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# **Modeling and optimization of a solar system based on concentrating photovoltaic/thermal collector**

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## **Abstract**

Concentrated photovoltaic thermal (CPV/T) solar collector systems are designed to provide simultaneously thermal and electrical energies. This paper analyzes a numerical model of a photovoltaic thermal collector in order to evaluate its performances from energy and economic viewpoints. Therefore, a two dimensional numerical model has been developed and applied in this study. This electrical/thermal model is based on the energy balance of the CPV/T receiver in order to calculate the net thermal and electrical output energy. A comparison between the numerical results and those obtained by experimental studies is presented in order to prove the viability of our developed model. The results show that the output power predicted by the numerical model has a good agreement with the experimental data with low mean percentage errors. Indeed, the effects of several parameters on the performance of the system were examined and discussed in details. The simulation process has allowed evaluating the power generation of the CPV/T system and performing a comprehensive economic analysis study under Chambéry and Tunisia conditions. The CPV/T system has proven its viability and feasibility especially in regions with high solar radiation.

## **Keywords:**

CPV/T, triple junction, thermal and electrical performances, power generation, economic study

## 1. Introduction

It is well-known that the sun is the most significant renewable energy source due to its abundant irradiation to the earth surface. Solar energy conversion systems have been the main focus of several current research studies. In particular, the concentrating solar collector is the key component of using the solar energy for simultaneous thermal and electrical energy production. In fact, Concentrated Photovoltaic Thermal solar collectors (CPV/T) systems directly-convert the solar energy into electrical and thermal energy. These cogeneration power systems can offer interesting solutions for several processes that require both PV and low/medium/high operating temperature. Moreover, conventional PV systems were suffering from low electrical conversion efficiencies with high outlet temperature since many decades. Hence, the use of such concentrating PV system will greatly enhance the effective solar density on PV cells. In the last years, a new important aspect of solar cell was discovered. A semiconductor junction stack that absorbs solar energy on a wider light spectrum than conventional PV cells is used in concentrating solar systems. Thanks to their resistance to high temperature the stack of photoelectric material (Ga, As, In, B, P) is regarded as a high performance PV cell. CPV/T systems are generally based on triple junction PV cells. In fact, cell efficiency can be increased logarithmically with the concentration ratio which makes them less influenced by the cell temperature increase (Buonomano, 2013; Davide, 2014; Basco, 2012; Zondag, 2008; Skoplaki, 2009)

With this regard, many advanced researches have recently beaten very high efficiencies making triple junction PV cells more commercially accessible. Thus, several research studies were conducted to investigate such systems at laboratory scale and even for industrial cases as well.

Further, most of the researches are focused only on the thermal and the electrical behavior of the CPV/T system. A photovoltaic/thermal parabolic trough collector with a triangular linear receiver recovered by triple junction cells was studied by Calise et al. (2012). This type of PV cells improved the system performances and its efficiency was found to be expressively better than the use of silicon cells, especially when the operating temperature is high. Coventry (2005) tested experimentally a parabolic trough photovoltaic thermal prototype. The combined efficiency reached 69 % under a concentration ratio equal to 37 suns. Cappelletti et al. (2015) reported a monitoring system to check the CPV/T energy production by the providence of an alarm in the presence of any discrepancy. Their model is also validated by a prototype

experimental data and it marked a good enhancement by the decrease of the solar collector shadowing.

Gibart et al. (2018) made a study on a cylindrical reflective surface, thanks to the simplicity of the technology. The results showed that the electrical and thermal efficiencies are higher than those of a conventional solar system. Furthermore, based on an economic study, it is expected that the system will have a return time of 10.5 to 12.8 years.

Quaia et al. (2012) and Ming et al. (2011) completed the first commercial scale demonstration for the CPV/T technology by the end of 2004 at the Center for Sustainable Energy Systems (CSES) at the Australian National University (ANU). They developed a combined solar collector (CHAPS) which provided electricity and hot water for the heating of a residential school with a combined efficiency of 69 %. The ANU produced mono-crystalline silicon PV cells. Under a concentration ratio of 30, PV cells were characterized by a low resistance in series around  $0.043 \Omega\text{cm}^{-2}$  and efficiency equal to 20 % at 25°C. Xu Ji et al. (2012) worked on two CPV/T systems in the research institute of the National University of Australia. A detailed study on a CPV/T and much work had already been done on the design of the collector as well as the development of new solar cells. They compared the system for two different types of PV cells. The researchers have admitted that GaAs cells have higher electrical efficiency, thanks to their low resistance in series that results an excellent system performance. However, for the crystalline cells, the generated system powers are decreased due to the high series resistance leading to high power losses. Nevertheless, crystalline cells are characterized by the better thermal efficiency.

Three absorber shapes of linear CPV/T systems (tubular, vertical plate and horizontal plate) were reported in Sharan et al. (1987). A Comparative performance between these forms was discussed. Results showed that the solar concentrator system with a tubular absorber provides the maximum electrical power, the optimum electrical efficiency and the lowest cell temperature. Thus, its efficiency reached the highest value compared to the other configurations.

Nowadays, it is still a challenge to achieve high outlet temperature from (CPV/T) systems. Multilayer thin film filters ( $\text{SiNx/SiO}_2$ ) were studied and fabricated to act as beam splitting. Felipe et al. (2014) investigated a CPV/T collector using  $\text{SiNx/SiO}_2$  thin film filters and demonstrated the feasibility of this technology. They also indicate that this type of system might exploit 85.6 % of the incoming solar spectrum. Proell et al. (2016) focused on the influence of the CPC reflectors on the PV efficiency. Authors studied experimentally the flux distribution

and, especially, they measured the angle modifier of the PV efficiency. Results showed the negative effect of a non-uniform irradiation on the PVT absorber which decreased their efficiency. Moh'd et al. (2017) examined the behavior of a (CPV/T) system that utilizes an Organic Rankine Cycle (ORC) integrated with a geothermal condenser and an energy storage unit. It was found that without cooling, the PV cell's efficiency reached 3.88 % in comparison to 18.92 %, while using the cooling system and 21.96 % by using the ORC as a waste recovery system.

Currently, the adoption of nanofluids in concentrated solar systems ~~can~~ present an interesting option, which attracted a significant attention. Based on a numerical model, Xu and Clement (2014) investigated the use of an (Al/water) nanofluid for cooling a linear parabolic CPV/T system. According to their results, the efficiency of the PV cell increase with an increase in nanoparticle volume fraction. Farideh and Ehsan (2017) investigated using nanofluids as the working fluid on the CPV/T system. The results indicated that using nanofluids in the laminar flow is more effective compared to the case of the turbulent regime. In diverse types of solar collectors' technologies; Verma and Tiwari (2017) reviewed the nanofluid application. However, relatively fewer informations are available for using nanofluids in PV/T systems, especially in CPV/T systems.

Based on previous works, several researchers have studied distinctive applications of CPV/T systems. In fact, Xu et al. (2012) proposed a novel low-concentrating solar photovoltaic/thermal system to heat water from 30°C to 70°C for domestic supply, space heating or associating a solar cooling system under an output electrical efficiency around 17.5%. While, CPV/T systems face different challenges, as a new application for this technology, a concentrated photovoltaic thermal system that drive an air conditioner was investigated (AL-ALili et al., 2012). The results showed that the performance of the proposed system is higher than the vapor compression cycle powered by photovoltaic panels and a solar absorption cycle. This new system is also able to meet the humidity and temperature requirements of buildings regardless of the climate. One of the proposed promising application for the exploitation of the CPV/T system is the coupling of a linear Fresnel concentrator with a channel photovoltaic/thermal collector that reached a total efficiency over 60% (Rosell et al., 2005).

Another advantage of the exploitation of the CPV/T system outputs is the increase of the potential cogeneration heat. However, this issue decreases the electric efficiency (Conventry,

2005; Calise, 2012; Xu et al., 2012). In fact, for high-temperature the most appropriate PV cells for these technologies is the triple-junction type, which's nominal efficiency reached 20% at 513K. Therefore, the use of such semi-conductor materials can lead to a higher outlet temperature at judicious conversion efficiency. Different applications make the perspective of using CPV/T systems with outlet high-temperature very interesting. With this regard, Mittelman et al. (2017) were interested in a CPV/T system equipped with triple junction cells with a nominal conversion efficiency of 37 %. The prototype operates at temperatures above 100°C and its output thermal energy can be useful for different processes such as steam production, refrigeration and water desalination. Moreover, some authors studied a combination of a parabolic dish and high efficiency solar photovoltaic cells at high temperature. They explored a concentrating PV/T system operating at 453 K with an acceptable thermal and electrical efficiency driving a two-effect absorption chiller (Buonomano et al., 2013). Lately, simplified models are used also to investigate CPV/T plants at high temperatures. The outcomes revealed that exploiting the wasted system heat for cooling might lead to greater overall efficiency (Kribus et al., 2006).

For higher temperature necessities, concentrating solar collectors are the only solution; several examples consist in the use of this high-temperature provided by the CPVT to drive a thermal motor (Vorobiev et al., 2006), an Organic Rankine Cycle (Kosmadakis, 2011) or a Solar Heating and Cooling system (Calise and Vanoli, 2012). A CPV/T installation based on a dish concentrator was considered for both water desalination and solar cooling applications (Mittelman et al., 2007).

Ben Youssef et al. (2017) proposed a numerical model of a CPV/T system operating under 200°C. The modeling gives a detailed analysis of the thermal and electrical performances of water heating for an application of the textile industry. Results of an innovative CPV/T system that incorporates spectral beam splitter and vacuum tube sensors showed that the thermal load of the cell can be reduced and the outlet temperature can be up to 250 or 300°C (Otanicar et al., 2015).

Accordingly, the all above mentioned results showed that the CPV/T technology has been greatly developed and it has been increasingly embraced. Consequently, it definitely holds a very high potential for market penetration in the energy sector.

In previous published studies, the main objectives were focused to improve the heat transfer in the CPV/T system with low outlet temperature and there were few papers in which they investigated medium or high temperature. In the present study, differently from traditional

photovoltaic systems, the CPV/T systems with triple junction PV cells, guarantees recovering the thermal energy with high electrical efficiency. Detailed analysis is performed using the 2-D developed numerical model in order to identify the significant parameters affecting the overall performance of the CPV/T system. Thus, the proposed model is applied to improve the cogeneration system capacity and to retain competitive prices. It is used to optimize the CPV/T system configuration, to evaluate the output temperature and power, and to examine its capacity and economic viability. Therefore, an evaluation and a comparative economic analysis under Tunisia and Chambéry climatic conditions is inspected.

## **2. Design and dynamic model of the CPV/T system**

### **2.1. CPV/T simulation: Mathematical model**

In the present study, the effects of several parameters influencing the performance of a CPV/T have been investigated. The simulated CPV/T consists of a parabolic trough concentrator equipped with a rectangular receiver channel and two-axis tracking system. As such, parabolic concentrating collectors receive an insignificant amount of diffuse radiation; their output energy depends essentially on the reflected beam radiation onto the absorber contained in the evacuated plane receiver.

The CPV/T system and the considered receiver are shown in Fig. 1. It involves a thermal unit for heat extraction from the coolant water which circulates through the rectangular pipe. This rectangular pipe is constructed and installed in contact with the photovoltaic cells, allowing simultaneously the cooling of the cells and the production of thermal energy. The bottom surface of the receiver (facing the concentrator) is equipped with triple-junction cells InGaP/InGaAs/Ge and the other surfaces are insulated. The sunrays focused on PV cells allow reaching a concentration ratio factor of 20. This ensures heating of the "selective layer" located immediately beneath the cells to promote conduction/convection heat transfer between the metal channel and the fluid.

