__Original Research Article__

Assessment of the thermal efficiency of a concentrated photovoltaic/thermal (CPV/T) hybrid system with water as heat transfer fluid

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ABSTRACT

Interest in solar energy is growing by the day, because it is clean and unlimited. Concentrated photovoltaic-thermal (CPV/T) systems are one of the systems that are attracting a great deal of attention among solar energy systems. In this work, a study of a hybrid concentrated photovoltaic-thermal (CPV/T) system that enables the simultaneous production of electrical and thermal energy has been presented. As the experimental realization of such devices is costly, it is necessary to develop numerical models.

Aims: The aim of this work is to evaluate the thermal efficiency of the system based on the thermal model, using an iterative simulation procedure.

Propose a numerical model to evaluate the thermal efficiency of a CPV/T hybrid system.

Methodology: Starting from the energy conservation equations, a numerical modeling and simulation of the concentrated photovoltaic-thermal hybrid (CPV/T) system is carried out. A parametric analysis is carried out to study the influence of concentration, water mass flow rate, cell surface area and Reynolds number on the system's thermal and electrical performance.

Results: The results show that thermal efficiency decreases with increasing Reynolds number and mass flow rate. However, it increases when the water mass flow rate is equal to 0.0001kg/s, from 0.4% to 0.7%, for a flow rate equal to 0.0010kg/s.

Conclusion: An interesting and useful finding was that the proposed numerical model allow the determination of the electrical as well as thermal efficiency of the hybrid CPV/T.

The results of this work are significant for the hybrid photovoltaic CPV/thermal cooling system, but the 3D study of the system is a future project.

The various results which are obtained by numerical simulation need to be validated by experimental methods.

Keywords: Numerical, Concentration, PV, Cell, Thermal, Hybrid, Efficiency.

1. INTRODUCTION

The surface temperature of photovoltaic panels increases due to the low efficiency of solar energy into electricity, as not all the energy absorbed by the photovoltaic cells can be converted into electrical energy[1]. To satisfy the law of conservation of energy, the remaining solar energy must be converted into heat, which is why it is important to develop methods of cooling photovoltaic cells to increase output efficiency. Several active and passive methods of cooling photovoltaic panels have been studied and analysed to date[1],[2], [3], [4]. From these studies came the idea of coupling the standard PV system with another thermal system, giving rise to a hybrid CPV/thermal system that generates electricity and heat at the same time, with a higher energy conversion rate from the solar radiation absorbed[5],[6],[7], [8],. It appears that controlling the temperature rise of the photovoltaic panels leads to gains in the electrical power of the panel[9], and the thermal energy extracted from the photovoltaic panels is used for a variety of low-temperature applications, but what about the thermal efficiency of such a system?

2. MATERIAL AND METHODOLOGY

2.1. Description and thermal analysis of the hybrid CPV/thermal system

2.1.1-System presentation

The hybrid CPV/water heating system studied (Figure 1) is made up of the following essential components:

- A concentrator, which concentrates sunlight using mirrors or lenses. It increases the density of light at the surface of the PV cell;
- A photovoltaic module converts solar radiation into electrical energy. It is made up of three layers: the first is a layer of glass, the front of which is exposed to the radiation, the second layer contains the photovoltaic cells and the third layer is the back of the module, made of tedlar;
- A substrate (heat sink) to absorb the heat,
- A channel, bonded to the substrate to ensure good thermal contact between the two elements, through which water circulates to remove the heat stored by the heat sink;
- Finally, a layer of insulation to minimize heat loss from the system.

A number of assumptions are made when studying the system. These assumptions include the design of the system, atmospheric conditions, the characteristics of the heat transfer fluid flow rate and other factors that have an impact on the thermal analysis of the collector. These assumptions are:

1. Heat transfer from the sides of the heat sink is ignored (or heat exchange is assumed to be negligible at the sides),
2. The PV cell is assumed to be at the same temperature as the substrate (heat sink),
3. Heat dissipation is assumed to take place by radiation and natural convection, and only at the top of the PV cell,
4. The outlet temperature of the heat transfer fluid (water) is that of the substrate solar cell.

