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Thermal and electrical analysis of a linear parabolic CPVT system

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Abstract. Thermal and electrical analysis of a linear parabolic concentrated photovoltaic/thermal hybrid solar collector (CPVT) was studied in this article. The energy balance equations were written for different parts of the CPVT collector. A non-linear algebraic equations system was derived for determining the temperature of the photovoltaic module, solar collector, the metallic layer and outlet fluid. Because of the presence of electrical efficiency in the energy balance's equation, the thermal analysis of PVT collector is dependent on the electrical analysis. The four-parametric current-voltage model was employed for electrical analysis. The CPVT system's equations were solved by numerical methods. The result of this simulation had a good conformity with the previous studies. The effect of different operational and design parameters on the electrical and thermal performances was also investigated.

Keywords: thermal efficiency; electrical efficiency; linear parabolic; photovoltaic/thermal collector

1. Introduction

Depletion of fossil fuel reserves and the harmful environmental impacts of their combustion products have convinced scientists to find alternative energy resources for sustainable and safe future in the context of energy and preventing energy crisis (Dincer and Rosen 1995). Renewable energy sources such as solar, wind, biomass, and geothermal can provide sustainable energy carriers via conversional facilities like reactors, turbines and photovoltaic panels (Najjar 2013, Granovskii *et al.* 2007). Solar energy is one of these resources developed dramatically within the last decade. Solar energy can be used for direct electricity generation by Photovoltaic panels (PVs) or for heating by solar collectors (SCs) (Tyagi *et al.* 2012). As of the end of 2014, 177 GW PV systems have been installed all over the world and only in 2014, 37.8 GW have been installed in the world. In addition, the amount of solar water heating collectors installed globally have been grown from 240 GW_{th} in 2010 to 406 GW_{th} in 2015 (IEA 2014). One of the new technologies for using solar energy is thermal photovoltaic (PVT) which basically combines the functions of a solar collector and a photovoltaic panel for both heating and electricity generation (Devabhaktuni *et al.* 2013). Electricity generation and heating are performed simultaneously in this system and the working fluid cools the PV module to increase its efficiency (Chow 2010, Zondag 2008).

Although the main idea of PVT has been proposed for 40 years, this technology is not

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economically affordable yet (Zhang *et al.* 2012). Hence, many researchers are investigating new configurations for PVTs. Concentrating PVT (CPVT) is a new hybrid system which uses lenses or curved mirrors to focus and a smaller photovoltaic array also reduces the balance of system costs. Furthermore, more sunlight onto a small PVT system. CPVTs possess the highest efficiency of all existing PV technologies, useful heat in a higher temperature can be generated in CPVT systems thanks to the higher incident radiation. In other hand, this effect decrease electrical efficiency (Yazdanpanah *et al* 2105, Khelifa *et al*. 2015). Many theoretical and experimental studies have been performed on CPVTs. Irshid and Othman (1988) used a V form downpipe as concentrator with a high concentration ratio. The downpipe's surface was covered with plane mirrors. They derived general equations for optimum concentration ratio, efficiency and the ratio of reflective area to exit aperture. Rönnelid *et al.* (1999), investigated the cooling methods for PVTs with low concentration ratios. The PV module's temperature was inversely correlated with efficiency. For preventing this, they proposed four solutions and the best one was to flow a cooled fluid stream from its behind for cooling. Mittelman *et al.* (2007) performed some experimental and theoretical works on CPVT systems. The performance of a high temperature CPVT was studied for applications like cooling and desalination. They concluded that the performance of the CPVT is better than other conventional systems in wide range of operating conditions. Bernardo *et al.* (2011) studied the energetic performance of a CPVT through an experimental method. They proposed a complete method for simulation and analysis of a CPVT with a parabolic concentrator and triangular shaped absorber which its two under layers was made of silicon cells and the upper layer was made of a thermal absorber. Calise and Vanoli (2012) eliminated the cover glass and replaced the mono-crystalline silicon cells by triple-junction cells which had a higher efficiency. They reported that the performance of the system was improved significantly even when working fluid works in high temperatures.

In most previous CPVT analyses, the electrical analysis and efficiency either was not considered or was expressed only by experimental equations which could be applicable only for specific system’s geometries. In other hand, these formulas don’t consider the configuration of the cells whereas the cells can be placed in various forms and their placement affects the system's analysis.