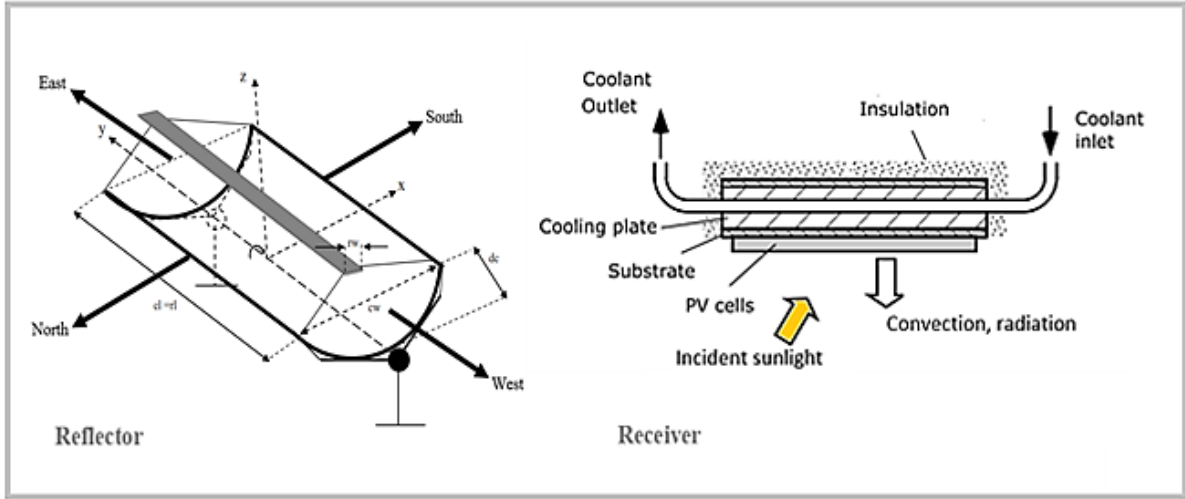


Fig. 1. Schematic representation of concentrating photovoltaic thermal system (CPV/T).

## 2.2. Numerical modeling: The Energy Balance Equations of the CPV/T System

In the present study, the receiver at the focal point of the CPV/T includes six layers as shown in Fig.2. The CPV/T loses heat to the surrounding through two different ways. The first way is by convection between PV layer and the surrounding ambient. In addition, the outside surface of the PV cell loses heat to the surrounding sky by radiation. As regarding to the thermal transfer between the different layers, the conductive thermal transfer is prevailing.

At the upper, the left and the right boundaries of the superimposed layers are insulated. At the inlet, the fluid is introduced at the inlet temperature ( $T_{in} = 298\text{ K}$ ).

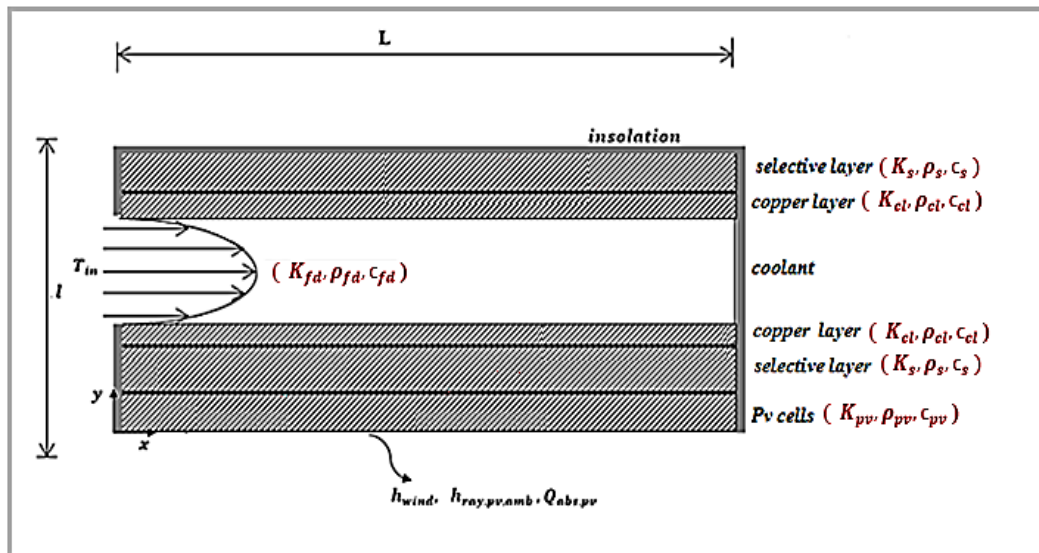
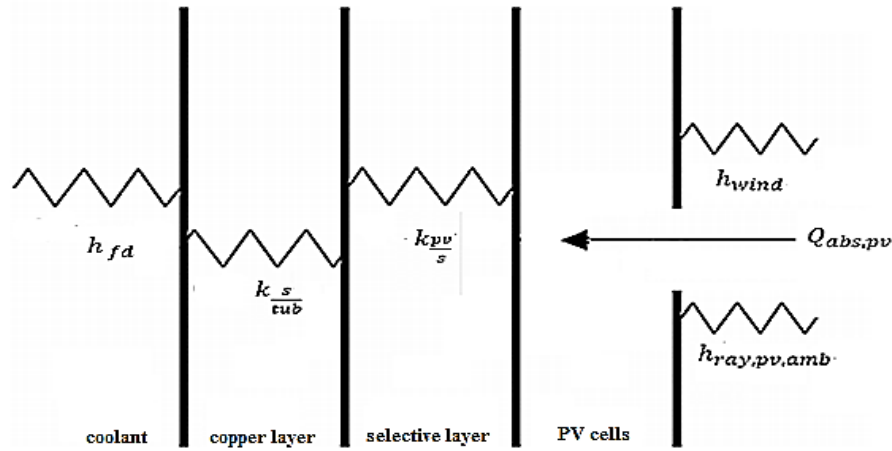


Fig. 2. Schematic design of receiver layers



All forms of heat transfer of different layers at the side of the planar receiver are shown in Fig.3 and they are defined in Table1.



**Fig. 3. Heat flow through CPV/T receiver**

**Table 1: Heat transfer coefficients of energy balance equation of the receiver.**

Heat flux w/m	Heat transfer mode : heat transfer path from/to
$h_{fd}$	Convection :fluid / cooper layer
$k \frac{s}{col}$	Conduction: copper layer / selective layer
$k \frac{s}{pv}$	Conduction : selective layer/ PV cells
$h_{wind}$	Convection : PV cells / ambience
$h_{ray,pv,amb}$	Radiation : PV cells / sky
$Q_{abs,pv}$	PV cells/ Concentrated solar radiation

Simplified models for the calculation of the CPV/T performance that are available in the literature cannot be applied to the investigated system due to the use of concentrating systems and triple-junction cells. Therefore, an appropriate model, based on energy balances of the system is developed in this paper.

This two dimensional model is based on a finite volumes method developed using FORTRAN which allows a simple formulation of equations.

Various assumptions are taken into account to facilitate the theoretical analysis. The thermal exchanges in the absorber are studied according to the following considerations:

- The dimension of the receiver and the surface of the collector are constants
- 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 constants
- The flow is driven by the pressure flow and is assumed to be in a fully developed state, it has the following analytical solution:  $u(y) = 4U_0(\frac{y}{h} - 1)(2 - \frac{y}{h})$  with  $h < y < 2h$ ,  $h$  is the width of the channel and  $U_0$  represents the peak velocity in the channel (Yang et al., 2015).

Considering these assumptions, equations governing the heat transfer in various components of the CPV/T receiver are given as follows:

▪ Fluid

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

▪ Rectangular pipe

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

▪ Selective layer

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

▪ PV cells

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

Assuming the top surface area as gray surface and considering that the area of the top surface is much lower than the one of the sky, the radiative heat transfer between PV cells and the sky can be calculated as follows (Duffie et al., 1980):

$$h_{ray,pv,amb} = \varepsilon_v \sigma (T_{sky}^2 + T_g^2)(T_{sky} + T_g) \quad (5)$$

The external sky temperature  $T_{sky}$  is required to estimate the radiative exchange and its variation according to the ambient temperature  $T_{amb}$ . It can be calculated as follows (Swinbank et al., 1963):

$$T_{sky} = 0.0522 * T_{amb}^{1.5} \quad (6)$$

The convection heat transfer coefficient  $h_{cv,pv,amb}$  from the outer surface of the PV layer, which is in contact with the ambient and depends on the wind velocity  $V_{wind}$ . The following equation represents the heat transfer from the receiver to the environment (Watmuff et al., 1977):

$$h_{cv,pv,amb} = h_{wind} = 2.8 + (3 * V_{wind}) \quad (7)$$

The conduction heat transfer coefficient  $k_{\frac{a}{b}}$  between two layers of component a and b can be expressed as a function of the thickness  $\delta_a, \delta_b$  and the conductivity of each component  $k_a, k_b$  by the following expressions (Duffie et al., 1980):

$$k_{\frac{a}{b}} = \frac{1}{\frac{\delta_a}{k_a} + \frac{\delta_b}{k_b}} \quad (8)$$

The thermal conductivity of nanofluid depends on the thermal conductivity of the original fluid  $k_{of}$ , the nanoparticles concentration  $\sigma$ , and their thermal conductivity  $k_{np}$ . It is based on the Maxwell relation as follows (Maxwell, 1873):

$$K_{nanofl} = \frac{(k_{np} + 2k_{of}) + 2\sigma(k_{np} - k_{of})}{(k_{np} + 2k_{of}) - \sigma(k_{np} - k_{of})} \quad (9)$$

The solar energy absorbed by PV cells  $Q_{abs,pv}$  is given as (Buonomano et al., 2013):

$$Q_{abs,g} = G_c G A_{rec} \eta_{op} \quad (10)$$

where  $G, G_c, A_{rec}, \eta_{op}$  are respectively the beam irradiation, the concentration ratio, the receiver area and the optical efficiency.

The concentration ratio ( $G_c$ ) is defined as the ratio between the area of the receiver  $A_{rec}$  and the aperture area of the concentrator  $A_{ap}$  (Buonomano et al, 2013; Ming et al, 2011; Calise and Vanoli, 2012; Kribus et al, 2006):

$$G_c = \frac{A_{ap}}{A_{rec}} \quad (11)$$

The CPV/T system produces both electrical and thermal energy which are conventionally related to the incident beam radiation and to the collector aperture area.

In fact, each type of the produced power is described by a separate expression. The overall performance of the CPV/T is often evaluated using the well-known thermal and electrical efficiencies.

The electrical efficiency of the triple-junction cells ( $\eta_{pv}$ ) is related to the concentration ratio  $G_c$  and to the PV cell temperature  $T_{pv}$  and it can be computed by the following equation (Buonomano et al, 2013; Ming et al, 2011; Calise and Vanoli, 2012; Kribus et al, 2006):

$$\eta_{pv} = 0.298 + 0.0142 \ln G_c + [-0.000715 + 0.0000697 \ln G_c] (T_{pv} - 298) \quad (12)$$

The optical, module and inverter efficiencies ( $\eta_{op}, \eta_{mod}, \eta_{inv}$ ) of the concentrator are assumed being constants. Therefore, the electric output net power can be estimated as follows (Buonomano et al, 2013; Ming et al, 2011; Calise and Vanoli, 2012; Kribus et al, 2006):

$$P_{pv} = G_c G A_{pv} \eta_{op} \eta_{mod} \eta_{inv} \eta_{pv} \quad (13)$$

where  $A_{pv}$  is the PV cells receiver area.

The output useful heat absorbed by the coolant can be described as (Buonomano et al, 2013; Ming et al, 2011; Calise and Vanoli, 2012; Kribus et al, 2006):

$$P_{th} = \dot{m}_{fd} C_{fd} (T_{out} - T_{in}) \quad (14)$$

Finally, in order to evaluate the performance of the CPV/T system, the thermal and electrical efficiencies ( $\eta_{th}, \eta_{elec}$ ) are calculated based on the following expressions (Buonomano et al, 2013; Ming et al, 2011; Calise and Vanoli, 2012; Kribus et al, 2006; Davide et al, 2014):

$$\eta_{th} = \frac{P_{th}}{A_{ap} G} = \frac{\dot{m}_{fd} C_{fd} (T_{out} - T_{in})}{A_{ap} G} \quad (15)$$

$$\eta_{elec} = \frac{P_{pv}}{A_{ap} G} = \frac{G_c G A_{pv} \eta_{op} \eta_{mod} \eta_{inv} \eta_{pv}}{A_{ap} G} \quad (16)$$

#### 4. Design data and model validation

In the following section, a comprehensive parametric study is performed with the scope of the performance analyses of present CPV/T under different operating conditions along with some of its varying design parameters.