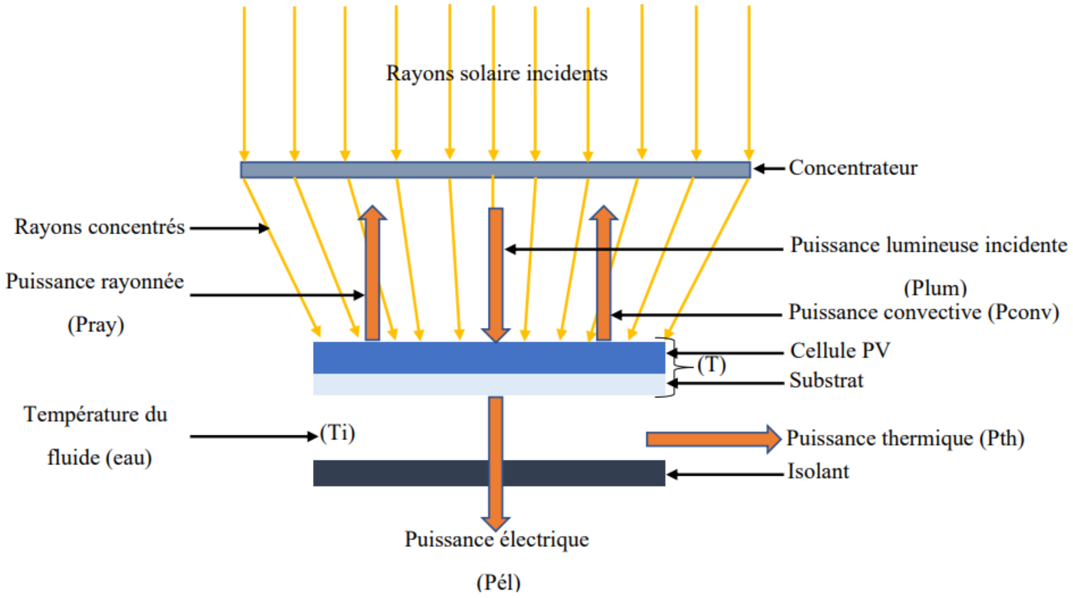

Fig.1. The model and components of the CPV/thermal hybrid system

2.1.2-Thermal analysis

The sun's rays are concentrated by a concentrator (mirror or lens) on the solar cell to increase the density of light on its surface. The PV cell reaches its steady-state temperature when the absorbed light power is equivalent to the sum of the electrical power supplied to the load, the thermal power absorbed by the working fluid and the power dissipated in the form of heat.

$$P_{lum} = P_{ele} + P_{th} + P_{ray} + P_{conv} \qquad (1)$$

With $P_{lum} = \tau \alpha A_0 C q_0$

τ : the transmissivity of the lens or concentrator; α : the absorptivity coefficient of the PV cell surface; A_0 : the surface area of the solar cell; C : the geometric concentration ratio of the concentrator (lens) , q_0 :the energy density in standard air conditions mass.

$$P_{ele} = \eta \tau \alpha A_0 C q_0 \qquad (2)$$

η : the conversion efficiency, expressed as: $\eta = 0.425(1 - 0.00175T)$ [10]

$$P_{ray} = A_r \varepsilon \sigma \left(T^4 - T_0^4\right) \qquad (3)$$

A_r the radiating surface; ε the emissivity of the surface; σ the Stephan Boltzmann constant; T_0 the ambient temperature.

$$P_{conv} = A_c h \left(T - T_0\right) \qquad (4)$$

A_c the convection surface; h : the convection transfer coefficient which can be calculated by the following correlation.:

$$Nu_f = 0.664 \mathrm{Pr}_f^{\frac{1}{3}} \mathrm{Re}_f^{\frac{1}{2}} = \frac{hL}{\lambda_f} \text{ [5], [11]} \qquad (5)$$

Were

Nu_f, Re_f et Pr_f are the Nusselt number, Reynolds number and fluid Prandtl number respectively.

$$P_{th} = \dot{m} c_p \left(T - T_i\right) \qquad (6)$$

$\dot{m}$ the mass flow rate of the water; c_p: the specific heat; T_i: the initial temperature of the water.

Thus:

$$\tau\alpha A_0 C q_0 - \eta\tau\alpha A_0 C q_0 - \dot{m} c_p \left(T - T_i\right) - A_c h\left(T - T_0\right) - A_r \varepsilon\sigma\left(T^4 - T_0^4\right) = 0 \qquad (7)$$

The equation (7) obtained is a degree 4 equation which is solved by Newton's method on the MATLAB environment.