In this study, a comprehensive approach to analysis of a linear parabolic CPVT system through a four parameter method was suggested. The energy model which considers electrical efficiency was solved by numerical methods to investigate the effect of different operational and design parameters on the thermal performance and the results were compared to the previous studies.

2. System description

The CPVT investigated in this study includes a parabolic concentrator and a uniaxial receiver which works just like as parabolic trough collectors (PTCs). In solar thermal PTC an extraction pipe is installed for heating the working fluid whereas in considered CPVT, parabola's focus is equipped with a triangular receiver as shown in Fig 1. A metallic substrate between the circular fluid channel and external surface is employed to accelerate conductive heat transfer.

The both sides of triangle which face the concentrator are covered by PV layers and the upper layer of triangle is an absorber. This triangular receiver includes an internal fluid channel for the fluid which is supposed to be heated. Therefore, the heat and electricity is generated simultaneously in the CPVT system.

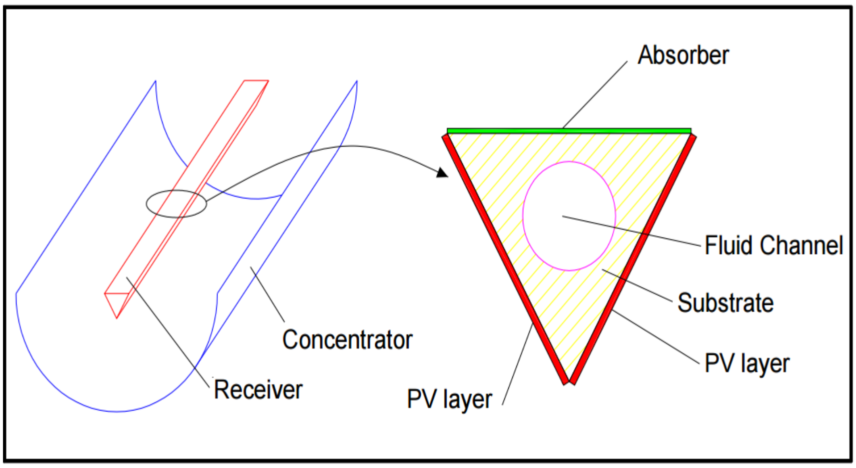

Fig. 1 Schematic of the CPVT studied in this article

3. Energy analysis

In this study, a suitable model based on energy balance is developed for the CPVT shown in Fig. 1. The general assumptions adopted for the model are the thermodynamic equilibrium, steady state, negligible kinetic and gravitational terms. In the energy balances, incident radiation is uniformly concentrated along the PV area (Evola and Marletta 2014). Water is used as cooling fluid, but other fluids can also be employed. The concentration ratio is defined as the ratio of the area which the PV is covered to the aperture area of the concentrator.

$$C_{pvt} = \frac{A_{ap}}{A_{pvt}} \tag{1}$$

The optical efficiency of the concentrator is considered to be constant (Mittelman *et al.* 2007). So, the radiation on the PV surface is

$$G_{pvt} = A_{pvt} I_b C_{pvt} \eta_{opt} IAM_{th} \tag{2}$$

The IAM, related to the thermal production is calculated based on the experiments which have been done by Bernardo *et al.* (2011)

$$\vartheta \langle 60 \qquad IAM_{th} = 1 - b_{0.th}\left(\frac{1}{\cos\vartheta} - 1\right)$$

$$\vartheta \geq 60 \qquad IAM_{th} = \left[1 - b_{0.th}\left(\frac{1}{\cos\vartheta} - 1\right)\right]\left(1 - \frac{\vartheta - 60}{30}\right) \tag{3}$$

At the same time, additional thermal energy is absorbed by the top thermal absorber (Bernardo *et al.* 2011)

$$Q_{top\text{-}sky} = A_{top} I_{tot} a_{top} \tag{4}$$

By assuming the top surface area as gray surface and considering the area of the top surface is much smaller than the one of the sky, the radiative heat transfer between the top absorber and the sky can be calculated as follow (Duffie and Backman 2013)

$$Q_{\text{pvt-conc}} = A_{\text{pvt}}\sigma\varepsilon_{\text{pvt}}(T^4_{\text{pvt}} - T^4_{\text{conc}}) \quad (5)$$