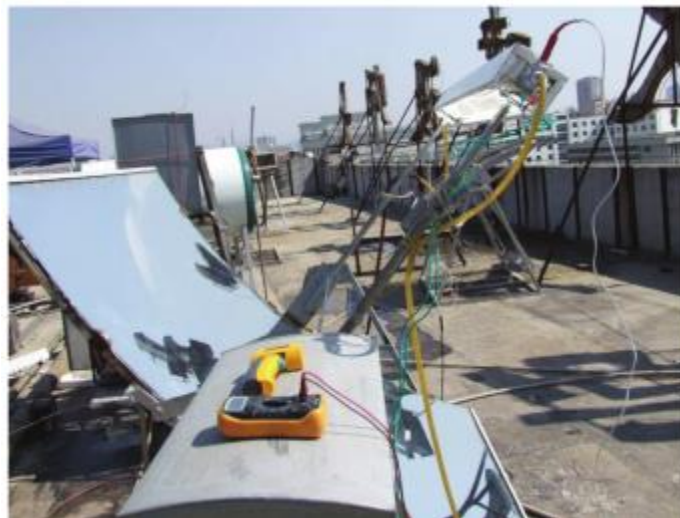
The present studies were performed considering the design parameters reported in Table 2.

**Table2: Geometric parameters of the simulated CPV/T system**

Parameter	value/unit
<b>CPV/T</b>	
aperture area	4*3 m <sup>2</sup>
concentration ratio	20
Optical efficiency	0.9
Rim angle	90°
<b>PV layer</b>	
type	Triple junction
area	0.15*4 m <sup>2</sup>
emissivity	0.98
thermal conductivity	50 w/m k
module efficiency	0.9
inverter efficiency	0.9
<b>Rectangular pipe</b>	
thermal conductivity	399 w/m k
<b>Selective layer</b>	
thermal conductivity	401 w/m k

In literature, some data are available for the CPV/T systems, since the experimental work is still in progress. In fact, few experimental studies are available on systems similar to the one adopted in the present study. Therefore, in order to validate the mathematical model described above, the receiver characteristics, the PV cell type, the design parameters and the boundary conditions are modified according to an experimented model illustrated in Fig.4 (Xu et al., 2012).

Finally, a comparison between numerical results and experimental ones are conducted.



**Fig. 4. Schematic plan of the experimental CPV/T model (Xu et al., 2012)**

Despite the validation of the electrical performance, it is still insignificant for this study since the experimental prototype is equipped with GaAs cells. However, the CPV/T system considered in this paper uses triple junction cells. As shown in table 3, the numerical model showed an acceptable agreement between experimental and numerical results with low errors.

**Table 3: Model validation: The simulation and experimental results of the CPV/T system.**

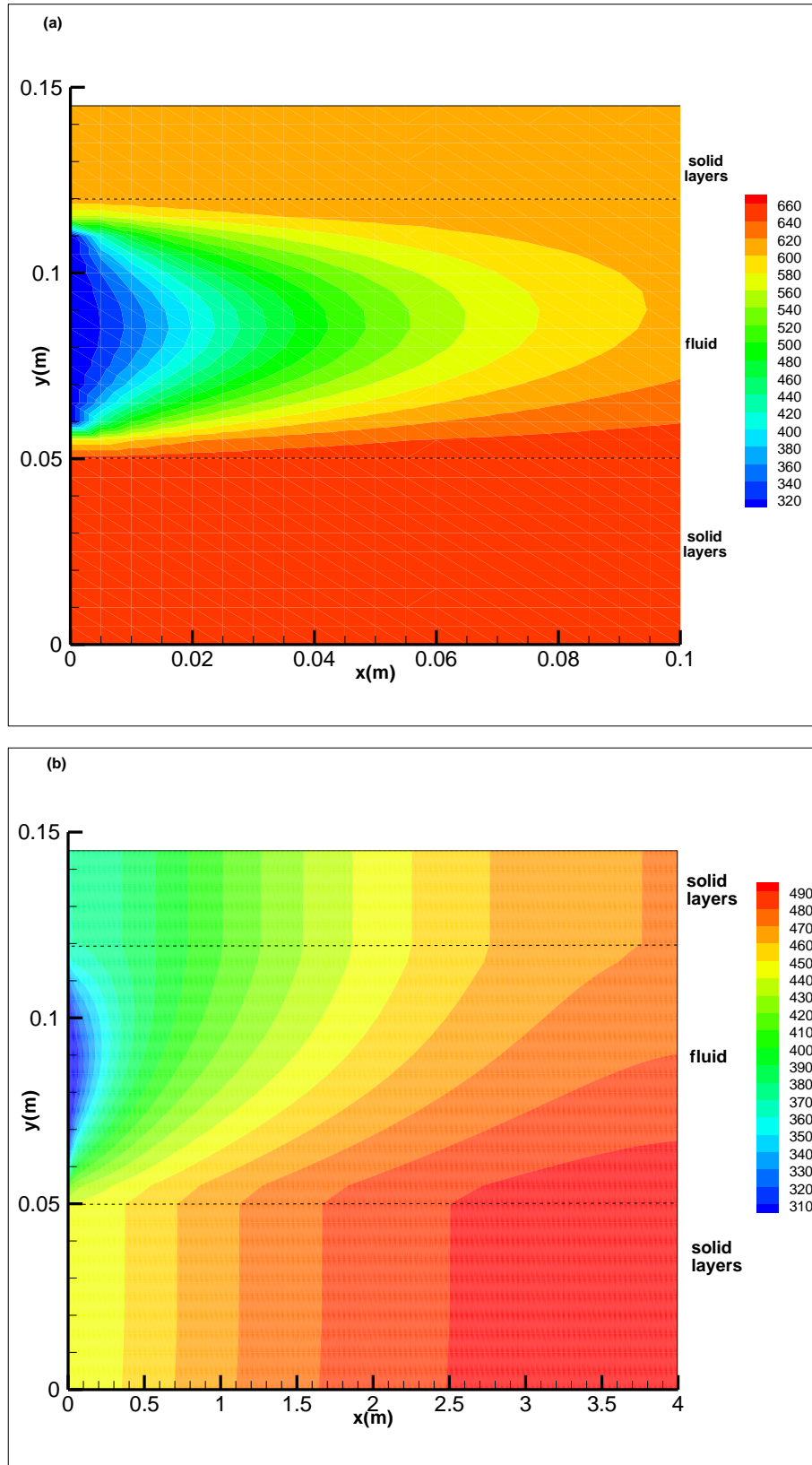
	$T_{out}$	$\eta_{PVcells} \text{ (max)}$	$\eta_{elec}$	$\eta_{therm}$
<b>Experimental</b>	39.1 °C	26.06%	5.73%	36.12 %
<b>Simulation model</b>	41.46 °C	25.57%	5.628%	40.7%
<b>Error</b>	5.6%	1.9%	1.8%	11%

## 5. Results and discussions

After guaranteeing the precision of the present numerical model, in this section, we are interested in the estimation of the thermal and electrical efficiencies of the CPV/T system. Results of the numerical simulation concerning the influence of several factors on the system's performance along with its output thermal and electrical power are presented.

The receiver temperature varies according to the characteristics of each layer and the point position (x, y). As shown in the figures below, the temperature of solid layers varies considerably over the length of the absorber channel, with a small degree of variation along the y-axis. Though, this is not the case for the fluid channel because its temperature varies extensively according to the width of the channel (Fig.5 (a)).

In fact, it is observed that convection effect is visibly displayed just in the beginning of the fluid injection ( $0 < x < 0.1\text{m}$ ), after that the heat conduction between layers becomes dominant. Fig.5 (b) shows the variation of the temperature over the whole length and the width of the absorber channel for different positions ( $0 < x < 4\text{m}$ ,  $0 < y < 0.15\text{m}$ ). Therefore, for the rest of the simulation results, the thermal effect is presented according to the y-direction and the other layers are along the x-direction.

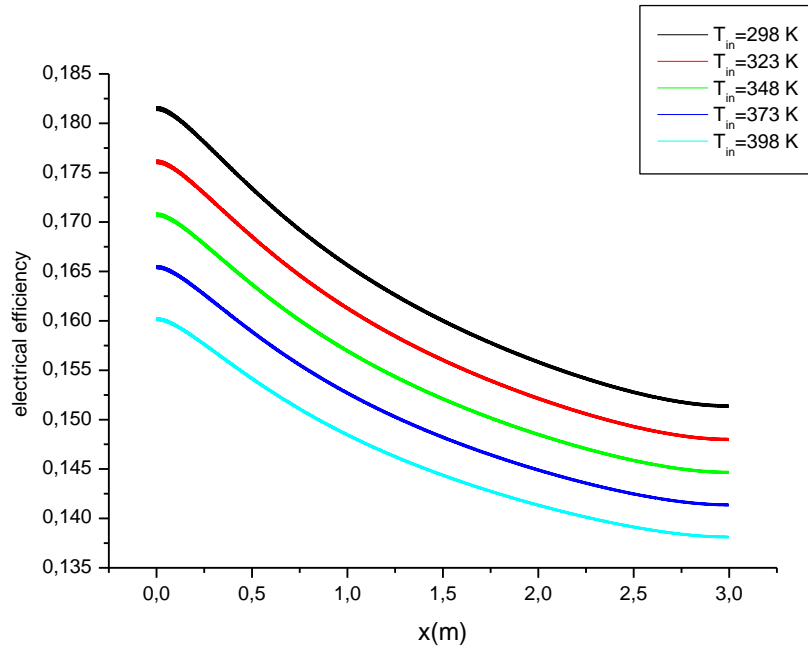


**Fig. 5. Temperature of the fluid layer (a) at the beginning of the channel (b) over the entire length of the receiver**

### 5.1. Effect of the inlet Temperature

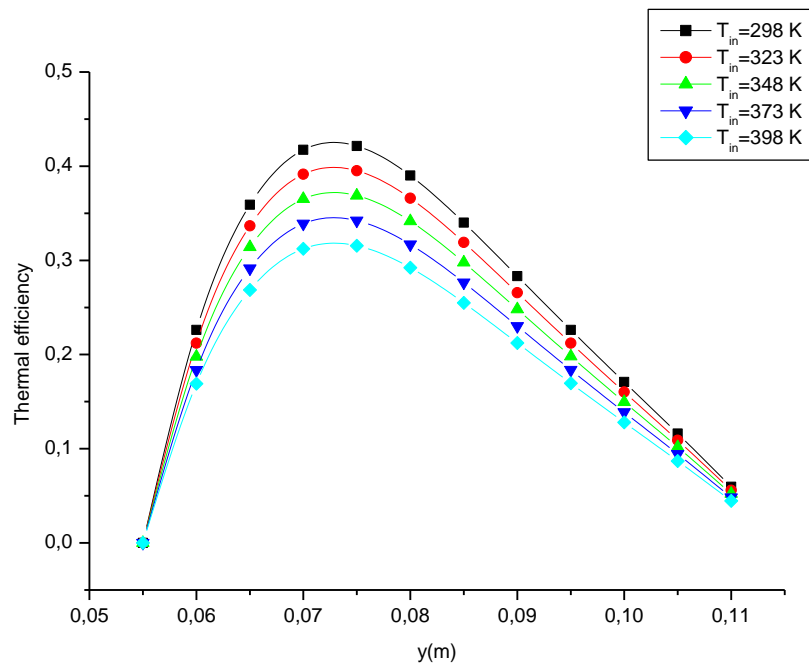
The variation of the CPV/T performance as a function of the environmental and boundary conditions is a primeval study. Actually, the overall performance of the system is scarcely sensitive to the variations of the ambient temperature. Certainly, the most important parameters are the fluid inlet temperature and the wind velocity.