3. RESULTS AND DISCUSSION

3.1-Influence of concentration ratio on temperature

Figures 2 and 3 below illustrate the cell temperature according to the energy balance equation at thermal equilibrium under concentrated illumination in the case of laminar flow. The temperature of the solar cell increases remarkably with increasing concentrated light. This increase in cell temperature is due to the unconverted heat received by the cell as a result of the increase in concentrated light. It rises from 298K to 909K when the light concentration increases from C= 1 Sun to C=100 Sun and for a water flow equal to 0.0002kg/s (**Figure 2**). These maximum temperatures are below the melting point of silicon, which is 1710K. It is therefore possible to obtain these temperatures whatever the water flow rate and for laminar flow (Reynolds number less than or equal to 2300). The cell temperature as a function of concentration becomes almost linear with the increase in the flow rate of the working fluid (water) and the Reynolds number. This is because a large proportion of the heat is transported by the fluid (water). For a water mass flow rate of 0.005kg/s, the temperature of the solar cell rises from 298K to 331K for a concentration of C=1 Sun and C=100 Sun respectively (**Figure 3)**. These results show that the water flow rate and Reynolds number are key factors in the influence of temperature for concentrated photovoltaic/thermal (CPV/T) hybrid systems.

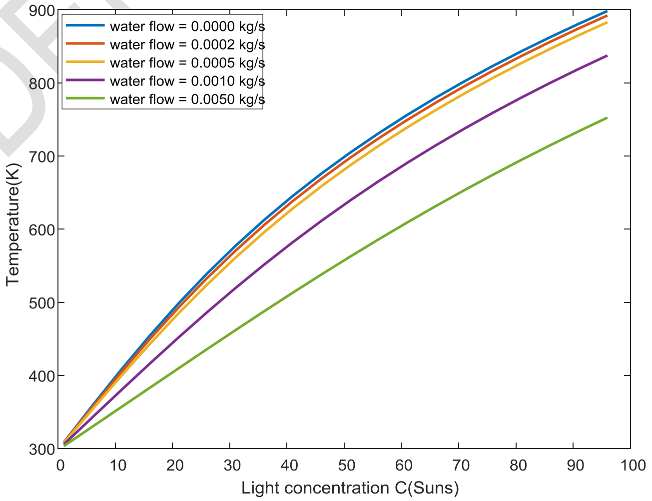

Fig. 2. Variation in photocell temperature as a function of light concentration for different values of water mass flow rate and for a Reynolds number of 1.

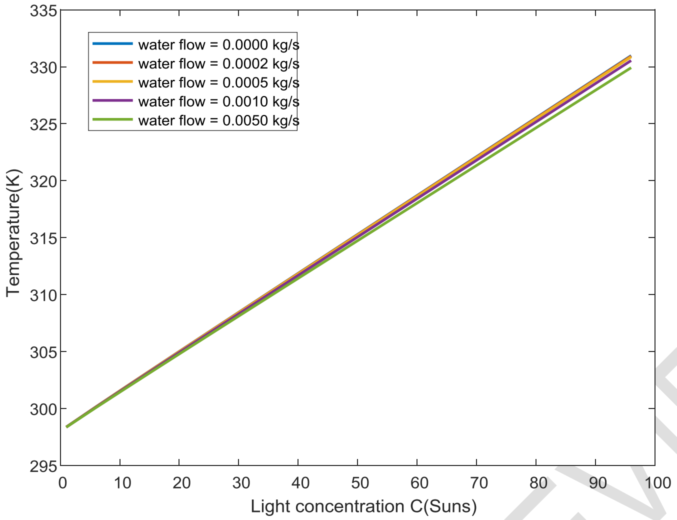

Fig.3. Variation in photocell temperature as a function of light concentration for different values of water mass flow rate and for a Reynolds number of 1000

