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Numerical Assessment of the Thermal Efficiency of a Concentrated Photovoltaic/Thermal (CPV/T) Hybrid System Using Air as Heat Transfer Fluid

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Abstract

In this paper, we propose a thermal model of a hybrid photovoltaic/thermal concentration system. Starting from the thermal balance of the model, the equation is solved and simulated with a MATLAB code, considering air as the cooling fluid. This enabled us to evaluate some of the parameters influencing the electrical and thermal performance of this device. The results showed that the temperature, thermal efficiency and electrical efficiency delivered depend on the air mass flow rate. The electrical and thermal efficiencies for different values of air mass flow are encouraging, and demonstrate the benefits of cooling photovoltaic cells. The results show that thermal efficiency decreases air flow rate greater than 0.7 kg/s, whatever the value of the light concentration used. The thermal efficiency of the solar cell increases as the light concentration increases, whatever the air flow rate used. For a concentration equal to 30 sun, the thermal efficiency is 0.16 with an air flow rate equal to 0.005 kg/s; the thermal efficiency increases to 0.19 with an air flow rate equal to 0.1 kg/s at the same concentration. 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 with air flow as cooling fluid.

Keywords

PV Cell, Concentrating, Thermal, Energy Conversion, Cooling, Hybrid System

1. Introduction

Due to growing global demand for energy, the planet's fossil sediment resources are gradually dwindling. In addition, the heavy use of fossil fuels and wood is causing serious environmental damage and global warming. The economic consequences of the oil crises of the 1970s drew attention to these problems and the solutions that could be found.

Faced with all these problems, mankind is increasingly turning to new sources of energy known as renewable energies because they are abundant, inexhaustible and non-polluting. Photovoltaic energy is emerging as an alternative source of energy to meet the energy needs of developing countries such as Burkina Faso, a sunny country.

Photovoltaic energy was discovered in 1839 by the French physicist Edmond Henri Becquerel, and the first photovoltaic cell was developed in the United States by Bell Laboratory researchers in 1954. Unfortunately for photovoltaic devices, at the current stage, only 20% of electromagnetic radiation is converted into electricity, while 80% is dissipated in the form of heat, causing the temperature of PV cells to rise and inevitably leading to a fall in efficiency.

Experiments and studies have shown that the best way to control cell temperature is to cool the cells and recover the heat accumulated in the PV modules. Scientists have developed hybrid (PV/T) systems to recover this heat using a heat transfer fluid. Hybrid photovoltaic/thermal collectors are systems that convert solar radiation into electricity and heat. The heat released by the solar cell to the cooling fluid can be used for other applications.

Numerous investigations are conducted since the development of solar hybrid systems [1] [2] [3] [4].

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 [5] [6]. 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 [7] [8] [9] [10]. It appears that controlling the temperature rise of the photovoltaic panels leads to gains in the electrical power of the panel [11], 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 [12]-[17].

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.* [18] conducted a study on a high concentrator photovoltaic with 5800× 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.

Assessment of the thermal efficiency of a concentrated photovoltaic/thermal (CPV/T) hybrid system with water as heat transfer fluid has been conducted by KONFE *et al.* [19].

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 0.0001 kg/s, from 0.4% to 0.7%, for a flow rate equal to 0.0010 kg/s.

As water is a scarce source, it would be interesting to study the performance obtained by using air as a heat transfer fluid.

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 with air as heat transfer fluid.

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 [19]:

- 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;

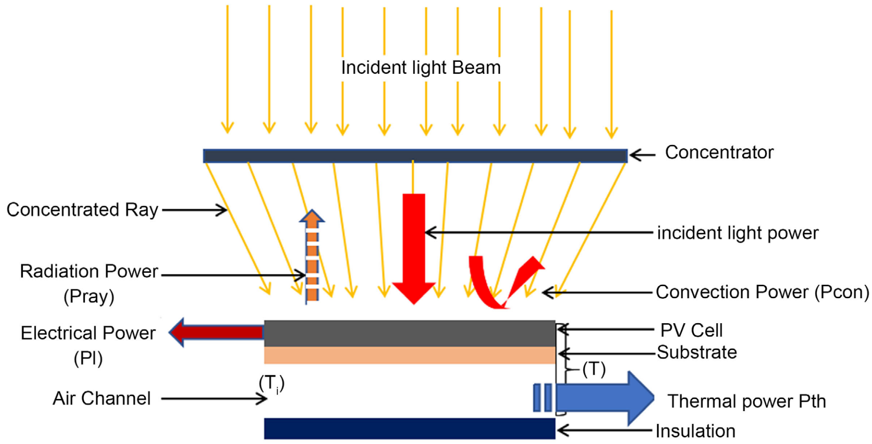

Figure 1. The model and components of the CPV/thermal hybrid system.