In fact, an increase of the inlet temperature determines a global increase of receiver layer temperatures, and the convective and radiative losses. This fact, leads to an intense drop of both electrical and thermal efficiencies, as shown in Fig.6, 7. Thus, due to this simultaneous decrease, the increase of outlet temperature is proportional to the increase of inlet temperature (Fig.8).

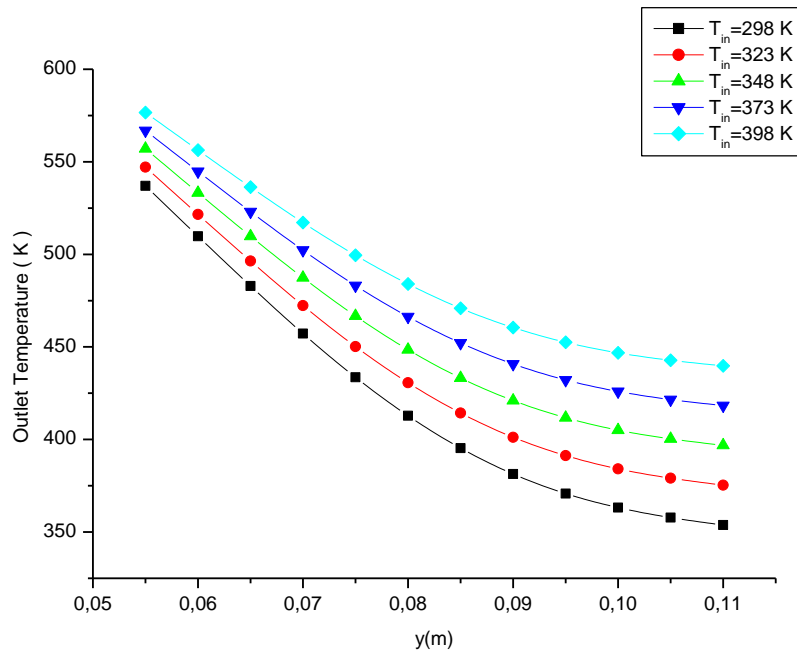


**Fig. 6. CPV/T electrical efficiency vs inlet temperature**





**Fig. 7. CPV/T thermal efficiency vs inlet temperature**



**Fig. 8. CPV/T outlet temperature vs inlet temperature**

## 5.2. Effect of Wind velocity

It is also necessary to take into account the impact of wind velocity on the CPV/T system. The wind is indispensable since it cools the cells. However, it must not be too strong to not damage the structure of the installation. In fact, the low wind velocity leads to higher PV layer temperature and of course exists the high convective and radiative losses. Therefore, the electrical efficiency decreases as clearly shown in Fig.9.

From another side, Fig.10 shows a decrease of the thermal efficiency with every increase of the wind velocity. This can be explained by the decrease of the fluid temperature due to the thermal losses.

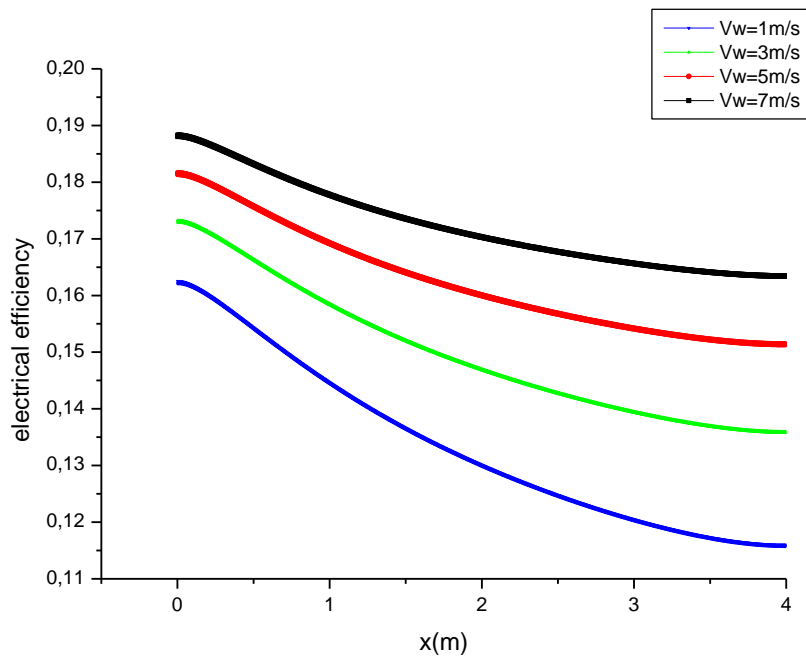


Fig. 9. CPV/T electrical efficiency vs wind velocity.

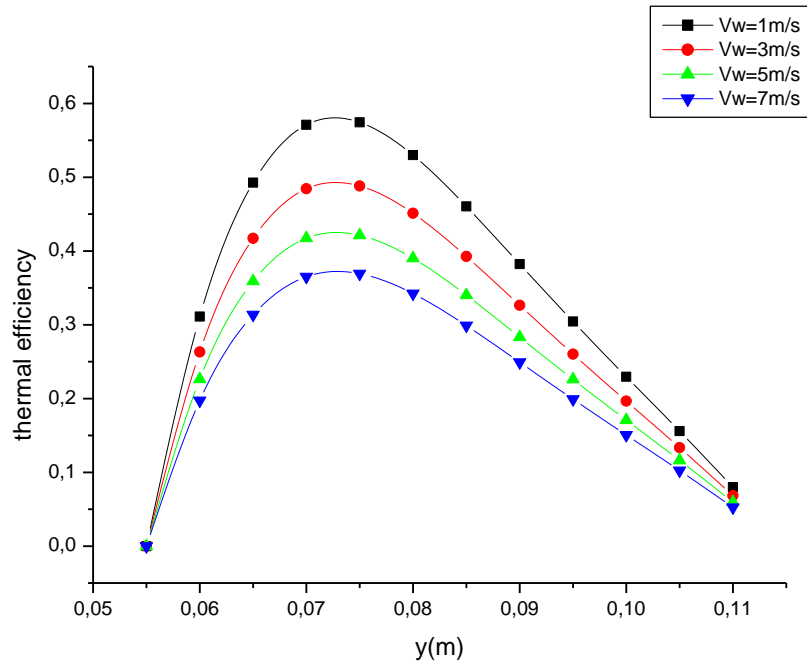


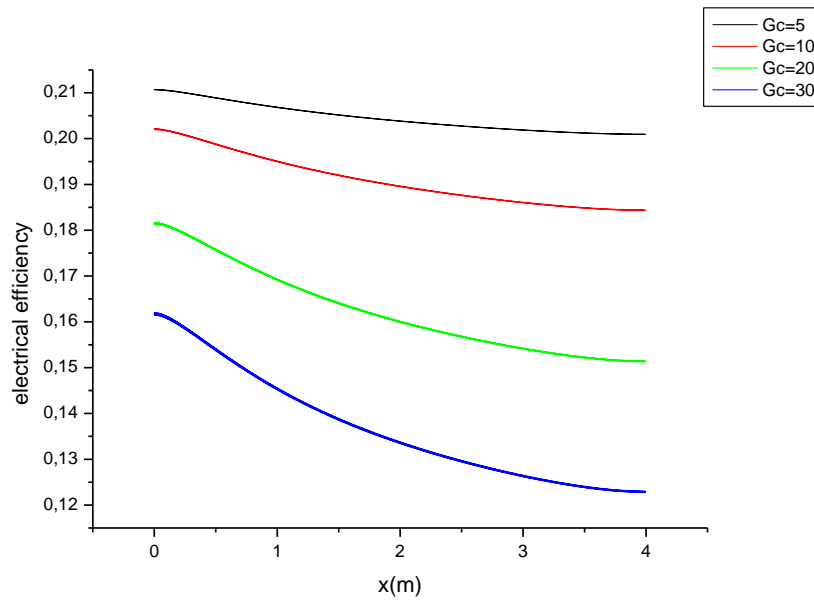
Fig. 10. CPV/T thermal efficiency vs wind velocity.

### 5.3. Effect of concentration factor GC

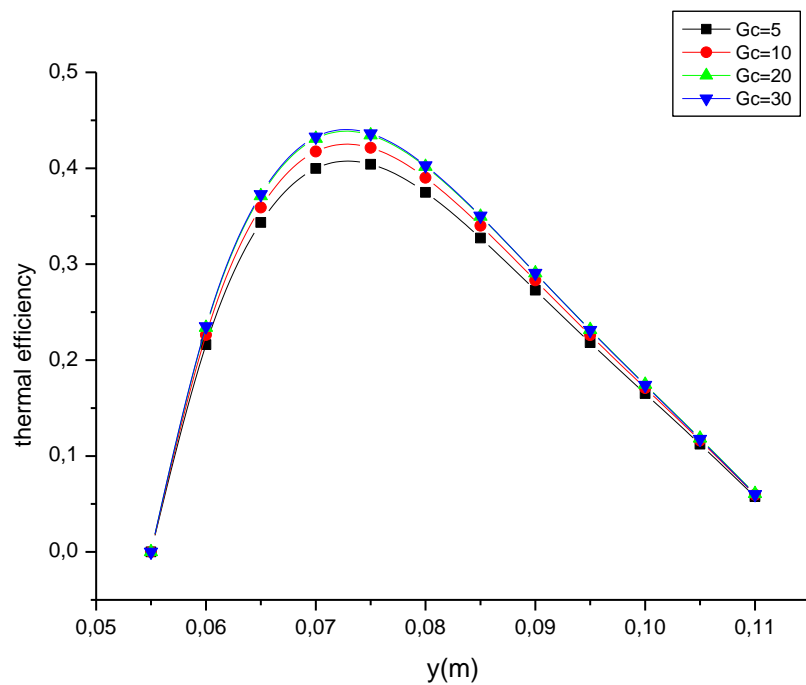
In this section, the effect of the CPV/T concentration ratio  $G_c$  is discussed. In fact, the variation of the width of the reflector affects significantly the concentration ratio, which can lead to an optimal design of the CPV/T system. Thus, the results of this parametric analysis are shown as below. In particular, Fig.11 and Fig.12 display that both thermal and electrical efficiencies are significantly affected by the increase of the concentration ratio. Obviously, the concentration ratio decreases for higher widths of the reflector as the absorber area is constant and the reflector area decreases. A ratio range of 5–30 was selected in accordance with the size of the system. The higher the width value is, the higher the solar energy incident on the receiver is. Especially, a decrease of the concentration ratio leads to a dramatic decrease in the heat exchange effectiveness. Therefore, the fluid will remove a lower heat. Consequently, the temperatures of the receiver layers, especially the PV cells increase, which causes the drop of the electrical efficiency as clearly shown in Fig.11.

As expected, the increase of the area of the reflector increases the exchange area, this decreases significantly radiative and convective losses. As a result, it improves slightly both the thermal efficiency and useful thermal powers (Fig.12).

Hence, from this parametric analysis, using the global efficiency as the objective function, it can be concluded that an optimal sizing of the CPV/T area has to be based on the concentration ratio optimization in order to optimize the whole system performances.



**Fig.11. CPV/T electrical efficiency vs concentration ratio.**



**Fig. 12. CPV/T thermal ef ficiency vs concentration ratio.**

#### 5.4. Effect of water velocity

Water velocity, related to the mass flow rate, is another important parameter in the CPV/T system designing. It governs the temperature of the outlet water, and affects straightly the thermal efficiency. In fact, the convection heat transfer coefficient depends on the coolant velocity variations; the higher the convection heat transfer coefficient is, the higher the heat transfer and the lower the outlet temperature are. Indeed, at high velocity, the flow residence time in the channel is too short, so less heat can be removed, resulting in higher rectangular pipe temperature and lower water temperature (Fig.13). This fact leads to a low PV cells temperature that increases its electrical efficiency (Fig.14). Besides, in this CPV/T system, higher water velocity may break the temperature stratification in the receiver and leads to the decrease of the instantaneous collector efficiencies. Fig.15 shows that when the water velocity continues to increase, a “critical water velocity rate” is reached in the middle of the receiver channel width (0.08 m) above which the thermal efficiency of the system goes down for high velocity and becomes high for low ones.