3.2- Influence of surface area on temperature

Figure 4below illustrates the variation in system temperature as a function of cell surface area. When the surface area increases from 0.1 to 0.5m², the temperature increases by 285K for C=100sun, 256K for C=80sun and 36K for C=10sun. It varies little when the surface area is greater than 0.5m² for a given concentration and mass flow rate of water. The heat received does not raise the temperature of the system to the melting temperature of the silicon for a given concentration. For a hybrid CPV/T system with cooling, whatever the surface area of the cell, the heat received has less influence on the temperature of the solar cell. This is because increasing the cell surface area reduces the concentration ratio. To design such a system with better thermal and electrical efficiency, the surface area of the solar cell should be around m²

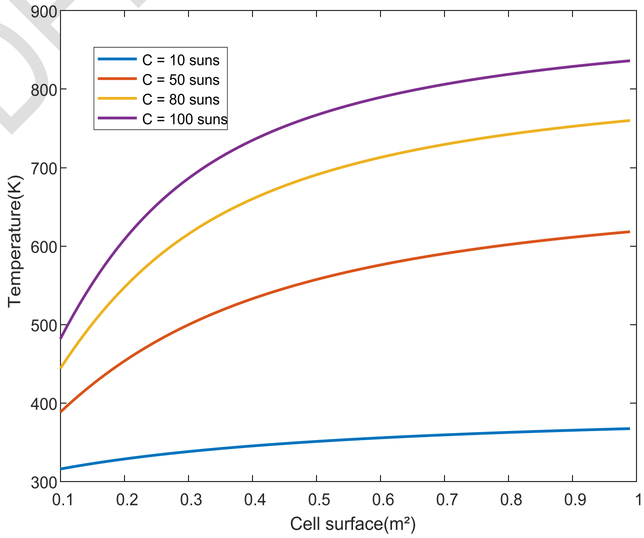

Fig.4. Temperature profile as a function of cell surface area for different values of light concentration and for a water flow rate equal to 0.005kg/s.

3.3-The effect of water mass flow rate on temperature

The parametric study carried out on the temperature of the cell (of the system or of the water) by varying the mass flow rate and the geometric concentration ratio **C** for a surface area of 0.5m² and a Reynolds number equal to 1000 shows that the temperature of the solar cell decreases and stabilises as a function of the mass flow rate and the concentration (**Figure 5**). This decrease can be explained by the fact that by increasing the water mass flow rate for a given concentration,the heat transported by the fluid is greater than the unconverted heat and joule effect losses. In order to reduce the effects of temperature when the geometric concentration ratio is high and achieve better electrical and thermal efficiency, the water mass flow rate is an essential parameter to take into account, depending on the size of the system.

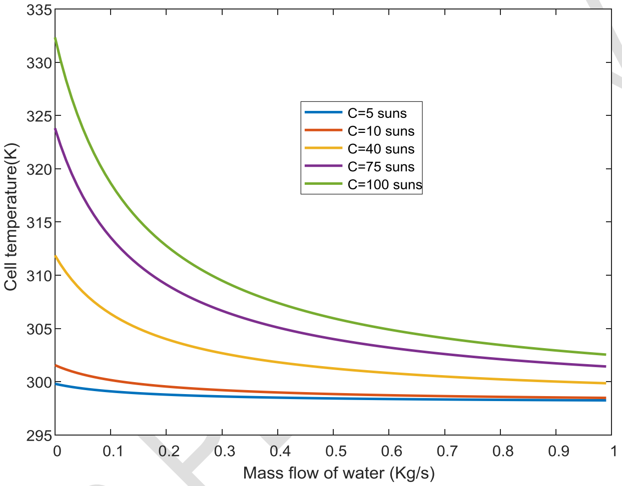

Fig.5. Variation in temperature as a function of mass flow rate for different values of concentration.

3.4 Effect of Reynolds number

Figure 6below shows the variation in system temperature as a function of Reynolds number. As the Reynolds number increases, the temperature of the system decreases. When the Reynolds number increases from 1 to 1000, the temperature decrease is 17K for C=100 suns, 11K for C=70 suns, 9K for C=50 suns. For a Reynolds number greater than 2300 (turbulent flow) the temperature tends towards a stable temperature. The Reynolds number has a greater impact on the temperature of the system (water or solar cell) because as it increases, the heat transported by the fluid increases and helps to reduce the temperature of the system.

