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Numerical study of a Parabolic Trough Photovoltaic/Thermal Collectors (CPV/T)

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Abstract: In areas of the world with high levels of sunshine, solar energy is becoming increasingly competitive. Delivering solutions that are both efficient and competitive in terms of unit energy costs is a key issue for renewable energies. Recently, concentrating photovoltaic/thermal collectors (CPV/T) have gained notable attention throughout the world due to their very good performance in terms of capturing, converting and storing thermal and electrical energy. The work presented concerns the modeling of a CPV/T installation for the simultaneous production of heat and electricity. In order to analyze CPV/T performance, a detailed mathematical model was implemented. This model is based on two-dimensional energy balances programmed on FORTRAN language. The simulation model calculates the temperatures of the main components of the system and the main energy flows. Results showed that the performance of the system is excellent even when the fluid temperature is very high (>100 °C).

Keywords:
Solar energy, CPV/T, energy balances

1. Introduction

The energy from the sun can be directly converted into electricity and thermal energy by the use of (CPV/T) technology. The application of an active cooling might increase the cost of the system, however, employing a concentrating element along would subside the extra cost and benefit in terms of the overall energy extraction. Using concentrator technology can improve energy flux density for solar photovoltaic power generation which converts solar radiation directly into electricity by using solar cell specially triple-junction model.
The heat energy transformed by the solar cell will be used recycle in the form hot water which not only reduce the solar cell temperature and enhance the solar cell efficiency, but also might obtain the heat energy, so the development of CPV/T is a trade-off between the production of electrical and thermal energy.
This process has great potential to improve hybrid power systems and retain competitive energy prices. This technique is being increasingly developed by many researchers world-wide. Several CPV/T systems have been designed, studied, and demonstrate both theoretically, experimentally and by simulation tools in the literature for different applications.
Kribus.A and Mittelman.G recently presented an investigation of the performance of CPVT poly-generation systems at elevated temperatures using simplified models [1] and the results show that using the waste heat of CPV systems for cooling can lead to higher overall efficiency than trying to generate additional electricity.
The research institute of the National University of Australia has carried out a detailed study on a thermal photovoltaic concentration system [2], much work has already been done on the design of the collector as well as the development of new solar cells. Xu Ji and Ming worked on two CPV/T systems, researchers concluded that GaAs cells have the best electrical efficiency, but crystalline cells are characterized by the better thermal efficiency. Due to the complexity of the technology, GIBART and Al [3] have chosen to study a cylindrical reflective surface. For a fixed cooling rate and two different water inlet temperatures, the results showed that the electrical and thermal efficiencies are higher than those of a conventional system and economically, it is expected that the system will have a return time of 10.5 to 12.8 years. S.Quaia at the Center for Sustainable Energy Systems

(CSES) [4, 5] at the Australian National University (ANU) developed a combined solar collector (CHAPS). The first commercial scale demonstration for this technology was completed by the end of 2004, it provides electricity and hot water for the heating of a residential college at the ANU. The solar cells manufactured by ANU are monocrystalline silicon cells designed to have a low resistance in series and its characterized by a yield of around 20% at 25°C (under a concentration of suns of 30).
Calise and Al [6] worked on a cylindro-parabolic concentrator with a triangular linear receiver; the lower surfaces of the triangular receiver are equipped with triple junction cells (InGaP/InGaAs/Ge). The properties of the prototype significantly increase the electrical efficiency of the system; it is improved by the use of this type of cells; its efficiency is significantly better than the use of silicon cells, especially when the operating temperature is high. For high-temperature, the most suitable PV material is the triple-junction whose nominal efficiency is 40% (at 25°C) drops around 20% at 240°C. The perspective of using high-temperature CPV/T is very interesting since it extends the number of possible applications. Among the most important foreseeable applications are single effect and double effect absorption cooling, water desalination, steam production and other industrial process.
The results of these studies and demonstrations show that CPV/T systems hold very high potential for market penetration in the energy sector due to their unique features. With regard to the phenomenon of PV cells operating at high temperatures, Gur Mittelman and Al [1] are interested in high temperature CPV/T. These collectors can operate at temperatures above 100°C and the thermal energy produced can be useful for processes such as refrigeration, desalination and steam production. In particular, they [7,8,9] performed some experimental and theoretical works dealing with CPV/T systems applications.
Then, most of the studies in the literature are about the heat transfer improvement of a CPV/T system with medium outlet temperature water and there is a limited number of papers where the outlet temperature is high. With this concept, in the present study a CPV/T system is proposed and its output power performance is analyzed. Detailed analysis is performed to identify the important parameters affecting the overall performance and design of this system usable in different application. A CPV/T system, differently from traditional photovoltaic systems, allows to recover thermal energy at high temperature; hence, a coupling between a CPV/T system and storages devices allows to satisfy demands. The model allows both to size the CPV/T system components and evaluating the output temperature and power.
Some simulations were performed and all these works are helpful to the further study on the hybrid concentrating system and provide practical data for the design of a large scale CPV/T power in future.