The heat transferred via radiation between the PVT and the concentrator is expresses as (Duffie and Backman 2013)

$$Q_{\text{pvt-conc}} = A_{\text{pvt}}\sigma\varepsilon_{\text{pvt}}(T^4_{\text{pvt}} - T^4_{\text{conc}}) \quad (6)$$

The convective heat transfer between the PVT and the air is calculated as follows (Incropera and Dewitt 2001)

$$Q_{\text{conv,pvt}} = A_{\text{pvt}} h_{\text{c.pvt}}(T_{\text{pvt}} - T_{\text{a}}) \quad (7)$$

The convection mechanism is definitively a forced convection. The corresponding heat transfer coefficient is calculated using the following correlation (Incropera and Dewitt 2001)

$$Nu = 0.664\ \text{Pr}^{\frac{1}{3}}\,\text{Re}^{\frac{1}{2}} \quad (8)$$

The heat flow of the absorber is (Incropera and Dewitt 2001)

$$Q_{\text{conv, top}} = A_{\text{top}} h_{\text{c, top}}(T_{\text{top}} - T_{\text{a}}) \quad (9)$$

The IAM obtained from theoretical data can be written as (Bernardo *et al.* 2011)

$$\vartheta \langle 60 \quad IAM_{\text{el}} = 1 - b_{0.\text{el}}\left(\frac{1}{\cos\vartheta} - 1\right), \vartheta \geq 60 \quad IAM_{\text{el}} = \left[1 - b_{0.\text{el}}\left(\frac{1}{\cos\vartheta} - 1\right)\right]\left(1 - \frac{\vartheta - 60}{30}\right) \quad (10)$$

Eventually, the heat absorbed by the cooling fluid is

$$Q_{\text{f}} = \dot{m}_{\text{f}}(h_{\text{f.out}} - h_{\text{f.in}}) \quad (11)$$

The overall energy balance for a control volume that included the triangular receiver is

$$\begin{aligned} &A_{\text{pvt}} I_{\text{b}} C_{\text{pvt}} \eta_{\text{opt}} IAM_{\text{th}} + A_{\text{top}} I_{\text{top}} \alpha_{\text{top}} = \dot{m}_{\text{f}}(h_{\text{out}} - h_{\text{in}}) + C_{\text{pvt}} A_{\text{pvt}} I_{\text{b}} \eta_{\text{opt}} \eta_{\text{pv}} IAM_{\text{el}} \\ &+ A_{\text{pvt}} I_{\text{b}} C_{\text{pvt}} \eta_{\text{opt}} IAM_{\text{th}} \rho_{\text{pvt}} + A_{\text{top}} \varepsilon_{\text{top}} \sigma(T^4_{\text{top}} - T^4_{\text{sky}}) + A_{\text{pvt}} \sigma\varepsilon_{\text{pvt}}(T^4_{\text{pvt}} - T^4_{\text{conc}}) + A_{\text{pvt}} h_{\text{c,pvt}} \\ &(T_{\text{pvt}} - T_{\text{a}}) + A_{\text{top}} h_{\text{c,top}}(T_{\text{top}} - T_{\text{a}}) \end{aligned} \quad (12)$$

The second energy balance is written for the control volume which includes the metallic substrate and the fluid channel. This control volume can be considered as a heat exchanger. This assumption can be acceptable due to the high heat transfer coefficient of metallic substrate (Duffie and Backman 2013; Incropera and Dewitt 2001). The performance of the heat exchanger can be obtained using NTU method as follows (Kakac and Liu 1998)

$$NTU = \frac{\dfrac{1}{\dfrac{1}{h_{\text{fluid}}} + r_{\text{sub}}} A_{\text{Hex}}}{\dot{m}_{\text{f}} C_{\text{f}}} \quad (13)$$

A_{Hex}, is the lateral area of the fluid channel, which is the heat exchanger area in this formula.

