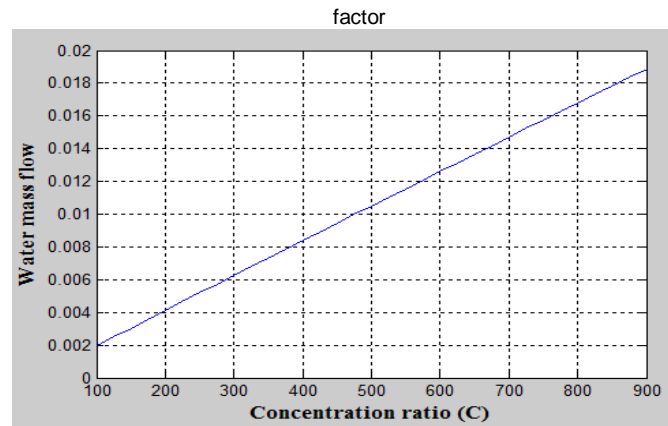


Fig. 12 The water mass flow as a function of the concentration factor

9. Conclusions

This paper presents a model of CPV/T systems and simulate it using the MATLAB program. It includes modeling of the reflective optics with parabolic Concentrator and the triple-junction cells (InGaP/InGaS/Ge) assembled with a dual axis tracker. The electrical and thermal energy production of these systems has been monitored in June at the Al Marj_City. The model allows evaluating the values of the electric and thermal energy of the concentrating photovoltaic thermal (CPV/T) system (hourly). The results showed that the CPVT system gives higher electrical and thermal power outputs and efficiencies at the highest concentration factor. Also the model can obtain the relation between the water mass flow, outlet fluid temperature and the concentration factor.

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