2. Detailed Description and performance analysis of CPV/T

The CPV/T system (Fig. 1) simulated in this paper consists of the parabolic trough concentrator, the receiver, the PV cells, the sun tracking system and the electrical/thermal power output structure.

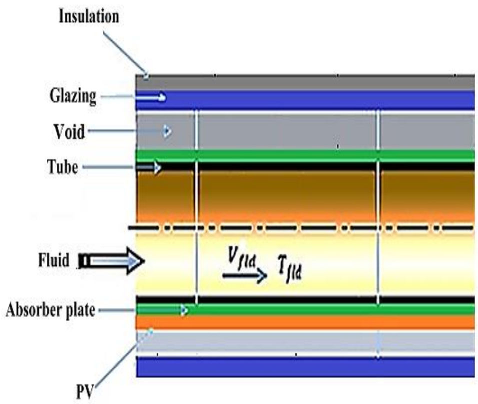

Figure 1 : CPV/T receiver layers

The prototype consisted in a parabolic through concentrator and a rectangular receiver channel. The bottom surface of the receiver (facing the concentrator) is equipped with triple-junction cells. In this hybrid concentrator, an evacuated channel for heating the fluid is installed at the focus of the parabola while in the considered system the focus of the parabola is equipped with a rectangular receiver. In particular, the sun rays focused on the triple-junction cell allow the heating of the absorber plate (selective layer), placed immediately below the cells in order to promote conductive heat transfer. The glass cover is used to minimize heat loss from the absorber and the insulating material is used in order to avoid heat loss.

The solar receiver plays a key role in the performance of energy generation because it houses the solar cells and it is used to recover the thermal solar power. Actually, this is the device where solar energy is converted in electrical and thermal power. The efficiency penalization can be reduced by cooling the photovoltaic cells; depending on the temperature of the cooling fluid, heat can also be recovered.
The CPV/T module is based on cells with a high conversion efficiency, in particular those based on III–V materials which can tolerate higher temperatures. Such cells are commercially available today; and an advanced cells currently under development have recently exceeded 47% efficiency.
Concentrating photovoltaic (CPV/T) systems can operate at higher temperatures than flat plate collectors. The cooling system can be adjusted to provide a wide range of temperatures by regulating the flow rate of the cooling fluid. Therefore, thermal energy may be provided to a variety of thermal processes in addition to the usual domestic heat application. Among the most important foreseeable applications are single effect and double effect absorption cooling, water desalination, steam production and other industrial process heat applications.

1.1. CPVT simulation model

Although simplified models for the calculation of CPV/T performance are available in literature, they cannot be applied to the system under investigation due to the use of concentrating systems and triple-junction cells. Therefore, an appropriate model, based on energy balances, has been developed in this paper.
This is a 2-D model based on finite volumes method developed in FORTRAN 90 which allows a simple formulation of the equations.
Various assumptions have been made to facilitate the theoretical analysis, the thermal exchanges in the absorber are studied according to the following assumptions:

- The flow of the fluid in the receiving tube is two-dimensional,
- The dimension of the receiver and the surface of the collector are constant,
- The heat transfer of the fluid is incompressible,
- The ambient temperature around the solar collector is uniform,
- The solar flux at the absorber is uniformly distributed,
- The physical properties of the elements are constant

Considering these assumptions, the equations governing the heat transfer in various components of CPV/T's receiver are given as follows:

- Fluid

$$\rho_{fd}\, c_{fd}\, \frac{\partial T_{fd}(x,y,t)}{\partial t} = -\dot{m}_{fd}\, c_{fd} \left[\frac{\partial\left(T_{fd}(x,y,t)\right)}{\partial x} + \frac{\partial\left(T_{fd}(x,y,t)\right)}{\partial y}\right] + k_{fd}\left(\frac{\partial^2 T_{fd}(x,y,t)}{\partial x^2} + \frac{\partial^2 T_{fd}(x,y,t)}{\partial y^2}\right) + h_{fd}\left(T_{tub} - T_{fd}\right) \quad (1)$$