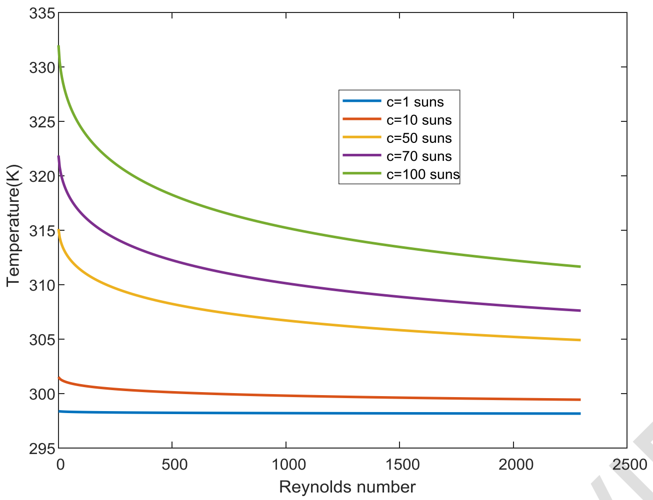

Fig.6. Variation of temperature as a function of Reynolds number for different values ofconcentration and for a water flow rate equal to 0.15kg/s.

3.5 Electrical and thermal performance of the system

3.5.1. Electrical efficiency

3.5.1.1 Electrical efficiency as a function of concentration

The parametric study carried out on the cell's electrical efficiency by varying the geometric concentration ratio **C** of 1-100 suns and the mass flow rate shows that the photocell's electrical efficiency increases until it reaches a maximum value for each given mass flow rate of water. Above the concentration corresponding to the maximum efficiency, we observe a linear decrease in electrical efficiency. This result is in line with that found by whatever the water flow rate**.** Temperature has a negative influence on the electrical efficiency of the solar cell when the geometric concentration increases for a constant water flow rate (**figure 7)**. This decrease can be explained by the fact that the increase in concentration contributes to raising the temperature of the system and consequently the decrease in electrical efficiency, which is given by the expression

$$\eta = 0.298 + 0.0142\ln(C) + \left[-0.000715 + 0.0000697\ln(C)\right]\left(T - 298\right)$$

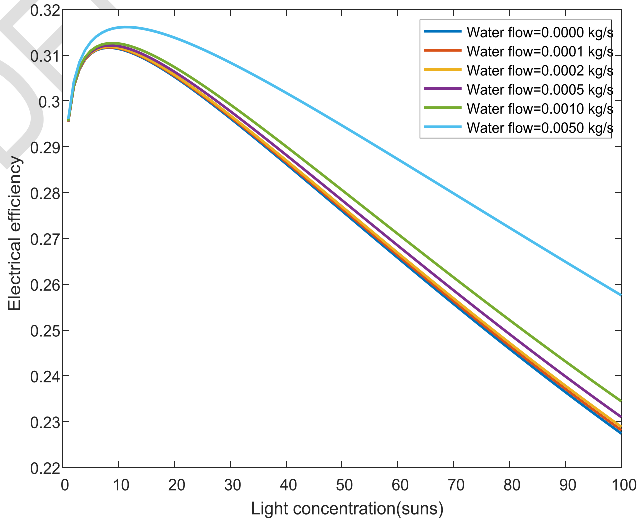

Fig.7. Electrical efficiency as a function of concentration

3.5.1.2 Electrical efficiency as a function of mass flow

The variation in electrical efficiency as a function of mass flow rate, illustrated in **Figure 8**below, shows that efficiency increases when the mass flow rate of water increases, whatever the value of the geometric concentration. In fact, when the water mass flow rate is increased for a given concentration, the heat transported by the fluid is greater than the unconverted heat and joule losses. This leads to a reduction in temperature and an increase in electrical efficiency, since electrical efficiency is linked to temperature by the relationship

$$\eta = 0.298 + 0.0142\ln(C) + \left[-0.000715 + 0.0000697\ln(C)\right]\left(T - 298\right).$$

For a hybrid photovoltaic/thermal concentration (CPV/T) system, to achieve acceptable electrical efficiency when the geometric concentration is high, the water mass flow rate must be increased.

