



Assessment of the Thermal Efficiency of a Concentrated Photovoltaic/Thermal (CPV/T) Hybrid System with Water as Heat Transfer Fluid

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/CJAST/2023/v42i434276

Open Peer Review History:

This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: <https://www.sdiarticle5.com/review-history/108496>

Original Research Article

Received: 06/09/2023

Accepted: 14/11/2023

Published: 22/11/2023

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.

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

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Propose a numerical model to evaluate the thermal efficiency of a CPV/T hybrid system. Starting from the energy conservation equations, a numerical modelling 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. 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. 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.

Keywords: Numerical; concentration; PV; cell; thermal; hybrid; efficiency.

1. INTRODUCTION

PhotoVoltaic/Thermal (PVT) hybrid solar collector was suggested as a solution for promoting the PV efficiency and the benefit of solar radiation. It is incorporation of solar PV with the Solar Thermal Collectors (STC) that serves in the simultaneous generation of electricity and heat with half the area needed and little extra cost [1]. Numerous investigations are conducted since the development of solar hybrid systems [2-5].

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. 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 [6-8]. 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 [9-12]. It appears that controlling the temperature rise of the photovoltaic panels leads to gains in the electrical power of the panel [13], and the thermal energy extracted from the photovoltaic panels is used for a variety of low-temperature applications. Several studies in the literature, both theoretical and experimental, report on electrical and thermal efficiencies [14-20].

However, these studies do not give the influence of certain parameters such as mass flow rate,

Reynold's number or tube length on these efficiencies.

K. Shanks et al [21] Conducted a study on a high concentrator photovoltaic with 5800x geometrical concentration ratio based on multiple primary Fresnel lenses focusing to one central solar cell.

His study was focus on the optical efficiency of each component which is simulated as well as experimentally measured to ensure the accuracy of the simulations.

The contribution of this paper is therefore to evaluate the electrical and thermal efficiency of a PV/Thermal hybrid collector model under concentration as a function of these different parameters.

2. MATERIALS 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 (Fig. 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.

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.

$$P_{lum} = P_{ele} + P_{th} + P_{ray} + P_{conv} \quad [7] \quad (1)$$

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

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

Thus:

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

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

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.

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

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

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

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

$$P_{conv} = A_c h (T - T_0) \quad (4)$$

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

$$Nu_f = 0.664 Pr_f^{\frac{1}{3}} Re_f^{\frac{1}{2}} = \frac{hL}{\lambda_f} \quad [9], [22] \quad (5)$$

Were

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

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

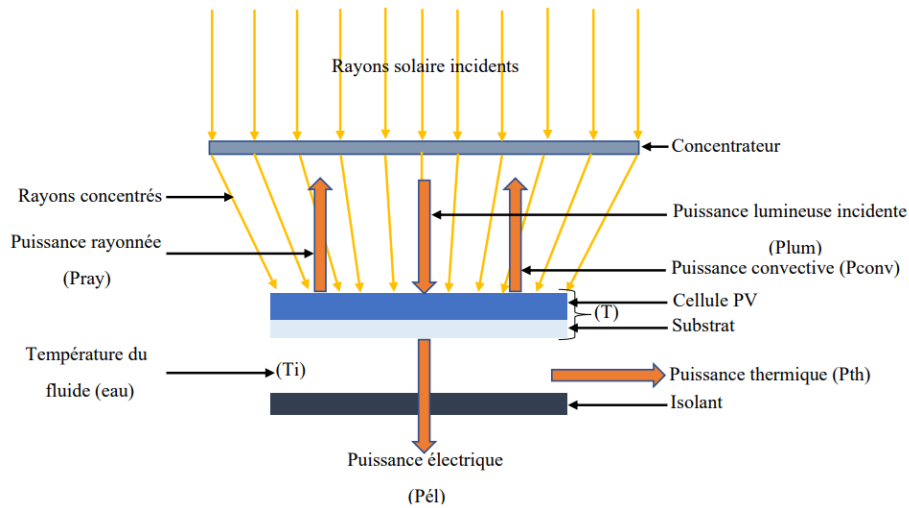


Fig. 1. The model and components of the CPV/thermal hybrid system

3. RESULTS AND DISCUSSION

3.1 Influence of Concentration Ratio on Temperature

Fig. 2 and 3 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 (Fig. 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 (Fig. 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.