The fluid's heat transfer coefficient, h_{fluid}, is calculated as follows (Incropera and Dewitt 2001)

$$Nu = 0.664\, \mathrm{Pr}^{\frac{1}{3}} \mathrm{Re}^{\frac{1}{2}} \tag{14}$$

The heat transfer effectiveness is

$$\varepsilon = 1 - e^{-NTU} \tag{15}$$

The energy balance for heat exchanger is

$$\dot{m}_{\mathrm{f}}(h_{\mathrm{out}} - h_{\mathrm{in}}) = \varepsilon C_{\mathrm{f}}(T_{\mathrm{sub}} - T_{\mathrm{in}}) \tag{16}$$

Where, T_{sub} is the temperature of the metallic substrate. The third equation is derived from an energy balance on a control volume including the PVT layer, and the metallic substrate

$$A_{\mathrm{pvt}} \frac{T_{\mathrm{pvt}} - T_{\mathrm{sub}}}{r_{\mathrm{pvt-sub}}} = \dot{m}_{\mathrm{f}}(h_{\mathrm{out}} - h_{\mathrm{in}}) + A_{\mathrm{top}} \frac{T_{\mathrm{sub}} - T_{\mathrm{top}}}{r_{\mathrm{top}}} \tag{17}$$

Where, the top thermal resistance, r_{top}, is the conductive resistance for both the metallic substrate and the top absorbing surface included between the fluid channel and the top surface. With respect to the control volume that includes the top side of the metal substrate and the top surface of the triangular receiver, fourth energy balance can be written as

$$\begin{aligned} A_{\mathrm{top}} \frac{T_{\mathrm{sub}} - T_{\mathrm{top}}}{r_{\mathrm{top}}} + A_{\mathrm{top}} I_{\mathrm{top}} &= A_{\mathrm{top}} I_{\mathrm{top}} \rho_{\mathrm{top}} + \\ A_{\mathrm{top}} \varepsilon_{\mathrm{top}} \sigma (T_{\mathrm{top}}^4 - T_{\mathrm{sky}}^4) &+ A_{\mathrm{top}} h_{\mathrm{c,top}} (T_{\mathrm{top}} - T_{\mathrm{a}}) \end{aligned} \tag{18}$$

Finally, the last energy balance considers the control volume that includes only the parabolic concentrator

$$\begin{aligned} & A_{\mathrm{pvt}} \sigma \varepsilon_{\mathrm{pvt}} (T_{\mathrm{pvt}}^4 - T_{\mathrm{conc}}^4) + I_{\mathrm{tot}} A_{\mathrm{conc}} \alpha_{\mathrm{conc}} = \\ & A_{\mathrm{conc}} \sigma \varepsilon_{\mathrm{conc,bock}} (T_{\mathrm{conc}}^4 - T_{\mathrm{sky}}^4) + A_{\mathrm{conc}} h_{\mathrm{c,conc,front}} (T_{\mathrm{conc}} - T_{\mathrm{a}}) + \\ & A_{\mathrm{conc}} h_{\mathrm{c,conc,bock}} (T_{\mathrm{conc}} - T_{\mathrm{a}}) \end{aligned} \tag{19}$$

Eqs. (15) and (19)-(22) make a system of five equations and the five unknowns. These equations are highly non-linear as a consequence of the radiative terms included in the energy balances and of the correlations for calculations of the heat transfer coefficients. This system must be solved by conventional numerical iterative techniques.

The overall performance of the CPVT is often evaluated using the well-known thermal and electrical efficiencies, which are conventionally related to the incident beam radiation and to the collector aperture area

$$\eta_{\mathrm{CPVT.th}} = \frac{\dot{m}_{\mathrm{f}}(h_{\mathrm{out}} - h_{\mathrm{in}})}{A_{\mathrm{ap}} I_{\mathrm{b}}} \tag{20}$$

$$\eta_{\mathrm{CPVT.el}} = \frac{C_{\mathrm{pvt}} A_{\mathrm{pvt}} I_{\mathrm{b}} \eta_{\mathrm{opt}} \eta_{\mathrm{Pv}} IAM_{\mathrm{el}}}{A_{\mathrm{ap}} I_{\mathrm{b}}} \tag{21}$$