Thus, it is thought that an optimal mass flow rate exists which allows the CPV/T system to produce the highest thermal and electrical efficiencies.

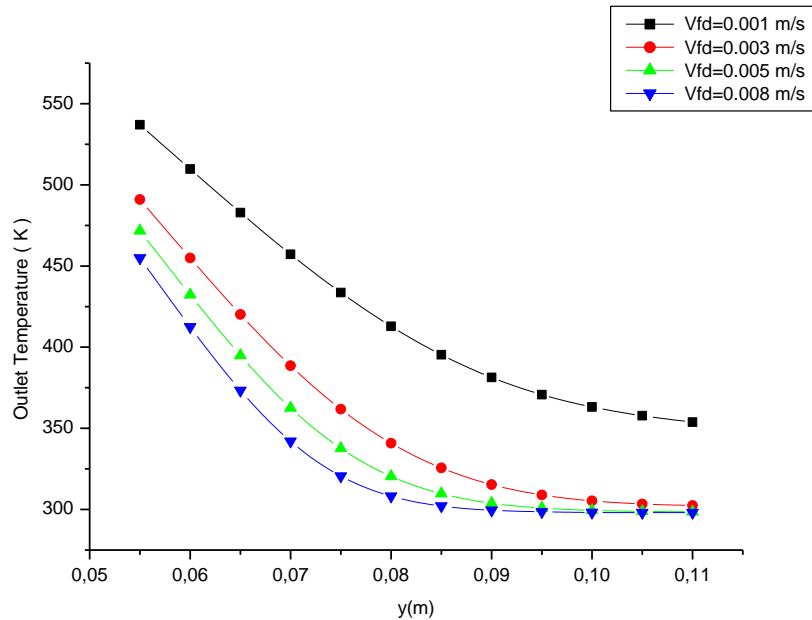
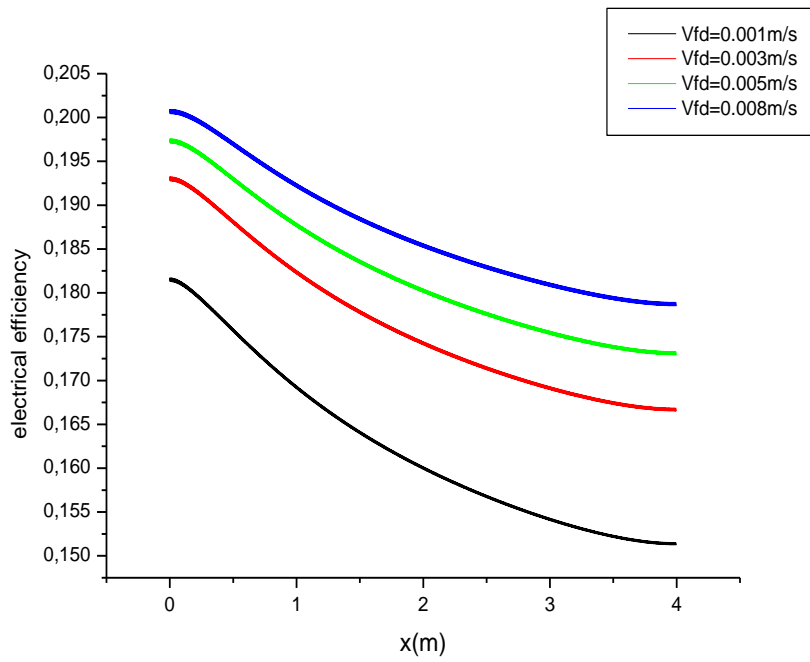
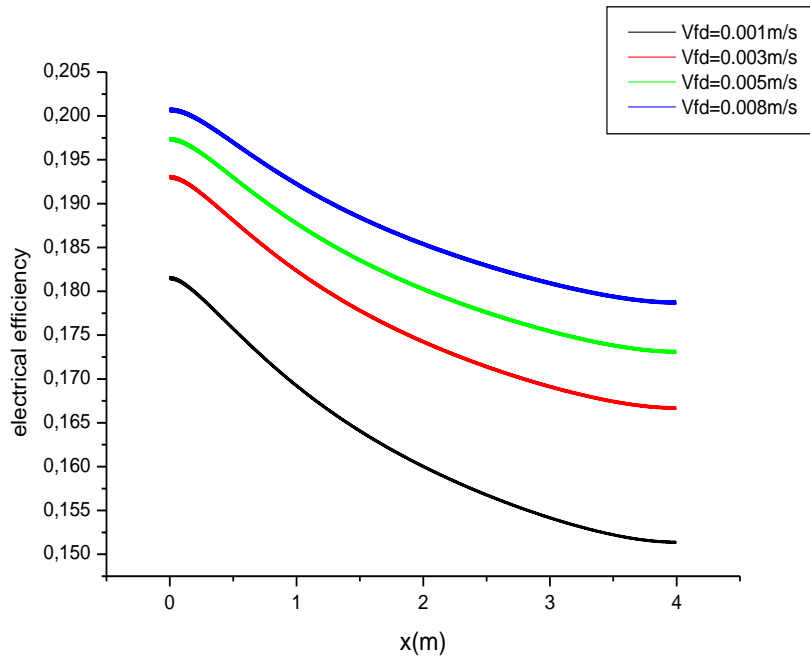


Fig. 13. Outlet fluid temperature vs fluid velocity



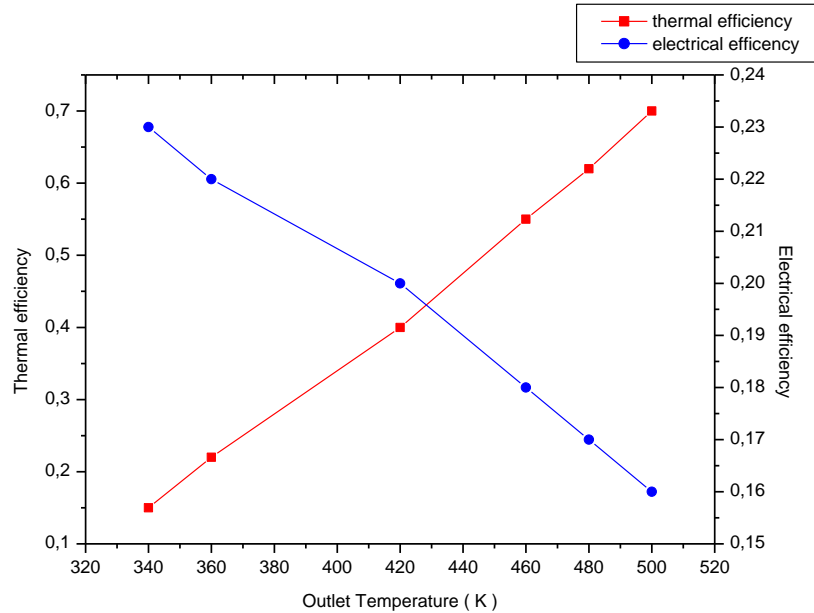
**Fig. 14. Electrical efficiency vs fluid velocity**



**Fig. 15. Thermal efficiency vs fluid velocity**

Therefore, it can be concluded that the fluid mean temperature is probably the most important design parameter for the present CPV/T system. This temperature should be compatible with constraints required by the final user (Fig.16). It should be also pointed out

that the use of the selected CPV/T system for high-temperature is possible, but it should be taken into account that in this case a reduction of both thermal and electrical efficiencies would be caused.



**Fig. 16. Electrical and thermal efficiency vs outlet temperature**

### 5.5. Effect of the insulation

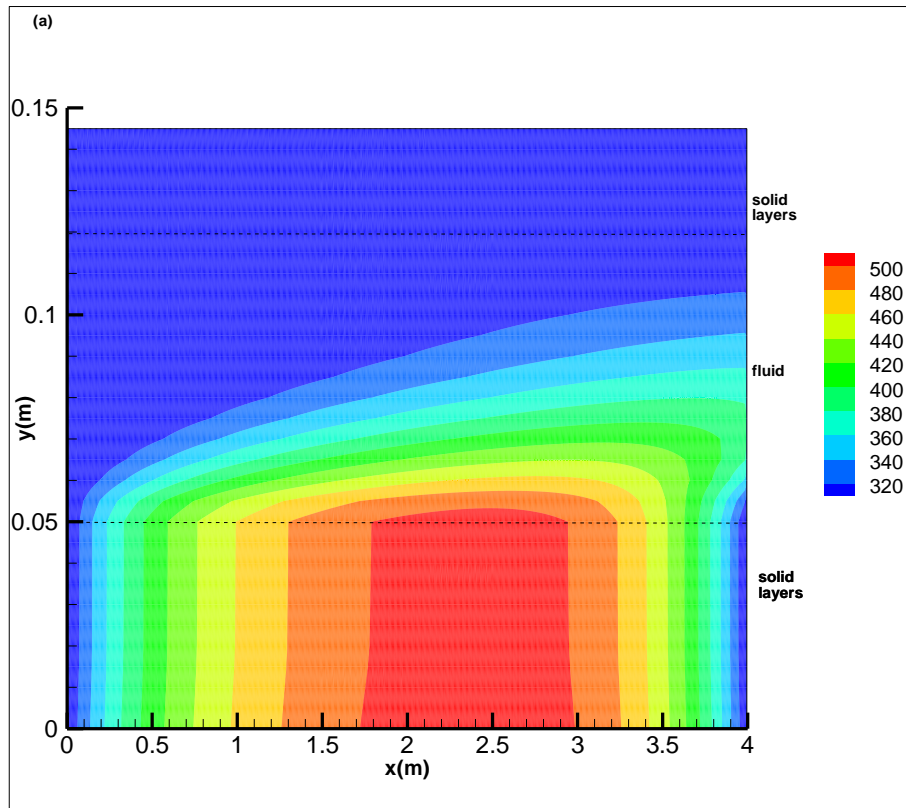
A study of the receiver insulation effect can be a good tool to evaluate CPV/T plan performances. In fact, the removal of the insulation could extremely increase thermal losses, but would especially increase the radiative heat absorbed by the upper surface.

In other words, the purpose of the below parametric study is to evaluate whether the removal or the addition of thermal insulation would improve or degrade the performance of the system. In order to analyze the effect of the insulation, we simulated the CPV/T efficiencies variations under these two conditions.

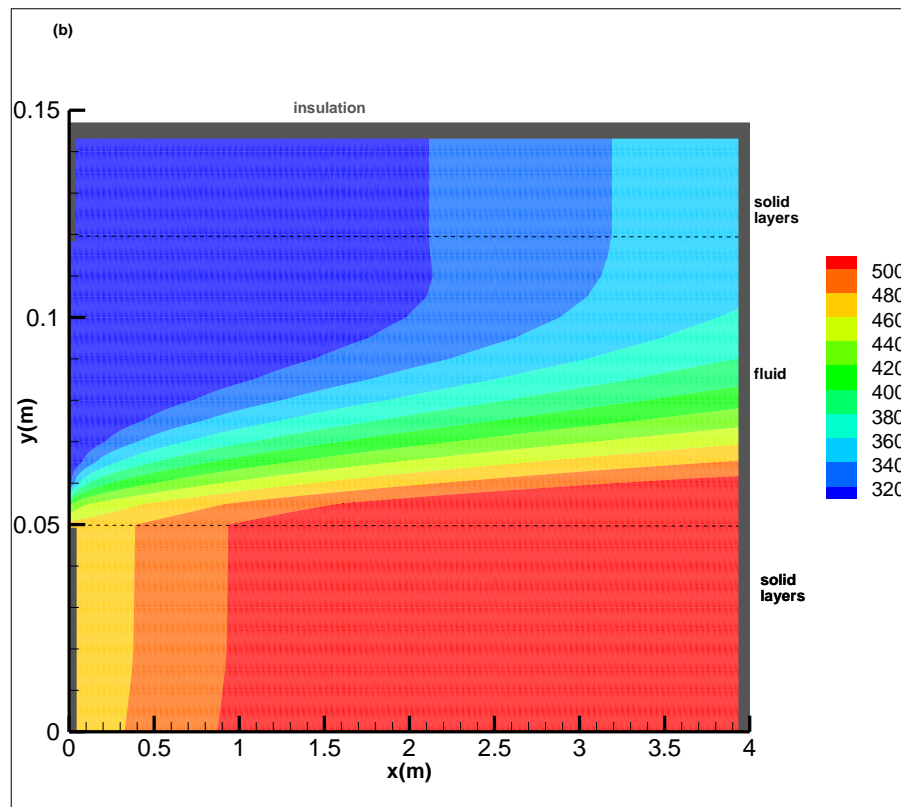
In fact, Fig.17 (a) illustrates that removing the insulation makes system boundaries directly connected with the ambient climate which make limits temperature colder than the lower surface of the receiver. Besides, this removal, especially, imposes symmetric in solid layers (Fig. 17 (b)). However, the insulation leads to a dramatic increase of boundary surface temperature whereas the temperature of the lower surface of the receiver does not significantly change. It decreases also losses to the environment. Thus, the thermal efficiency increased

considerably (Fig.18). However, the thermal insulation leads to a large temperature difference between the selective and PV layer and especially the upper surface. Therefore, this results in a decrease in the electrical efficiency by 15%.