4) The outlet temperature of the heat transfer fluid (air) is that of the substrate solar cell.

2.1.2. Thermal Analysis

A mathematical model has been developed to evaluate the performance of the hybrid photovoltaic/thermal system with a CPV/T parabolic concentrator. **Figure 1** shows the different powers exchanged by the solar cell.

- **Expressing power**

The powers exchanged by the solar cell are:

Absorbed light power:

$$P_{lum} = \tau_0 \alpha_0 A_0 C P_{ecl} \tag{1}$$

The electrical power supplied to the external load:

$$P_{el} = \eta_{el} \tau_0 \alpha_0 A_0 C P_{ecl} \tag{2}$$

The electrical efficiency of the solar cell and is given by:

$$\eta_{el} = 0.298 + 0.0142 \ln c + \left(-0.000715 + 0.000069 \ln c\right)\left(T - 298\right) \quad [20]$$

The power dissipated by radiation:

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

The power dissipated by convection

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

h is given by the following Mac Adams formula: $h = 5.7 + 3.8 \times v$.

Thermal power absorbed by air circulation

$$P_{th} = \dot{m} c_p \left(T - T_i\right) \tag{5}$$

T_i is the initial inlet temperature of the cooling fluid, which in our study is air.

The photocell reaches its steady-state temperature when the light power absorbed is equivalent to the sum of the electrical power supplied, the thermal power absorbed by the air flow and the power dissipated, as given by equation (6) below:

$$P_{lum} = P_{el} + P_{th} + P_{ray} + P_{con} \tag{6}$$

By replacing the powers by their expressions in the equation below, we obtain the thermal equation of the solar cell given by Equation (7) below:

$$\tau_0 \alpha_0 A_0 c P_{ecl} = \eta_{el} \tau_0 \alpha_0 A_0 c P_{ecl} + \dot{m} c_p \left(T - T_i\right) + A_0 h \left(T - T_0\right) + A_0 \varepsilon \sigma \left(T^4 - T_0^4\right) \tag{7}$$

Injecting the expression for the photo-conversion efficiency into Equation (7), we obtain:

$$\begin{aligned} &\left(0.298 + 0.0142 \ln c + \left(-0.000715 + 0.0000697 \ln c\right)\left(T - 298\right)\right) \tau_0 \alpha_0 A_0 c P_{ecl} \\ &- \tau_0 \alpha_0 A_0 c P_{ecl} + \dot{m} c_p \left(T - T_i\right) + A_0 h \left(T - T_0\right) + A_0 \varepsilon \sigma \left(T^4 - T_0^4\right) = 0 \end{aligned} \tag{8}$$

By expanding and ordering the decreasing powers of T, we obtain the following equation:

$$\begin{aligned} &0.51107 \tau_0 \alpha_0 A_0 c P_{ecl} - 0.0065706 \tau_0 \alpha_0 A_0 c P_{ecl} \ln c \\ &+ \left(-0.000715 + 0.0000697 \ln c\right) \tau_0 \alpha_0 A_0 c P_{ecl} T - \tau_0 \alpha_0 A_0 c P_{ecl} \\ &+ \dot{m} c_p T - \dot{m} c_p T_i + A_0 h T - A_0 h T_0 + A_0 \varepsilon \sigma T^4 - A_0 \varepsilon \sigma T_0^4 = 0 \end{aligned} \tag{9}$$