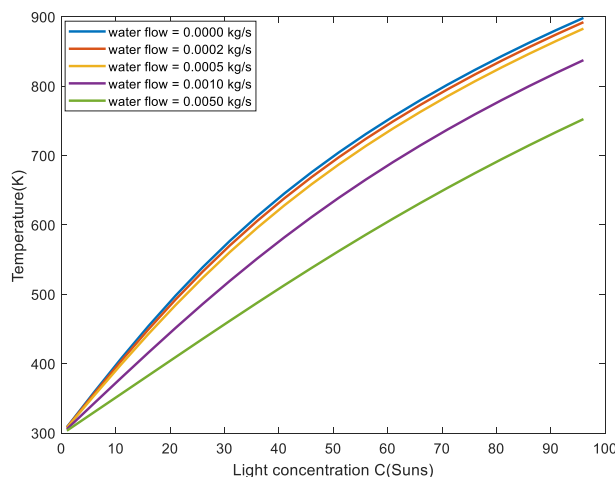


Fig. 2. Variation in photocell temperature as a function of light concentration for different values of water mass flow rate and for a Reynolds number of 1

3.2 Influence of Surface Area on Temperature

Fig. 4 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

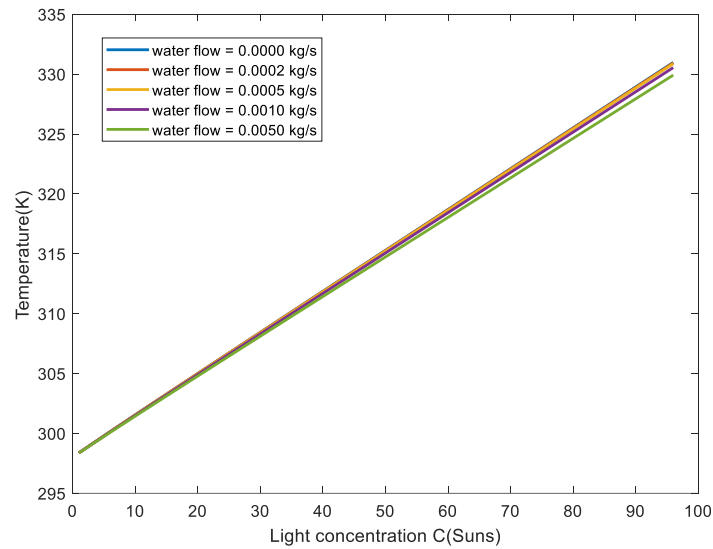


Fig. 3. Variation in photocell temperature as a function of light concentration for different values of water mass flow rate and for a reynolds number of 1000

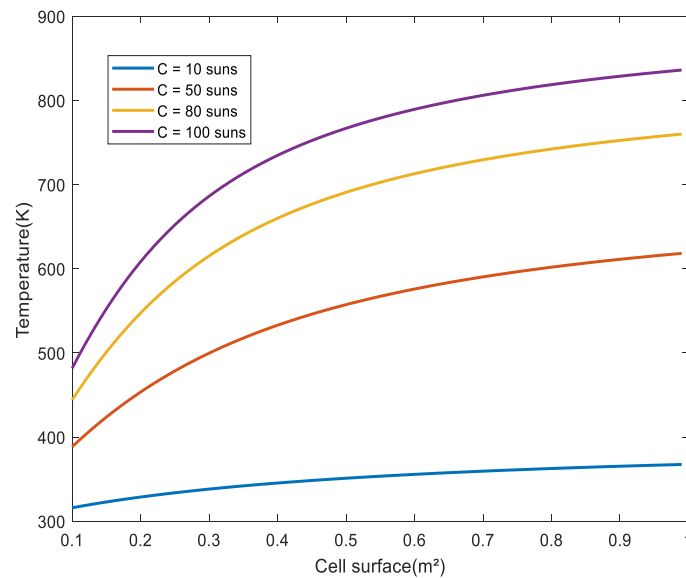


Fig. 4. Temperature profile as a function of cell surface area for different values of light concentration and for a water flow rate equal to 0.005 kg/s

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 (Fig. 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.

3.4 Effect of Reynolds Number

Fig. 6 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.