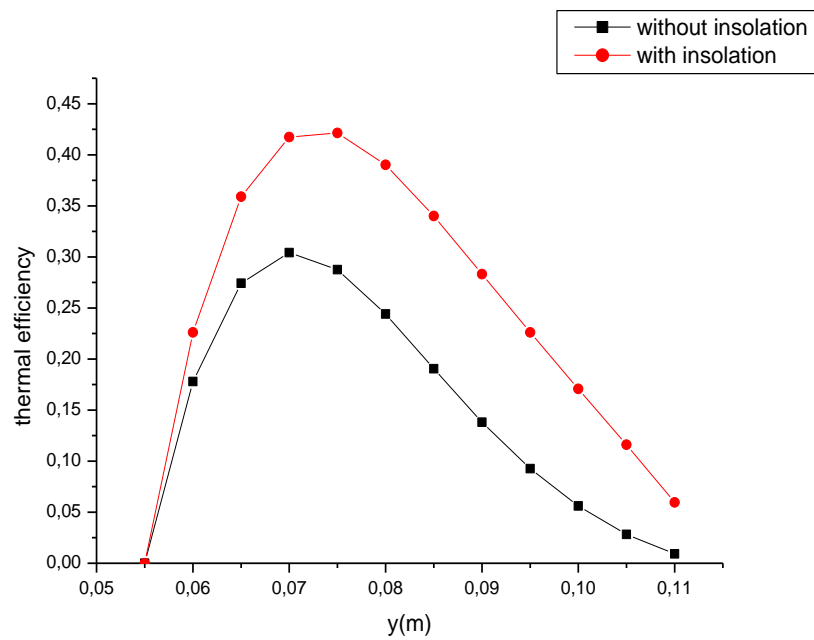
Fig.19 shows that the variation of the electrical efficiency is very important especially on the limits, because on the left and right boundaries the radiative and convective exchange ensures the cooling of the PV cells, which improves the average electrical efficiency by 2%. Thus, the results suggest that for the boundary conditions assumed in this study, the use of insulating boundaries is extremely cost-effective for the investigated CPV/T system.



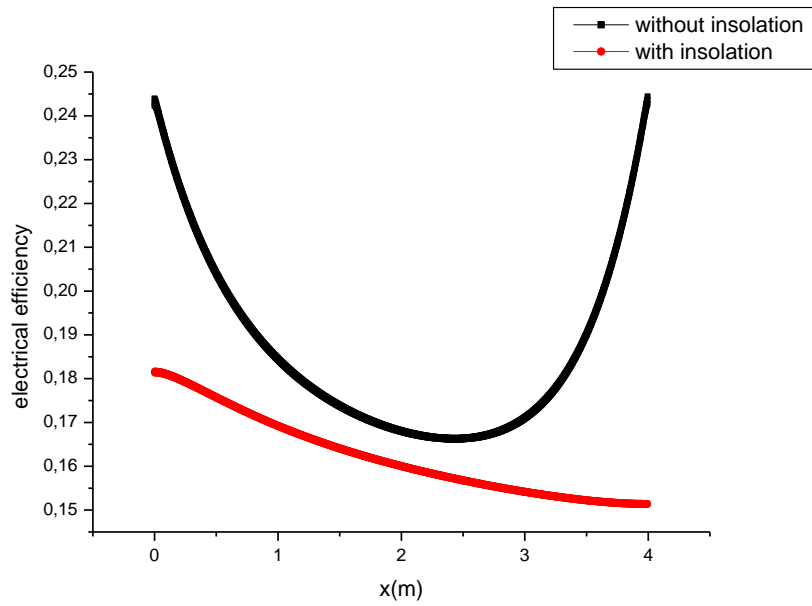




**Fig. 17. Receiver layers temperatures (a) without insulation (b) with insulation**



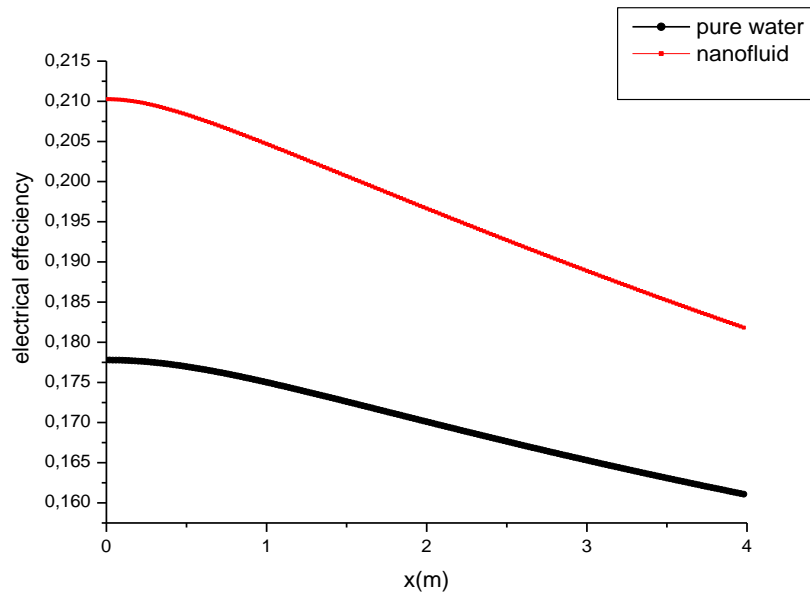
**Fig. 18. Thermal efficiency vs insulation**



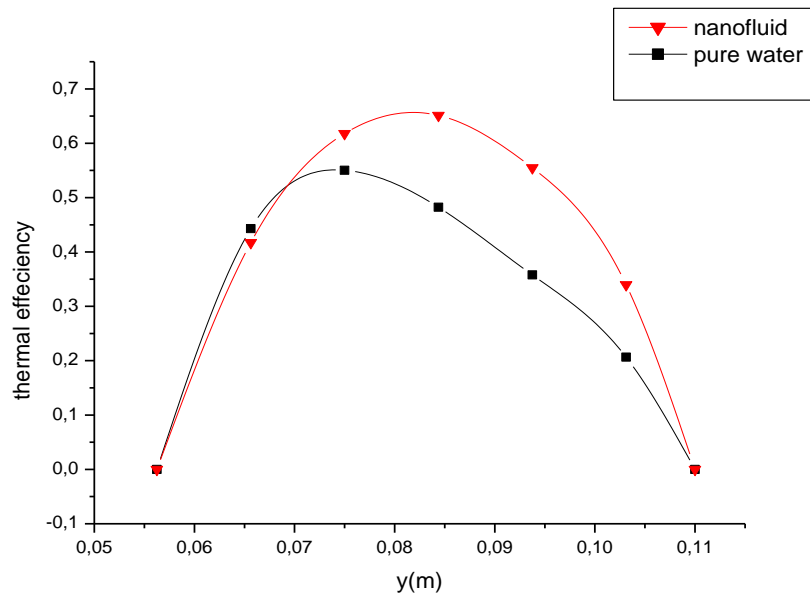
**Fig. 19. Electrical efficiency vs insolation**

## 5.6. Effect of Nano-fluid

During all previous parametric studies, water was investigated as the working coolant. In this part, the influence of adapting the nanofluid as a working fluid on the CPV/T performances will be studied. The concentrations effect ( $\sigma=0\%$ ,  $\sigma=0.2\%$ ) of nanoparticles (copper; Cu) on the electrical and thermal performance of the system is shown. The results reveal that adding nanoparticles to the original fluid provides the greatest electrical and thermal efficiency in comparison to the pure water (as shown in Fig.20-21). The choice of nanofluids improves the heat transfer coefficient between the rectangular pipe and fluid, which increases the outlet temperature and decreases the PV cell temperature. This fact can enhance both thermal and electrical efficiency. Indeed, according to these figures, one can remark that enhancing the nanofluid concentration of nanoparticles from 0% to 0.2% results respectively in an improvement of about 15% and 0.2% of the thermal and electrical efficiency between (water +Cu) and pure water as a coolant fluid. This aspect can be explained by the fact that the adding of these nanoparticles enhances the density, the viscosity and the thermal conductivity of the pure water. Consequently, using the nanofluid as a coolant can be an effective technique to ameliorate the total efficiency of the CPV/T system.



**Fig. 20. Electrical efficiency vs nature of the coolant**

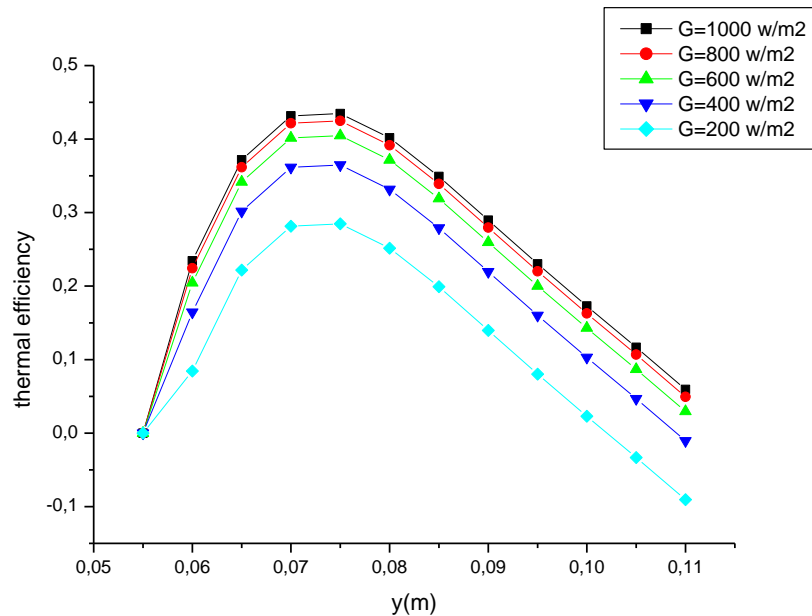


**Fig. 21. Thermal efficiency vs nature of coolant**

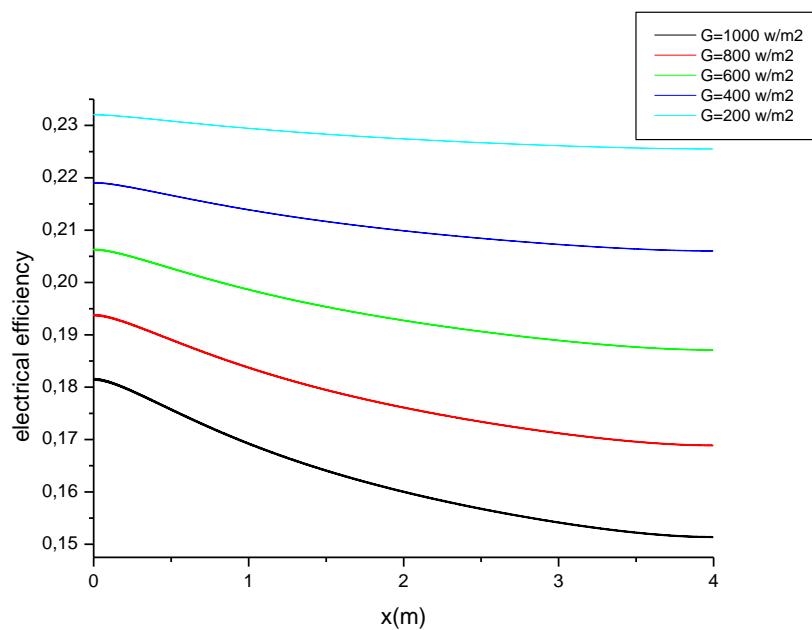
### 5.7. Effect of the beam radiation

The parametric analysis also includes the variation of beam radiation  $G$ , evaluating its corresponding effect on the performance of the CPV/T system. In particular, Fig.22-23 indicate that thermal efficiencies increase when the radiation increases however, the electrical efficiency decreases. It can be explained by the fact that the receiver layers temperature increase especially the PV cell temperature that reach hardly their optimal working temperature.