Let:

$$\begin{aligned} A_t = &-A_0 \varepsilon \sigma T_0^4 - \tau_0 \alpha_0 A_0 c P_{ecl} - A_0 h T_0 - \dot{m} c_p T_i + 0.51107 \tau_0 \alpha_0 A_0 c P_{ecl} \\ &- 0.0065706 \tau_0 \alpha_0 A_0 c P_{ecl} \ln c \end{aligned}$$

$$B_t = \left(-0.000715 + 0.0000697 \ln c\right) \tau_0 \alpha_0 A_0 c P_{ecl} + \dot{m} c_p + A_0 h$$

$$C_t = A_0 \varepsilon \sigma$$

we obtain the following polynomial equation of degree 4:

$$C_t T^4 + B_t T + A_t = 0 \tag{10}$$

- **Expression of yields**

Before calculating the overall efficiency, the equivalent thermal efficiency and the electrical efficiency are calculated using the following relationships

$$\eta_{el} = 0.298 + 0.0142 \ln c + \left(0.0000697 \ln c - 0.000715\right)\left(T - 298\right) \tag{11}$$

$$\eta_{th} = \frac{\dot{m} c_p \left(T - T_i\right)}{\tau_0 \alpha_0 A_0 c P_{ecl}} \tag{12}$$

Overall efficiency is represented by the sum of thermal efficiency and equivalent thermal efficiency

$$\eta_{gl} = \eta_{el} + \eta_{th} \tag{13}$$

The Equation (10) 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

Figure 2 below shows the temperature profile as a function of light concentration for different air mass flow rates.

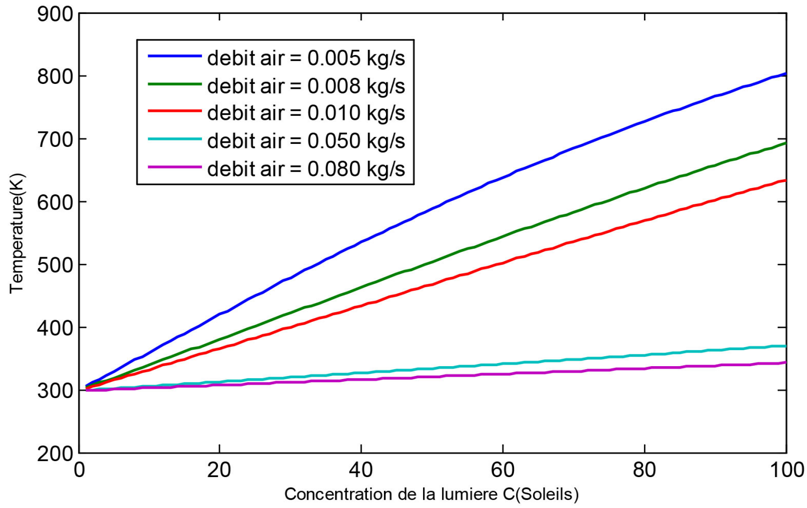

Figure 2. Temperature profile for C varying from 0 sun to 100 sun for different air mass flow rates.

Figure 2 shows that the temperature of the solar cell increases as the light concentration increases. This increase in temperature is explained by the increase in heat received by the solar cell as the light concentration increases. However, the temperature of the solar cell decreases as the air mass flow rate increases. This is because the air circulating in the channel absorbs some of the heat received by the solar cell, thereby cooling it. The higher the air mass flow rate, the greater the amount of heat transported by the air and the lower the cell temperature.

3.2. Influence of Surface Area on Temperature

Figure 3 below shows the temperature profile as a function of cell surface area for different values of solar concentration.

Figure 3 shows that the temperature increases with the increase in concentration whatever the value of the cell surface. Under $S = 0.04\ \text{m}^2$ and $\dot{m} = 0.08\ \text{kg/s}$, when the concentration increases from 10 suns to 100 suns, the cell temperature rises from 353 K to 576.9 K. However, under $S = 0.1\ \text{m}^2$ the temperature rises from 359.2 K to 803 K.

Note that the temperature of the fluid at the outlet is dependent on the surface area of the cell. As we increase the surface area of the cell, the temperature of the fluid at the outlet increases, whatever the value of the concentration. This increase in temperature is explained by the fact that the solar cell receives a large proportion of the heat from the sun's rays.