- Tube

$$\rho_{tub}\, c_{tub}\, \frac{\partial T_{tub}(x,y,t)}{\partial t} = k_{\frac{s}{tub}}\left(T_s - T_{tub}\right) - h_{fd}\left(T_{tub} - T_{fd}\right) + k_{tub}\left(\frac{\partial^2 T_{tub}(x,y,t)}{\partial x^2} + \frac{\partial^2 T_{tub}(x,y,t)}{\partial y^2}\right) \quad (2)$$

- Selective layer

$$\rho_s\, c_s\, \frac{\partial T_s(x,y,t)}{\partial t} = -k_{\frac{pv}{s}}\left(T_s - T_{pv}\right) - k_{\frac{s}{tub}}\left(T_s - T_{tub}\right) + k_s\left(\frac{\partial^2 T_p(x,y,t)}{\partial x^2} + \frac{\partial^2 T_p(x,y,t)}{\partial y^2}\right) \quad (3)$$

- PV cell

$$\rho_{pv}\, c_{pv}\, \frac{\partial T_{pv}(x,y,t)}{\partial t} = Q_{abs,pv} - h_{ray,g,pv}\left(T_{pv} - T_g\right) - k_{\frac{pv}{s}}\left(T_s - T_{pv}\right) + k_{pv}\left(\frac{\partial^2 T_{pv}(x,y,t)}{\partial x^2} + \frac{\partial^2 T_{pv}(x,y,t)}{\partial y^2}\right) - E_{elec} \quad (4)$$

- Glass

$$\rho_g\, c_g\, \frac{\partial T_v(x,y,t)}{\partial t} = Q_{abs,g} - h_{wind}\left(T_g - T_{amb}\right) - h_{ray,g,amb}\left(T_g - T_{sky}\right) + h_{ray,g,pv}\left(T_{pv} - T_g\right) + h_{ray,g,p}\left(T_s - T_g\right) + k_g\left(\frac{\partial^2 T_g(x,y,t)}{\partial x^2} + \frac{\partial^2 T_g(x,y,t)}{\partial y^2}\right) \quad (5)$$

The CPV/T system produces both electrical and thermal energy, and each type of power product is described by a separate expression. The overall performance of the CPV/T 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.
The optical, module and inverter efficiency ($\eta_{op,}\eta_{mod,}\eta_{inv}$) of the concentrator are assumed being constant [9]. Therefore, the electric output net power can be defined as follows [10, 11]:

$$P_{pv} = G_c G A_{pv} \eta_{op} \eta_{mod} \eta_{inv} \eta_{pv} \quad (6)$$

The electrical efficiency of the triple-junction PV (η_{pv}) experimentally related to the concentration ratio and to the PV cells temperature [12].

$$\eta_{pv} = 0.298 + 0.142 \ln G_c + [-0.000715 + 0.0000697 \ln G_c]\,(T_{pv} - 298) \quad (7)$$

The concentration ratio (GC) is defined as the ratio between the area of the receiver (A_{rec}) and the aperture area (A_{ap}) of the concentrator:

$$G_c = \frac{A_{rec}}{A_{ap}} \quad (8)$$

The thermal output power can be described as [13]:

$$P_{th} = \dot{m_{fd}}\, C_{fd}(T_{out} - T_{\text{in}}) \quad (9)$$

Finally, the thermal and electrical efficiency (η_{th}, η_{elec}) are calculated based on the following definitions:

$$\eta_{th} = \frac{P_{th}}{A_{ap}G} = \frac{\dot{m_{fd}}\, C_{fd}(T_{out} - T_{\text{in}})}{A_{ap}G} \quad (10)$$

$$\eta_{elec} = \frac{P_{elec}}{A_{ap}G} = \frac{G_c G A_{pv} \eta_{op} \eta_{mod} \eta_{inv} \eta_{pv}}{A_{ap}G} \quad (11)$$