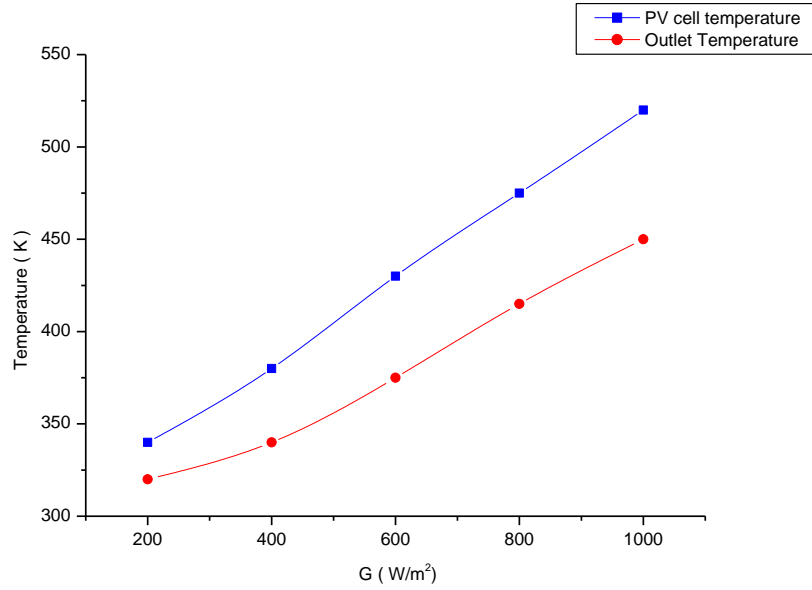
The variation of the thermal and electrical efficiencies is very significant. In fact, the higher the solar radiation is, the higher PV cell and outlet temperature are, which results both radiative and convective losses, as shown in Fig.24. Besides, when the beam radiation is infrequent, the fluid temperature increases lowly. In particular cases, the useful energy is even negative when the radiation is weak and the fluid outlet temperature is lower than the inlet one.



**Fig. 22. Thermal efficiency vs beam radiation**



**Fig. 23. Electrical efficiency vs beam radiation**



**Fig. 24. Water and PV cells temperature vs beam radiation**

## **6. Economic analyses of a CPV/T system: comparison between Tunisia and Chambéry conditions**

The developed numerical model allowed us to evaluate the instantaneous thermal and electrical performance of the CPV/T under different conditions. This study also determines that the use of the CPV/T technology is gainful expressly for those climates where the availability of beam radiation is particularly high.

Under this context, in the following section, a comparative analysis of the annual cogenerated power based on CPV/T system will be investigated between two cities; Chambéry and Tunisia.

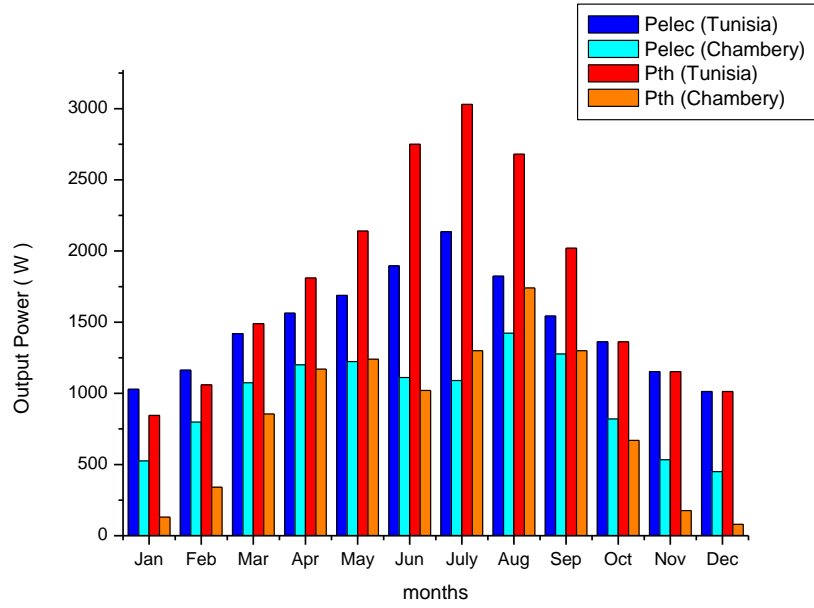
The annual climatic conditions of the studied regions are referenced to 'PVGIS' software tool (Huld et al., 2005) and they are summarized in table 4.

**Table 4. Direct normal irradiance and average temperature related to Tunisia and Chambéry cities.**

Month	G: Direct normal irradiance (W/m <sup>2</sup> )		Average daily Temperature (°C)	
Cities	Chambéry	Tunisia	Chambéry	Tunisia
<b>Jan</b>	186	402	4.4	12
<b>Feb</b>	295	468	4.4	13
<b>Mar</b>	428	608	10.6	14
<b>Apr</b>	492	700	14.4	16
<b>May</b>	502	793	16.4	19
<b>Jun</b>	585	986	22.4	22
<b>Jul</b>	687	1010	22.4	25
<b>Aug</b>	622	927	22	26
<b>Sep</b>	501	702	18.4	24
<b>Oct</b>	312	586	15.3	22
<b>Nov</b>	191	462	10.5	18
<b>Dec</b>	158	397	5.9	15

Fig.25 illustrates the annual CPV/T cogenerated power for these two cities. One can obviously deduce that, the CPV/T production has not the same trend of variation throughout the year.

As expected, one can observe that the highest output thermal and electrical powers for both cities are reached in the summer period (June, July and August). Conversely, the lowest are achieved in the cold period (November, December and January). It is noted also that Tunisia has the greater thermal and electrical performances than Chambéry. It noticed a difference about 0.8kW and 0.3kW respectively in the maximum thermal and electrical output power between these cities. It has to be mentioned that, these effects are endowed by important solar deposits in terms of direct normal solar radiation level and sunshine hour's duration.



**Fig. 25. Yearly CPV/T performances in Tunisia and Chambery cities**

Results show the high annual potential of the CPV/T system in achieving a higher conversion rate of the absorbed solar radiation especially in high solar radiation area. We can deduce that this technology can replace many conventional systems and it may prove its long-term economic viability. Consequently, an economic analysis has to be accomplished in order to evaluate the actualized cost of the CPV/T system over its life span. The maintenance and operating costs of the system ( $C_{maintenance}$ ,  $C_{operating}$ ) are related to the installation cleaning, regulatory system and the insurance in case of malfunctions due to weather conditions or user mismanagement. These costs (eq.7) depend on the system size and, together with the capital CPV/T system cost  $C_{CPV/T}$  constitute the project cost (sherif et al, 2006; Carlo and Fabio, 2013):

$$C_{project} = C_{CPV/T} + C_{maintenance} + C_{operating} \quad (17)$$

The investment cost of the CPV/T system  $C_{CPV/T}$ , is also estimated taking into account the current costs of the different components of the system (PV cells  $C_{PVcells}$ , inverter  $C_{inverter}$ , pump, tank  $C_{Tank}$ , tracking system  $C_{tracking\ system}$ , cables  $C_{additional\ components}$ ... and so forth). The cost of the CPV/T system (eq.8) takes into account also the different necessary devices based on the following formula (sheriff et al, 2006; Carlo and Fabio, 2013):

$$C_{CPV/T} = C_{PVcells} + C_{optic} + C_{tracking\ system} + C_{additional\ components} + C_{coolingsystem} + C_{inverter} + C_{Tank} + C_{design} \quad (18)$$

Considering a system life span equal to 20 years, the yearly variation of the costs of the various sub-systems and the whole system are estimated. The yearly trend variations of the generated cash flows are illustrated in Fig.26.

In order to assess the cost-effectiveness of the CPV/T project, we have to calculate the net present value (NPV), the internal rate of return (IRR) and the payback period (DPB). The NPV and the DPB can be computed using the following expressions (sheriff et al, 2006; Carlo and Fabio, 2013):

$$NPV = \sum_{t=0}^T c_f (1 + k)^{-t} - E_c \quad (19)$$

$$DPB = \frac{E_c}{\sum_{k=0}^T \frac{c_f}{(1+k)^t}} \quad (20)$$

Where  $c_f$  is the expected cash flow per period,  $k$  the required rate of return,  $E_c$  the extra cost and  $T$  is the number of periods over which the project is expected to generate incomes (system life span).

Indeed, in order to have a clearer view of the economic performance of the system taking into account the gas and electricity costs, an economic efficiency of the CPV/T system,  $\eta_{ec}$ , can be given by the expression as follows (Aste et al., 2014):

$$\eta_{ec} = \frac{P_{th} * C_g + P_{el} * C_{el}}{G * A} \quad (21)$$

Where  $P_{th}$ ,  $P_{el}$  are respectively the thermal and the electrical energy produced by the CPV/T system.  $C_g$ ,  $C_{el}$  are respectively the cost of the electricity and naturel gas.

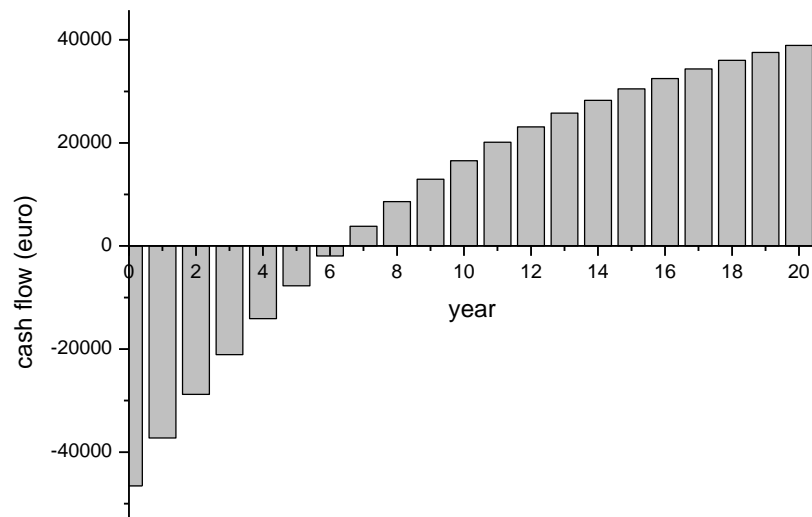
All economic results are reported in Table 5. We can conclude that a discount pay-back (DBP) of about 7 years, a NPV of about 39 k€, an IRR equal to 19%, compared to a discount rate of 10% have been obtained.

Finally, the overall economic efficiency of the investigated CPV/T configuration in Chambéry and Tunisia is equal to 35% and 38% respectively. These results represent satisfactory outcomes, especially in Tunisia city, it is due to the high beam solar radiation and the lower gas prices compared to Chambéry region, which insure a non-negligible difference about 3% in the economic efficiency.