3.3. The Effect of Air Mass Flow Rate on Temperature

Figure 3, **Figure 4** opposite shows the temperature profile as a function of air mass flow rate for different light concentrations.

Figure 4 shows that increasing the air mass flow rate leads to a decrease in the temperature of the solar cell. For an air flow rate equal to 0.025 kg/s the cell temperature is 340.6 K under a concentration of 30 suns. For an air flow rate of 0.1 kg/s, the cell temperature rises to 315.1 K at the same concentration. For a concentration of 100 suns the cell temperature is 442.1 K for an air flow rate of 0.025 kg/s and 315.1 K for an air flow rate of 0.01 kg/s. When the air flow rate is less than 0.1 kg/s, there is a sudden drop in temperature, but if it is greater than 0.1 kg/s, there is a slight decrease in temperature. This decrease can be explained by the fact that the air circulating in the channel absorbs some of the heat received by the solar cell, thereby cooling it. These results show the strong influence of the air mass flow rate on the temperature profile of the solar cell.

Figure 4 shows that when the concentration is high, so is the temperature. However, if the concentration is low, the cell temperature is also low. This is because the photocell receives a large amount of heat when the concentration is high.

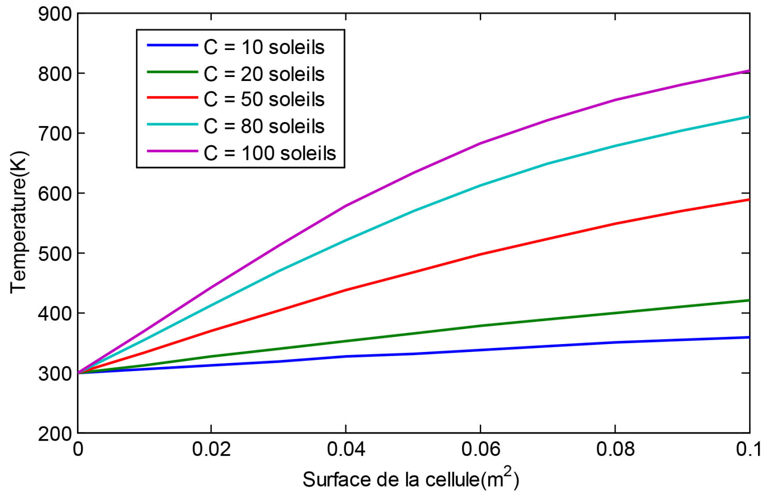

Figure 3. Temperature variation as a function of cell surface area for different concentrations.

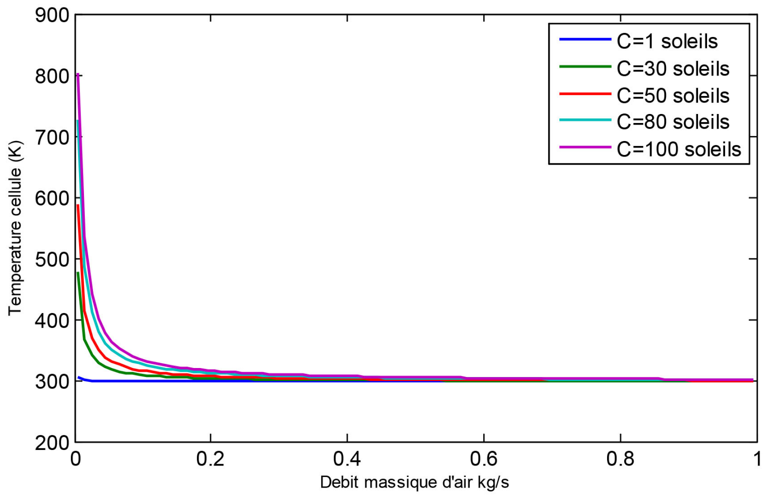

Figure 4. Temperature profile for $\dot{m}$ varying from 0 kg/s to 1 kg/s for different concentrations.

3.4. Electrical and Thermal Performance of the System

3.4.1. Electrical Efficiency

1) Electrical efficiency as a function of concentration

Figure 5 opposite shows the electrical efficiency profile as a function of concentration for different air mass flow rates.