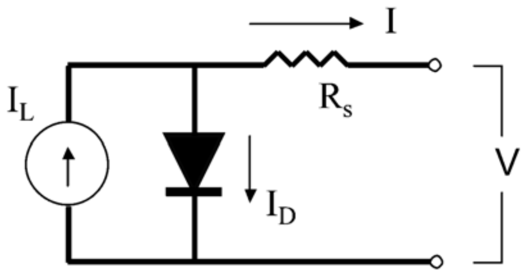

Fig. 2 Equivalent electrical circuit in the four-parameter photovoltaic model

3. Electrical analysis

The emersion of electrical efficiency in the balance equations correlates the energy analysis of the PVT collector to the electrical analysis of the photovoltaic module. The regulation of solving the energy balance equations of the PVT collector is such that, if electric models are used, the efficiency of photovoltaic module is assumed to be the same as its efficiency in the reference mode. Then, energetic parameters of the PVT collector are calculated and finally the efficiency of the photovoltaic module should be corrected and continued to reach a convergence condition. So, electrical simulation is necessary to calculate the thermal parameters of the PVT collector.

According to the literature, electrical efficiency is obtained by following experimental equation

$$\eta_{pv} = 0.298 + 0.0142 \ln(C_{pvt}) + \left[-0.000715 + 0.0000697 \ln(C_{pvt})\right](T_{pvt} - 298) \tag{22}$$

As mentioned, the disadvantage of this method is that it can't be applicable if the geometry of the system changes. On the other hand, this formula doesn’t indicate the configuration of Cells whereas they can be ordered in different configurations and affect the analysis of the system.

In addition, electrical efficiency is calculated by some other researchers as follows; (Evans 1981, Schott 1985)

$$\eta_{el} = \eta_{el,ref}[1 - 0.0045(T_{cell} - T_{amb,ref})] \tag{23}$$

This equation has some deficiencies. First, it results the same electrical efficiency for the photovoltaic module in reference condition and low solar insulation conditions. It is because of the same temperature for the PV module and the ambient. Second, Eq. (23), cannot estimate the variation details of some electrical parameters.

Different models are proposed for prediction of the behavior of PV modules or in other word, general current-voltage characteristic curve. Sarhaddi *et al.* (2010) used a Five-parameter for electrical analysis of an air collector. The following four parameter model for I-V characteristic curve is used in this study

$$I = I_L - I_o[\exp((V + IR_s)/a) - 1] \tag{24}$$

$$a = \gamma k T_{cell}/q \tag{25}$$

Where I and V represent current and voltage under the load and the four parameters of this model are; *a*, *Io*, I_L and *Rs*, which are ideality factor, light current, diode reverse saturation current and series resistance, respectively. Furthermore, *q*, *y*, *k* are electron's charge, non-dimensional coefficient for regression of diode curve and Boltzmann constant. The second terms on the right-hand side of Eq. (24) indicate diode current (I_D). Fig. 2 indicates the equivalent electrical circuit for the four parameter photovoltaic model.

Normally, the values of parameters are given by PV modules provider in reference condition for each PV module. Equations for calculating these four parameters in reference condition are summarized as follows

$$I_{\mathrm{L,ref}} = I_{\mathrm{sc,ref}} \tag{26}$$

$$I_{\mathrm{o,ref}} = \frac{I_{\mathrm{sc,ref}}}{\exp(V_{\mathrm{oc,ref}} / a_{\mathrm{ref}})} \tag{27}$$

$$a_{\mathrm{ref}} = \frac{2V_{\mathrm{mp,ref}} - V_{\mathrm{oc,ref}}}{\dfrac{I_{\mathrm{mp,ref}}}{I_{\mathrm{sc,ref}} - I_{\mathrm{mp,ref}}} + \ln\left(1 - \dfrac{I_{\mathrm{mp,ref}}}{I_{\mathrm{sc,ref}}}\right)} \tag{28}$$

$$R_{\mathrm{s,ref}} = \frac{a_{\mathrm{ref}} \ln\left(1 - \dfrac{I_{\mathrm{mp,ref}}}{I_{\mathrm{sc,ref}}}\right) + V_{\mathrm{oc,ref}} - V_{\mathrm{mp,ref}}}{I_{\mathrm{mp,ref}}} \tag{29}$$