1.2. Thermal transfer mode: Heat transfer coefficients

The mode of thermal transfer between glass-ambient, glass- PV cells, glass-selective layer is a radiative and convective form; the coefficients are given by the following expressions [14, 15]:

$$h_{ray,g,s} = \sigma \frac{1}{\frac{1}{\varepsilon_p} + \frac{1-\varepsilon_g}{\varepsilon_g}} (T_s^{\,2} + T_g^{\,2})(T_s + T_g) \quad (12)$$

$$h_{ray,g,pv} = \sigma \frac{1}{\frac{1}{\varepsilon_{pv}} + \frac{1-\varepsilon_g}{\varepsilon_g}} (T_{pv}^{\,2} + T_g^{\,2})(T_{pv} + T_g) \quad (13)$$

$$h_{ray,g,amb} = \varepsilon_v \sigma\, (T_{sky}^{\,2} + T_g^{\,2})(T_{sky} + T_g) \quad (14)$$

$$h_{cv} = h_{vent} = 2.8 + (3 * V_{wind}) \quad (15)$$

The conduction heat transfer coefficient between two layers of component m and n can be expressed by the following expressions [16]:

$$k_{\frac{m}{n}} = \frac{1}{\frac{\delta_m}{k_n} + \frac{\delta_n}{k_n}} \quad (16)$$

The solar energy absorbed by the glass $Q_{abs,g}$ and by the PV cells $Q_{abs,pv}$ are given by the following expression [17, 18]:

$$Q_{abs,g} = G_c G A_{rec} \eta_{op} \quad (17)$$

$$Q_{abs,pv} = Q_{abs,v} \tau_g \quad (18)$$

2. Results and discussion

2.1. Digital Resolution method

The final form of the mathematical model is a system of discretized equations that cannot be solved analytically but rather by numerical methods.

Currently, there are several numerical methods of resolution. These include finite differences, finite elements and finite volumes.
In our case for the modeling of the heat transfer phenomenon in the absorber of a CPV/T sensor, we adopted the finite volume method in view of the simplicity of the physical geometry studied and we programmed simulations in FORTRAN.
The methods of finite volumes were among the first to reach an advanced stage of development for the calculations of stationary and unsteady flows. They allowed a full consideration of the effects of nonlinearity and compressibility as well as the viscosity effects using the Navier-Stokes equations, and turbulence.

2.2. Results

The model has allowed results evaluation in order to identify the main technical characteristics necessary for the realization of the most efficient CPV/T system. The main input variables of the simulation process are: installation site, optics type, concentration factor and characteristics of each receiver layer (PV cell, glass, selective layer, metallic channel and fluid)
On the basis of the CPVT model discussed in the previous section, electrical and thermal efficiencies were analyzed as a function of different parameters.
The parametric analysis presented in this study aims at evaluating the effect of the variation of some of the parameters on the overall performance of the system. One of the main parameters is the geometry of the receiver. In fact, the variation of the lengths of the sides of the receiver significantly affects some operating parameters, such as: concentration ratio and heat transfer area.
Increasing the length of the receiver causes a decrease of the operating temperature and an increase of the heat exchange area, consequently determining the increase of heat exchange effectiveness. Fig. 2, 3 clearly shows that an increase of the length of the receiver also determine an increase of fluid temperature. Furthermore, PV cells temperature increase as a consequence of the increase of the receptive surface temperature.