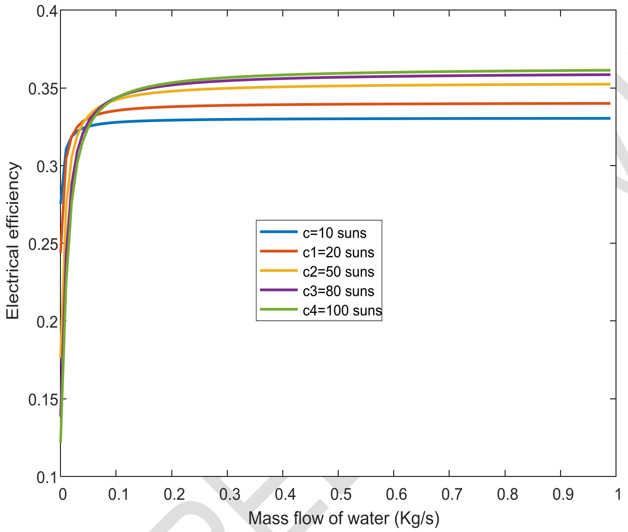

Fig.8. Electrical efficiency as a function of mass flowrate

3.5.1.3 Electrical efficiency as a function of Reynolds number

It is clear that increasing the Reynolds number increases the electrical efficiency. When the Reynolds number was increased from 1 to 2300 (laminar flow), the electrical efficiency increased from 17.86% to 35.53% respectively for c=100 sun. Thereafter, the decrease in electrical efficiency continued slowly as the temperature tended towards a stable value as the Reynolds number increased. For a low concentration (1 sun) the electrical efficiency tends towards 30%.

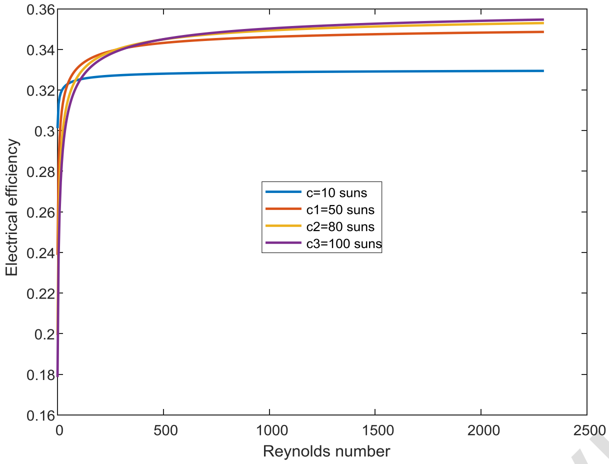

Fig.9. Electrical efficiency profile as a function of Reynolds number.

3.5.2. Thermal efficiency

3.5.2.1 Thermal efficiency as a function of concentration

In this section, the effect of concentration is discussed. Varying the concentration ratio significantly affects the temperature of the system. This leads to an increase in thermal power and consequently an increase in thermal efficiency, as shown in **Figure 10.** The results of this parametric analysis show that the thermal efficiency also increases as a function of the mass flow rate of the heat transfer fluid (water). When the mass flow rate is equal to 0.0001kg/s the efficiency increases from 0.4% to 0.7%, for a flow rate equal to 0.0010kg/s from 0.4 to 7.17% and for a water flow rate equal to 0.010kg/s from 0.4 to 43.54% for a concentration varying from 1 -100 suns. The greater the mass flow rate, the greater the thermal energy absorbed, hence the higher the thermal efficiency.