As mentioned, Eqs. (26)-(19) obtain model parameters in the reference conditions. For calculating voltage and current and model parameters in new performing condition, some translation equations are used such as follows

$$a / a_{\mathrm{ref}} = T_{\mathrm{cell}} / T_{\mathrm{cell,ref}} \tag{30}$$

$$I_{\mathrm{o}} / I_{\mathrm{o,ref}} = (T_{\mathrm{cell}} / T_{\mathrm{cell,ref}})^3 \exp[\varepsilon N_{\mathrm{c}} [1 - (T_{\mathrm{cell,ref}} / T_{\mathrm{cell}})] / a_{\mathrm{ref}}] \tag{31}$$

$$I_{\mathrm{L}} = (G / G_{\mathrm{ref}})[I_{\mathrm{L,ref}} + \alpha(T_{\mathrm{cell}} - T_{\mathrm{cell,ref}})] \tag{32}$$

$$\Delta T = T_{\mathrm{cell}} - T_{\mathrm{cell,ref}} \tag{33}$$

$$\Delta I = \alpha(G / G_{\mathrm{ref}}) \Delta T + [(G / G_{\mathrm{ref}}) - 1] I_{\mathrm{sc,ref}} \tag{34}$$

$$\Delta V = \beta \Delta T - R_{\mathrm{s}} \Delta I \tag{35}$$

$$I_{\mathrm{new}} = I_{\mathrm{ref}} + \Delta I \tag{36}$$

$$V_{\mathrm{new}} = V_{\mathrm{ref}} + \Delta V \tag{37}$$

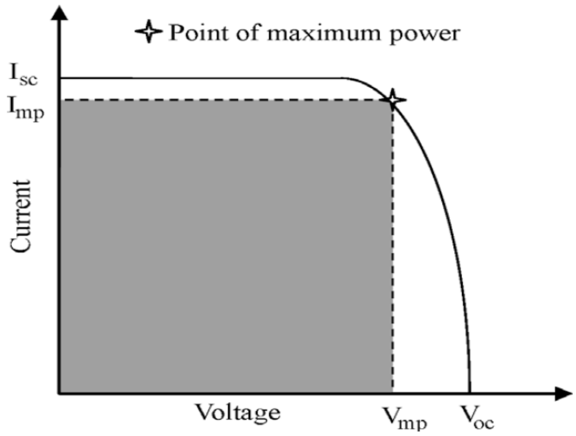

Fig. 3 A general current-voltage characteristic curve and its parameters

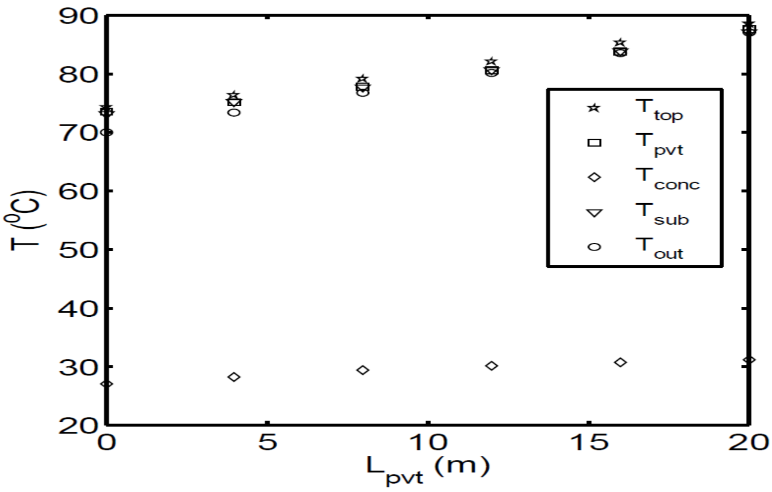

Fig. 4 Variation of the temperatures of the system with length of the CPVT

where *e*, *Nc*, *a* and *b* are semiconductor band gap energy (1.12 eV for silicon solar cells), cells number in series, current temperature coefficient and voltage temperature coefficient, respectively but new values of $V_{mp,ref}$, $I_{mp,ref}$ are obtained from the maximum area of the rectangle represented in the Fig. 3, which is the solved I-V characteristic curve.