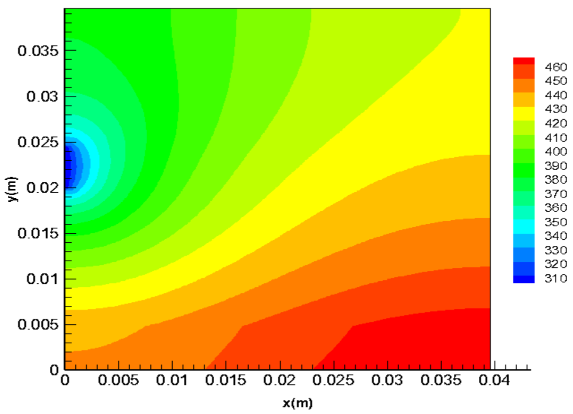

Figure 2: CPV/T layers temperature vs channel length

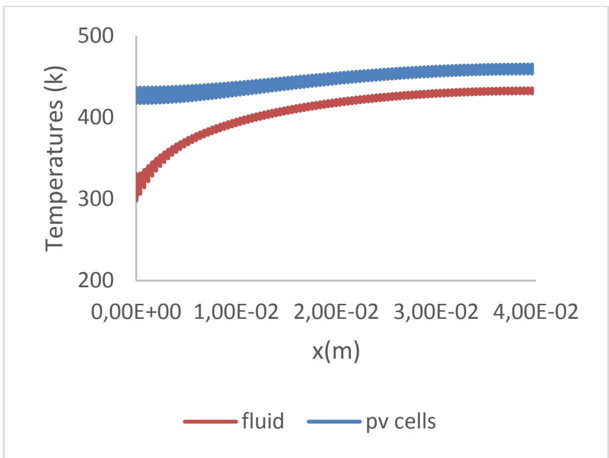

Figure 3: fluid and PV cell temperature vs channel length

As shown in Figures 4 and 5, the CPV/T PV cell and fluid temperature begin to increase from sunrise to midday-solar from which it will diminish until sunset. It can be seen that the maximum of the thermal efficiency and the minimum electrical efficiency of the CPV/T are recorded at midday-sun and they differ from one date to another. This can be explained by the variation of the elevation of the sun in its apparent itinerary in the sky.

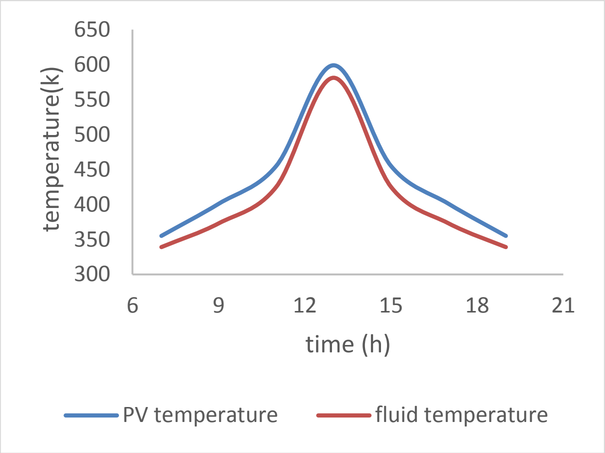

Figure 4: Temporal evolution of PV cell and fluid temperature of the CPV/T

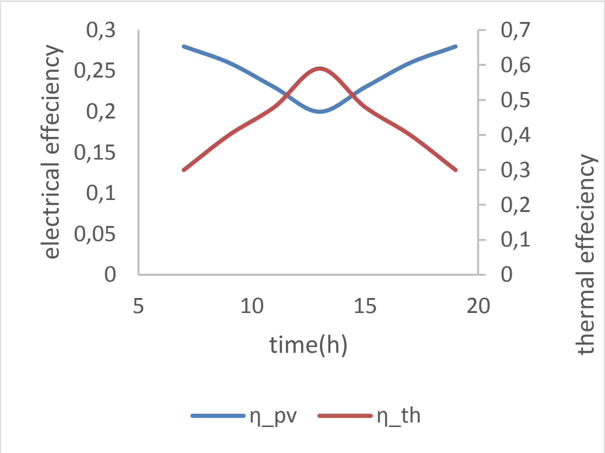

Figure 5: Temporal evolution of electrical and thermal efficiency of the CPV/T

Fig. 4 reports the variation of the thermal and electrical efficiency with water temperature. Increasing the temperature of water leads to an increase in the temperature of the triple-junction PV cells and therefore, its electrical efficiency poorly degraded. In fact, the peculiar properties of the concentrated photovoltaic cells employed in the present concentrator allow the electrical power to remain around a good electrical production even at the higher temperature. We can conclude that the increase of outlet thermal power increase the electrical efficiency. This is due to an increase in the level of the absorber temperature, and the decline of the thermal losses.

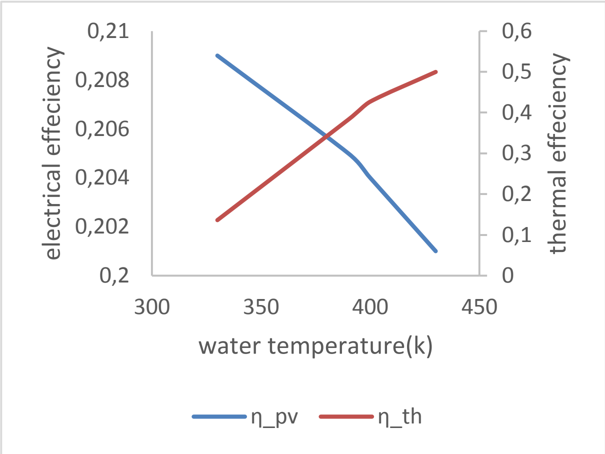

Figure 6: CPVT thermal and electrical efficiency vs fluid temperature.