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 (Fig. 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

$$\eta = 0.298 + 0.0142 \times \ln(C) + [-0.715E3 + 0.697E4 \times \ln(C)](T - 298)$$

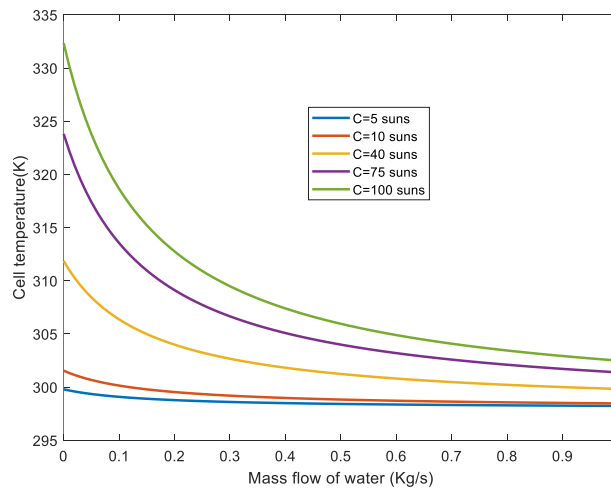


Fig. 5. Variation in temperature as a function of mass flow rate for different values of concentration

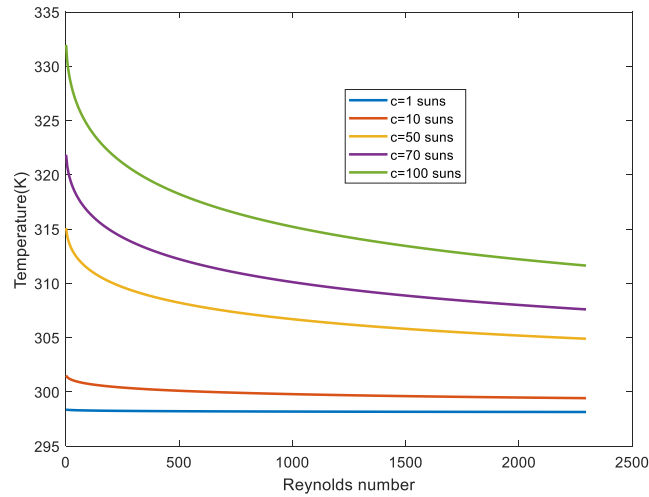


Fig. 6. Variation of temperature as a function of Reynolds number for different values of concentration and for a water flow rate equal to 0.15kg/s

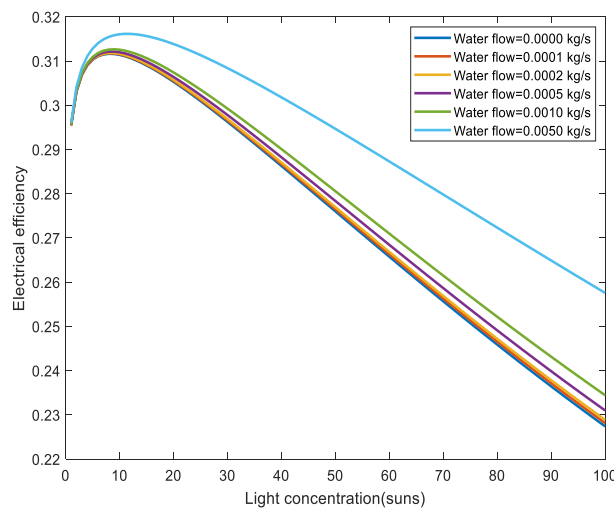


Fig. 7. Electrical efficiency as a function of concentration

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 Fig. 8 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.

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.

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%.

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 Fig. 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.

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 Fig. 10. The curves in Fig.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.