Finally, the electrical efficiency of photovoltaic module can be obtained as follows

$$\eta_{el} = \frac{I_{mp} V_{mp}}{G \ A_{PVT}} \tag{38}$$

4. Results and discussion

In this part, the parametric study with the aim of energetic and electrical analysis of a linear

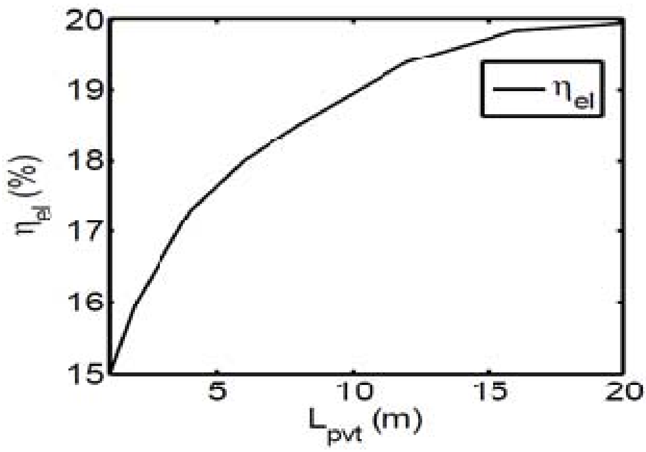

Fig. 5 Variation of the electrical efficiency with length of the CPVT

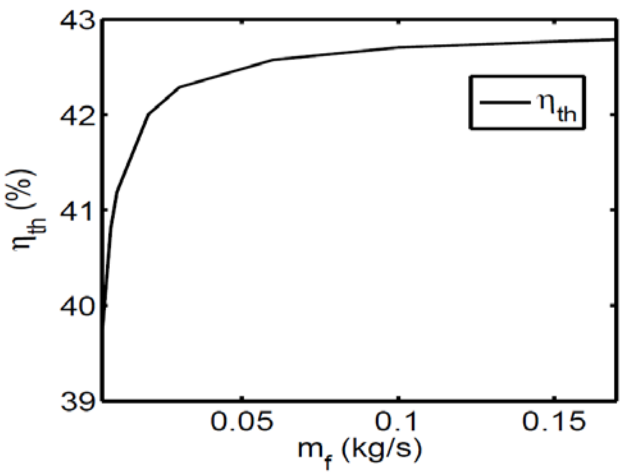

Fig. 6 Variation of the thermal efficiency with the cooling fluid flow rate

parabolic CPVT has been performed considering the variation of some of main parameters in different conditions.

Axial length of the CPVT can change in a wide range. As indicated in Fig. 4, all of the mentioned temperatures are increased when the CPVT system's length is increased. In fact, the increment in length heightens the outlet temperature of the fluid and causes a general raise in the system's temperature. Specially, higher temperatures of the PV cause a lower electrical efficiency which is represented in Fig. 5. Moreover, a higher temperature of the PV and absorber causes more loss in convection and radiation which result a slight decrement in the thermal efficiency. Therefore, it is concluded that for maximizing the efficiency of the CPVT, the length of the system should be minimized and the mean temperature difference of the working fluid should not be highly increased.

The other considered factor is the flow rate variation of the cooling water, which is inversely proportional with the system's temperature. Lower PV temperatures result in higher electrical efficiency and also, the loss in solar radiation and the convection which is caused by decrement of

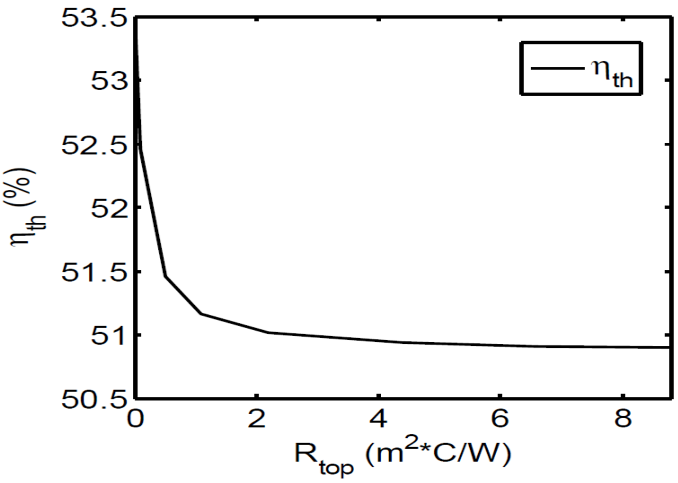

Fig. 7 Variation of the thermal efficiency with thermal resistance of the absorber

the temperature, increases the thermal efficiency (Fig. 6).