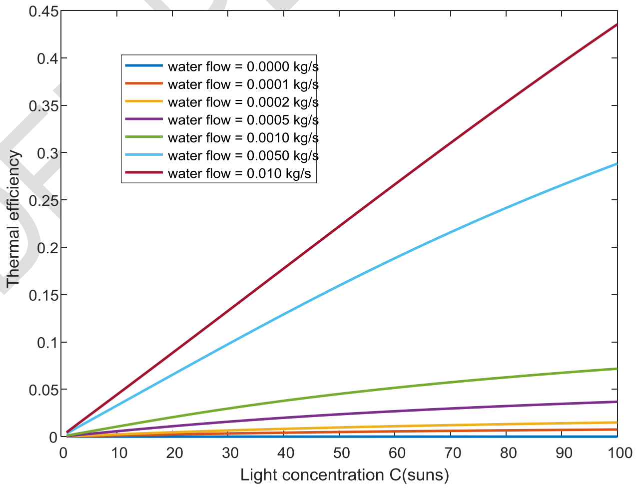

Fig.10. Thermal efficiency profile as a function of geometric concentration

3.5.2.2 Thermal efficiency as a function of water mass flow rate

The mass flow rate of the working fluid is another important parameter in the CPV/thermal hybrid system with cooling. It governs the fluid outlet temperature and affects both thermal power and thermal efficiency. The influence of mass flow rate on thermal efficiency is shown in Figure 10. The curves in Figure 11 show that the thermal efficiency decreases as a function of the geometric concentration ratio. For C=100 suns, the thermal efficiency decreases from 86.54% to 36.59% for a flow rate of 0 to 1kg/s; for C=40 suns, it varies from 87.62% to 37.30% for a mass flow rate of 0 to 1kg/s.

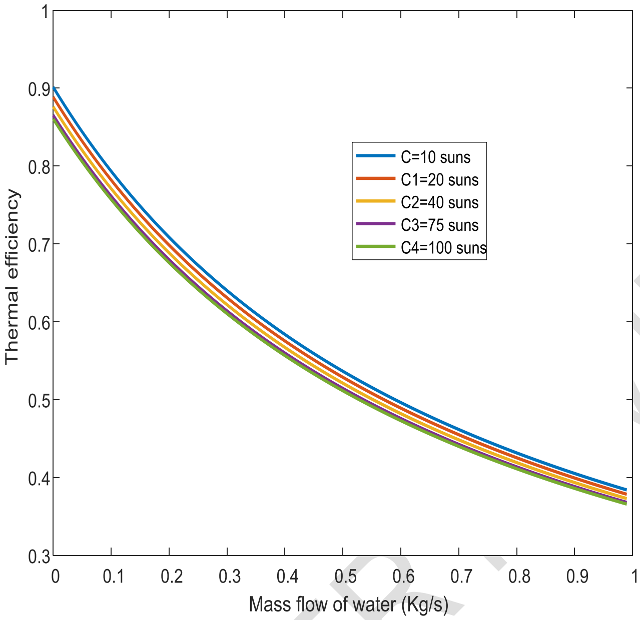

Fig.11. Thermal efficiency profile as a function of water mass flow rate

3.5.2.3 Thermal efficiency as a function of Reynolds number

The variation in thermal efficiency as a function of Reynolds number is shown in Figure 12. It can be seen that increasing the Reynolds number decreases the thermal efficiency because increasing it decreases the temperature of the photocell (fluid), as shown in Figure 5, and therefore the thermal power.

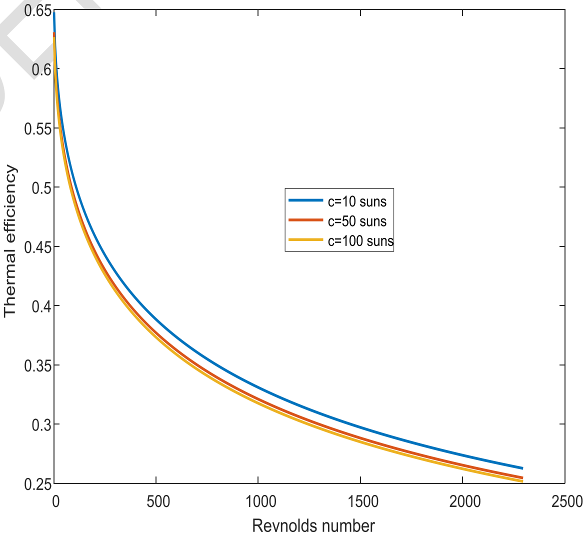

Fig.12. Thermal efficiency profile as a function of Reynolds number.

4. CONCLUSION

The thermal model proposed for the CPV/thermal photovoltaic system with water as the heat transfer fluid is based on the principle of conservation of energy. With this model, the temperature of the solar cell decreases and becomes almost horizontal as the water flow rate increases, tending towards the uncooled temperature as the surface area increases for concentration values between 1-100X. The performance results show that the water flow rate is the main factor in thermal efficiency.

The results of this work are significant for the hybrid photovoltaic CPV/thermal cooling system, but the 3D study of the system is a future project.

The various results which are obtained by numerical simulation need to be validated by experimental methods.

A forthcoming publication will be devoted to an experimental comparative study with those of the numerical.

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