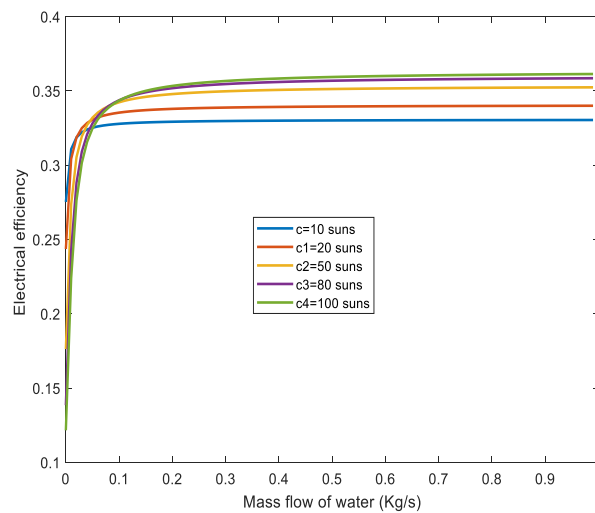


Fig. 8. Electrical efficiency as a function of mass flow rate

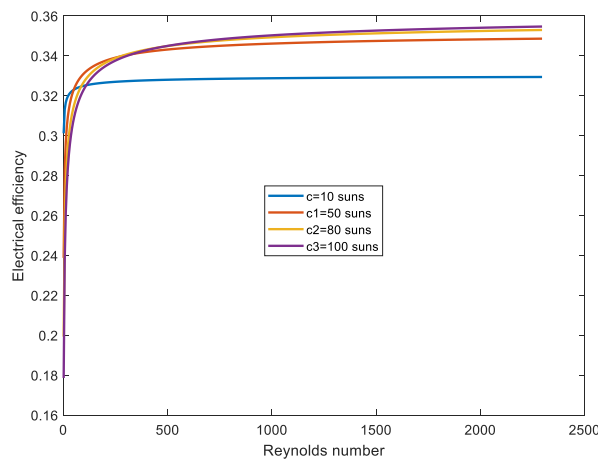


Fig. 9. Electrical efficiency profile as a function of reynolds number

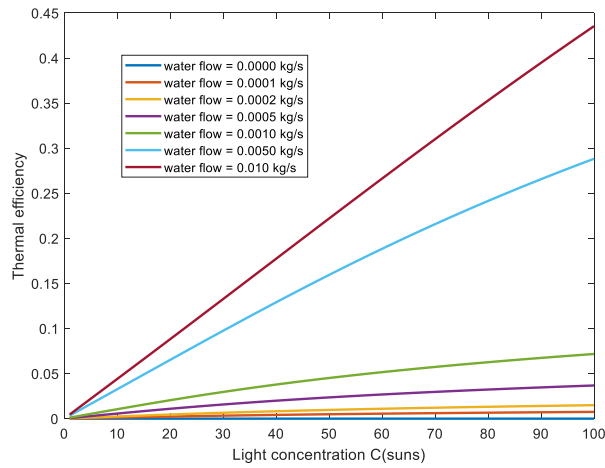


Fig. 10. Thermal efficiency profile as a function of geometric concentration

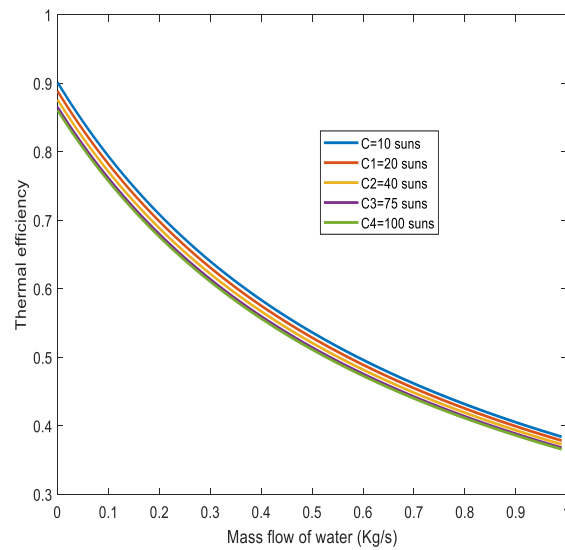


Fig. 11. Thermal efficiency profile as a function of water mass flow rate

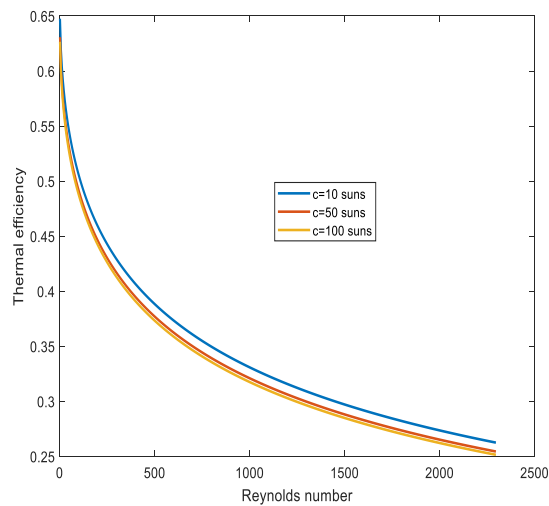


Fig. 12. Thermal efficiency profile as a function of reynolds number

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 Fig. 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 Fig. 5, and therefore the thermal power.

4. CONCLUSION

In this paper, we carry out the conceptual design of the Concentrated Photovoltaic/Thermal (CPV/T) hybrid system and the steady-state modelling for the evaluation of temperature, electrical and thermal performance.

From the heat balance the fourth-degree thermal equation as a function of the photocell temperature was solved using MATLAB software.

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.

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

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.

ACKNOWLEDGEMENTS

The ISP, Uppsala University, Sweden is gratefully acknowledged for their support to project BUF01.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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