Another parameter is the thermal resistance of the absorbing surface of the receiver. It is obvious that insulation of the system directly affect the thermal resistance. Insulation can reduce thermal losses but in other hand, it reduces the heat absorbed by the surface. The result from this analysis shows that the thermal efficiency is inversely correlated with the insulation (Fig. 7). More insulation causes lower heat transfer between the upper layers of receiver and cooling water which results in the higher temperatures in the top, and the reduction in other temperatures such as outlet temperature of cooling water. Hence, thermal efficiency decreases as indicated in Fig. 7. Therefore, insulation of the upper layer should be selected optimally to reach higher thermal efficiency.

5. Conclusions

Although CPVT systems possess the highest efficiency over all existing PV technologies, those solar systems are not currently used in the PV rooftop segment and are far less common than conventional PV systems. Ongoing research and development on CPVT systems is rapidly improving their competitiveness in the utility-scale segment and in areas of high solar insolation. In this research, thermal and electrical analysis of a linear parabolic CPVT system in a different configuration has been studied. The results showed the followings;

• Both thermal and electrical efficiency are high for variety of operating conditions compared to other solar technologies.

• A higher temperature of the working fluid, which is the result of increasing the length of the CPVT's length, causes a reduction in both electrical and thermal efficiencies. That is why having an efficient cooling system is crucial.

• Thermal and electrical efficiencies are directly correlated with the fluid flow rate.

• Using an insulated surface instead of a surface with high absorbing coefficient is recommended for the receivers with great surface areas. On the other hand, because of the lower absorbed solar radiation, the loss in thermal efficiency should be considered.

• The thermal efficiency of the CPVT is decreased by increasing the thermal resistance of the absorber but gets stalled on about 51%.

• However an increase in the cooling fluid flow increases the thermal efficiency, after a certain flow, efficiency remains approximately constant

In this study, silicon solar cells were considered in the CPVT structure. However, selecting another type of solar cells and the optical device may completely change the configuration and the operational parameters, specially the working temperatures, of the CPVT system. In addition, for high concentrator photovoltaic (HCPV) systems, an active tracking system as well as economic parameters should be taken into account. Those issues will be addressed in the authors' future works.

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Nomenclature

A	Area [m^2]
a	Ideality factor (eV)
b_0	IAM curve coefficient
C	Specific Heat [J/Kg/K]
C_{PVT}	Concentration ratio
d	Fluid channel diameter (m)
G	Solar radiation intensity [W/m^2]
h_c	Convective heat transfer coefficient [W/m^3/K]
h_f	Fluid specific enthalpy [J/Kg]
I	radiation [W/m^2]
IAM	Incidence Angel Modifier
L	Length [W/m^2]
$\dot{m}$	mass flow rate [Kg/s]
N	Number
Nu	Nusselt Number
P	Pressure [Kpa]
P	Electrical Power [W]
Pr	Prandtel Number
Q	Heat [J]
r	Area specific thermal resistance [m^{2}K/W]
Re	Reynolds Number
T	Temperature [C]
V	Voltage [V]

Greek Symbols

α	Absorptance
ε	Emmitance

ρ	Density [Kg/m^3]
ρ_{PVT}	PVT reflectance
σ	Stephan-Boltzmann constant
ϑ	Angle of incidence [Degree]
μ	Viscosity [Kg/m/s]
η_{PV}	PV efficiency
η_{opt}	Optical efficiency
η_{th}	Thermal Efficiency
η_{el}	Electrical efficiency

Subscripts

amb	Ambient
ap	Aperture
b	Beam
c,Cell	Cell, module
Conc	Concentrator
D	Diode
el	Electrical
f	Fluid
Hex	Heat exchanger
in	Inlet
mp	Maximum power
oc	Open circuit
out	Outlet
PVT	Photovoltaic/Thermal
rec	Receiver
ref	Reference condition
s	Series
sc	Short circuit
sky	Sky
sub	Substrate
top	Top surface
tot	Total
t	tube
th	Thermal