**Table.5 : Economic results**

CPV/T module cost		CPV/T system cost		Economic analysis results						Prices
Component	Cost(€)	component	Cost(€)	year	Cash-flow (€)	year	Cash-flow (€)	year	Cash-flow (€)	<b>Gaz</b> 0.05€/kWh (FR) 0.02€/kWh (Tun)  <b>Electricity</b> 0.15€/kWh (Fr) 0.17€/kWh (Tun)
PV cells	42000	Modules( 1)	43729	0	-46558	7	3833	14	28252	
Optic	787	Cooling system	386	1	-37246	8	8611	15	30481	
Additional component	642	Inverter	643	2	-28781	9	12955	16	32507	
Tracking system	300	Design	1800	3	-21085	10	16546	17	34350	
Total	43729	total	46558	4	-14089	11	20136	18	36024	
				5	-7729	12	23103	19	37457	
				6	-1948	13	25800	20	38931	



**Fig. 26. Economic analysis during the lifetime of the CPV/T system**

## 7. Conclusions

In the present study a 2-D numerical model of a photovoltaic thermal concentrator has been developed. The proposed CPV/T configuration is based on triple junction PV cells located in the bottom surface of the receiver pipe. The electrical/thermal model is based on the energy balance of the CPV/T receiver in order to calculate the net thermal and electrical output energy under several factors such as wind velocity, concentration ratio, coolant flow rate, thermal receiver insulation, use of nanofluid and beam radiation level.

A comparison between the numerical results and those obtained by experimental studies is presented in order to prove the viability of the developed model. The results show that the

output power predicted by the numerical model has a good agreement with the experimental data with low mean percentage errors.

The sensibility analysis showed mainly that lower the wind velocity is, the higher PV cells electrical efficiency decrease is. Also, the decrease of the concentration ratio leads to a dramatic decrease in the heat exchange effectiveness and therefore a drop of thermal and electrical efficiencies. Moreover, the coolant has a critical water velocity rate achieved in the center of the receiver channel width above which the thermal efficiency of the system goes down for high velocity and becomes high for low ones. The thermal insulation leads to a considerable thermal efficiency increase and improves the average electrical efficiency by 2% which is very promising for the cost-efficiency of the investigated CPV/T system. Besides, it was concluded that enhancing the nanofluid concentration of nanoparticles from 0% to 0.2% results respectively an improvement about 15% and 0.2% of the thermal and electrical efficiency between (water +Cu) and pure water as a coolant fluid.

Finally, an economic analysis comparing the CPV/T system cost-effectiveness and profitability under Tunisia and Chambéry conditions has been conducted. Assuming a CPV/T lifetime equal to 20 years, respect of an initial investment of approximately 46 k€, a NPV about 38 k€, an internal rate of return equal to 19% and an economic efficiency equal to 35%,38% respectively for Chambéry and Tunisia have been found. The results ensure that the region of Tunisia has the best system performances and it presents a promising region for exploiting the power of CPV/T energy cogeneration.

## References

- Buonomano, A., Calise, F., Dentice, M., Vanoli, L., 2013. A novel solar trigeneration system based on concentrating photovoltaic/thermal collectors. Part 1: Design and simulation model. *Energy* 61, 59–71.
- Davide, D.C., Bortolato, M., Padovan, A., Quaggia, M., 2014. Experimental and numerical study of a parabolic trough linear CPVT system. *Energy Procedia* 57, 255–264.

- Bosco, N., Sweet, C., Ludowise, M., Kurtz, S., 2012. An Infant mortality study of III–V multijunction concentrator cells. *IEEE Photovoltaic*; 2:411–6. Available from <<http://dx.doi.org/10.1109/Jphotov.2012.2199082>>.
- Zondag, H A., 2008. Flat-plate PV thermal collectors and systems: a review. *Renewable and Sustainable Energy Reviews* 12, 891–896.
- Skoplaki, E., Palyvos, J A., 2009. On the temperature dependence of photovoltaic module electrical performance: a review of efficiency/power correlations. *Solar Energy* 83, 614–638.
- Calise, F., Palombo, A., Vanoli, L., 2012 .A finite-volume model of a parabolic trough photovoltaic/thermal collector: Energetic and exergetic analyses Francesco. *Energy* 46, 283–294.
- Coventry Joe, S., 2005. Performance of a concentrating photovoltaic/thermal solar collector. *Solar Energy* 78, 211–222.
- Cappelletti, A., Reatti, Martelli, F., 2015. Numerical and Experimental Analysis of a CPV/T Receiver Suitable for Low Solar Concentration Factors. *Energy Procedia* 82, 724–729.
- Gibart, Buffet, 2008. Etude d'un capteur solaire mixte-photovoltaïque thermique à concentration, Convention : No. 459–78-1 ESF.
- Quaia, V., Lughì, M., Giacalone, G., Vinzi, 2012. Technical-economic evaluation of a Combined Heat and Power Solar (CHAPS) generator based on concentrated photovoltaics'. *International Symposium on Power Electronics, Electrical Drives, Automation and Motion, IEEE*.
- Ming, Li., Xu, Ji., Guoliang, Li., Shengxian, Wei., YingFeng, Li., Feng, Shi., 2011. Performance study of solar cell arrays based on a Trough Concentrating Photovoltaic/Thermal system, *Applied Energy* 88, 3218–3227.
- Xu, Ji., Ming, Li., Weidong, Lin., Wenbo, Wang., Liuling, Wang., Xi Luo., 2012. Modeling and Characteristic Parameters Analysis of a Trough Concentrating Photovoltaic/Thermal System with GaAs and Super Cell Arrays. *International Journal of Photo energy* Volume, ID–782560.
- Sharan, S.N., Mathur, S.S., Kandpal, T.C., 1987. Analytical performances evaluation of combined photovoltaic-thermal concentrator-receiver systems with linear absorbers. *Energy Conversion and management* 27, 361–365.
- Felipe, C., Robert, A., Taylor., Tian, Z., Ivan, P.W., Gary, R., Vernie, E., Evatt R.H., 2014. Experimental testing of SiNx/SiO<sub>2</sub> thin film filters for a concentrating solar hybrid PV/T collector. *Renewable Energy* 72, 79-87.

- Proell, M., Karrer, H., Brabec, C.J., Hauera, A., 2016. The influence of CPC reflectors on the electrical incidence angle modifier of c-Si cells in a PVT hybrid collector. *Solar energy* 126, 220-230.
- Moh'd, A. Al., Mohammad, B., Mansour, M., 2017. A combined CPV/T and ORC solar power generation system integrated with geothermal cooling and electrolyser/fuel cell storage unit. *Energy* 133, 513-524.
- Farideh, Y., Mehran, A., 2017. Performance of nanofluid-based photovoltaic/thermal systems: A review. *Renewable and Sustainable Energy Reviews* 76, 323-352.
- Verma, S.K., Tiwari, A.K., 2017. Characterization of Nanofluids as an advanced heat transporting medium for Energy Systems. *Materials to day proceedings Part A*, 4095-4103.
- Zelin, Xu., Clement, K., 2014. Concentration photovoltaic–thermal energy co-generation system using nanofluids for cooling and heating. *Energy Conversion and Management* 87, 504-512.
- Xu, Ji., Ming, Li., Weidong, Lin., Wenbo, Wang., Liuling, Wang., Xi Luo., 2012. Modeling and Characteristic Parameters Analysis of a Trough Concentrating Photovoltaic/Thermal System with GaAs and Super Cell Arrays. *International Journal of Photo energy* Volume, ID–782560.
- Al-Alili, A., Hwang, Y., Radermacher, R., Kubo, I., 2012. A high efficiency solar air conditioner using concentrating photovoltaic/thermal collectors. *Applied Energy* 93, 138–147.
- Rosell, J.I., Vallverdú, X., Lechón, M.A., Ibáñez M., 2005. Design and simulation of a low concentrating photovoltaic/thermal system. *Energy Conversion and Management* 46, 3034–3046.
- Mittelman, G., Kribus, A., Dayan, A., 2007. Solar cooling with concentrating photovoltaic/thermal (CPVT) systems. *Energy Conversion and Management* 48, 2481-2490.
- Buonomano, A., Calise, F., Dentice, M., Vanoli, L., 2013. A novel solar trigeneration system based on concentrating photovoltaic/thermal collectors. Part 1: Design and simulation model. *Energy* 61, 59–71.
- Kribus, A., Daniel, K., Mittelman, G., Hirshfeld, A., Flitsanov, Y., Dayan, A., 2006. A miniature concentrating photovoltaic and thermal system. *Energy Conversion and Management* 47, 3582–3591.

- Vorobiev, Y., González-Hernández, J., Vorobiev, P., Bulat, L., 2006. Thermal photovoltaic solar hybrid system for efficient solar energy conversion. *Solar Energy* 80, 170-176.
- Kosmadakis, G., Manolakis, D., Papadakis, G., 2011. Simulation and economic analysis of a CPV/thermal system coupled with an organic Rankine cycle for increased power generation. *Solar Energy* 85, 308–24.
- Calise, F., Vanoli, L., 2012. Parabolic Trough Photovoltaic/Thermal Collectors: Design and Simulation Model. *Energies* 5, 4186–4208.
- Mittelman G., Abraham K., Ornit M., Dayan, A., 2007. Water desalination with concentrating photovoltaic/thermal (CPVT) systems. *Solar Energy* 83, 1322–1334.
- Ben Youssef, W., Maatallah, T., Menezes, C., Ben Nasrallah, S., 2017. Assessment viability of a concentrating photovoltaic/thermal-energy cogeneration system (CPV/T) with storage for a textile industry application. *Solar energy* 159, 841-851.
- Otanicar, T P., Theisen, S., Norman T., Tyagi, H., Robert, A., Taylor, c., 2015. Envisioning advanced solar electricity generation: Parametric studies of CPV/T systems with spectral filtering and high temperature PV. *Applied Energy* 140, 224–233.
- Yang Hu., Decai Li., Shi, S., Xiaodong, N., 2015. Full Eulerian lattice Boltzmann model for conjugate heat transfer. *Physical review* 92, 063305.
- John, A.D., William, A.B., 1980. *Solar engineering of thermal processes*.
- Swinbank, W.C., Roy, QJ., 1963. Long-wave radiation from clear skies. *Meteorol Soc* 89, 339.
- Watmuff, JH., Charters, WWS., Proctor D., 1977. Solar and wind induced external coefficients solar collectors 2nd quarter. *Rev Int d'Helio-technique* 56.
- Maxwell, JC., 1873. *A treatise on electricity and magnetism*. Oxford: Clarendon Press.
- Buonomano, A., Calise, F., Dentice, M., Vanoli, L., 2013. A novel solar trigeneration system based on concentrating photovoltaic/thermal collectors. Part 1: Design and simulation model. *Energy* 61, 59–71.
- Xu, Ji., Ming, Li., Weidong, Lin., Wenbo, Wang., Liuling, Wang., Xi Luo., 2012. Modeling and Characteristic Parameters Analysis of a Trough Concentrating Photovoltaic/Thermal System with GaAs and Super Cell Arrays. *International Journal of Photo energy* Volume, ID–782560.
- Huld, T., Šúri, M., Dunlop, E., Albuissou, M., Wald, L., 2005, Integration of HelioClim-1 database into PVGIS to estimate solar electricity potential in Africa. *Proceedings from 20th European Photovoltaic Solar Energy Conference and Exhibition*, 6-10 June 2005, Barcelona, Spain. Available from < <http://re.jrc.ec.europa.eu/pvgis/>>.

- Sherif, R.R., King, H.L., Cotal, D.C., Law, C.M., Fetzner, K., Edmondson, G.S. Glenn, G. Kinsey, D. Krut, N.H. Karam, 2006. Concentrator triple-junction solar cells and receivers in point focus and dense array modules. In European PV Conference, Dresden.
- Carlo, R., Fabio, P., 2013. Design And modeling of a concentrating photovoltaic thermal (HCPVT) system for a domestic application. *Energy and Buildings* 62, 392–402
- Aste, N., Del Pero, C., Leonforte, F., 2014. Water flat plate PV-thermal collectors: a review. *Solar Energy* 10, 98–115.