Fig.5 reports the variation of the thermal and electrical efficiency with the PV cell temperature. Increasing the temperature of PV cells leads to an increase in the temperature of the cooling fluid and therefore, its electrical efficiency decreases and the thermal efficiency increase. The thermal efficiency increases as the coolant temperature increases in spite of higher thermal losses to the environment since the energy not converted to electricity is mostly regained as heat. The peculiar properties of the concentrated photovoltaic cells employed in the present concentrator allow the electrical power to remain around a good electrical production even at the higher temperature.

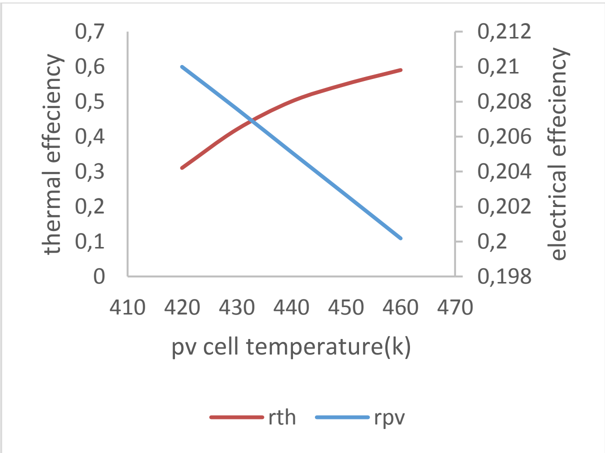

Figure 7: CPVT thermal and electrical efficiency vs PV cell temperature

Fig.6 illustrates the fluctuation of the thermal and electrical efficiencies for varied speed of fluid. When the water's speed is increased, a decrease of thermal and electrical efficiency are respectively observed. In fact, increasing the flow rate depress heat transfer between the fluid and the absorber, therefore the maximum useful energy absorbed will decrease and will influence the electrical power which reach to the weak . This is explained by the fact that the increase in the coolant flow will decrease the residence time of the fluid particles in the absorber and its temperature will decrease thereafter.

We note that the increase in water flow causes the PV production decline. This is because when the flow rate increases, the cooling PV cells becomes more sophisticated and subsequently heating of the PV cells. This heating is detrimental to the performance of CPV/T concentrators since cell voltage drops sharply with temperature. So at high temperatures, it is always interested to decrease the flow rate of the coolant.

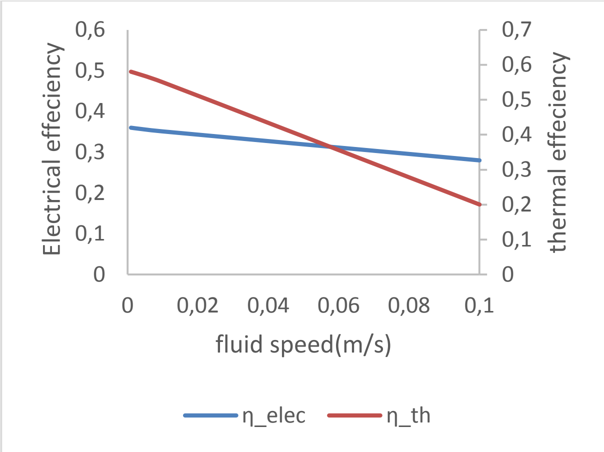

Figure 8: CPVT thermal and electrical efficiency vs fluid speed

Fig. 7 reports the variation of the thermal and electrical efficiencies with the inlet water temperature. Increasing the inlet temperature of water leads to an increase in the temperature of the PV cell and therefore, its electrical efficiency decreases. Similarly, the thermal efficiency decreases according to an increase in water inlet temperature. This is due to an increase in the level of the absorber temperature, consequently the thermal losses is on the rise.

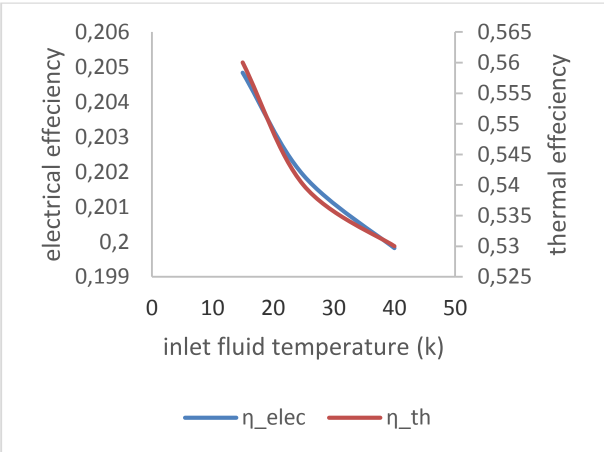

Figure 9: CPVT thermal and electrical efficiency vs inlet temperature.

The parametric analysis also includes the variation of beam radiation, evaluating its corresponding effect on the performance of the CPV/T. In particular, Fig 8 shows that electrical efficiencies decrease when the radiation increases but the thermal efficiencies is proportional to beam radiation

The drop of the increase of the thermal efficiency is very high whereas the variation of electrical efficiency is marginal. In fact, the higher the radiation, the higher both radiative and convective losses mainly as a consequence of the increase of the CPV/T operating temperature. In other words, when the radiation is scarce, the increase in fluid temperature is very low. The useful energy is even negative when the radiation is very weak. In this case, the fluid outlet temperature is lower than the inlet one. This analysis shows that the performance of the CPVT is extremely dependent on the available (specially beam) radiation.

Solar energy due to high reflection and low transmisstance. The choice of a glazed solar collector provides the best compatibility between electrical and thermal efficiencies.

Therefore, the use of such technology is profitable only for those climates where the availability of beam radiation is particularly high.

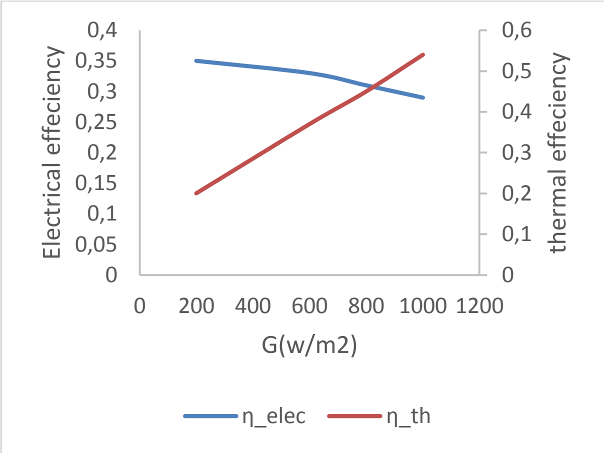

Figure 10: CPVT thermal and electrical efficiency vs beam radiation

Conclusion

In this paper the potential of the concentrating photovoltaic technology has been evaluated from the thermal and electrical point of view. The main aims have been the simulation of a (CPV/T) system on FORTRAN under different operating conditions.

The effect of many factors as the beam radiation, the flow rate, the temperature of fluid and PV cells of the collector were examined. Their effects on the output of the coolant temperature, the recovered thermal power and PV power generation will be very useful for optimizing thermal parabolic trough solar concentrators.

The simulation process has allowed to define the best configuration of the CPV/T system and to evaluate the high potential. The possible range of temperatures is wide enough to satisfy the requirements of several attractive thermal applications.

Under some conditions, the solar cooling is even significantly less expensive than conventional system. This is in contrast with solar concentrated based on photovoltaic thermal collectors, which is found to be significantly more performant than conventional cooling system. The existence of such incentives will make the CPVT system even more competitive than the results presented here. This can also be viewed from another perspective: a CPV/T cooling plant will require a lower level of incentive, relative to other solar technologies, in order to become competitive against conventional cooling.

Nomenclature

A surface area, m^2

C_{fd} Specific heat of fluid, J $Kg^{-1}K^{-1}$

G beam irradiation, W/m^2

G_c Concentrating photovoltaic thermal solar collectors

$\dot{m}_{fd}$ Mass flow rate of fluid, Kgs^{-1}

P_{elec} Electrical power, W

P_{th} Thermal power, W

h heat transfer coefficient, W/m2/K

Symbols Greek

τ transmittance

δ thickness, m

ε Emissivity

ρ density, Kg/m3

η efficiency

η_0 Electrical efficiency at reference temperature (298 K)

Indices

PV photovoltaic

g glass

out outlet

th thermal

op optical

in inlet

inv inverter

th thermal

el electrical

ap aperture

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