Figure 5 shows that the profile of electrical efficiency as a function of light concentration has two parts:

- At low concentrations ($C \le 6$ soleils), electrical efficiency increases with concentration.
- At high concentrations ($C \ge 6$ soleils), electrical efficiency decreases with concentration.

Figure 5 also shows that when the concentration is low, the heat received by the solar cell is also low, so the electrical efficiency increases. But when the concentration is high, the heat received by the solar cell is high, so the temperature will be high and the electrical efficiency will therefore fall. The higher the temperature, the lower the efficiency of the cell.

2) Electrical efficiency as a function of mass flow

Figure 6 opposite shows the profile of electrical efficiency as a function of air mass flow rate for different solar concentrations.

- At low air flow rates ($\dot{m} = 0.08\ \text{kg/s}$), electrical efficiency increases rapidly with air flow rate. This increase in electrical efficiency can be explained by the decrease in temperature.
- For intermediate operating states ($0.08\ \text{kg/s} \le \dot{m} \le 0.1\ \text{kg/s}$), electrical efficiency increases slightly with air flow rate.
- At high air flow rates ($\dot{m} \ge 0.1\ \text{kg/s}$), electrical efficiency is maximum and constant.

Figure 6 also shows that the electrical efficiency increases as the air mass flow rate increases. This increase in electrical efficiency can be explained by the decrease in temperature as the air mass flow rate increases.

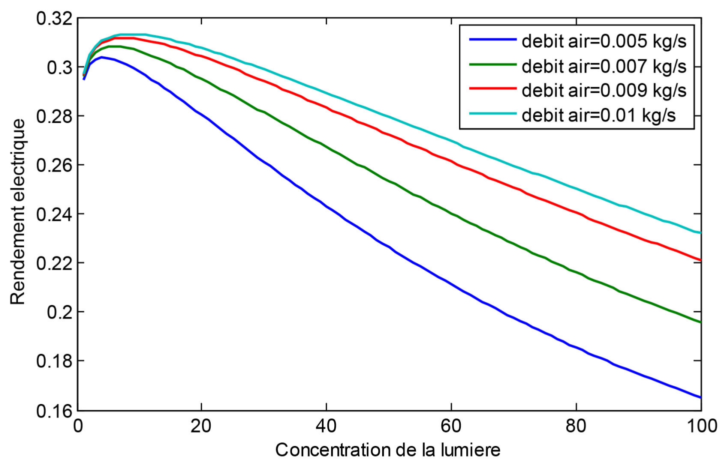

Figure 5. Electrical efficiency profile for C varying from 0 soleil to 100 soleils for different air flow rates.

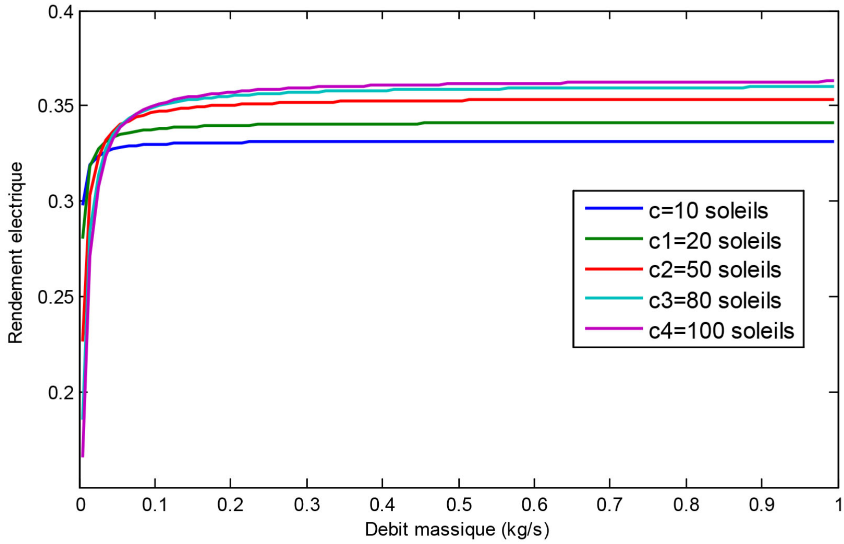

Figure 6. Electrical efficiency profile for $\dot{m}$ varying from 0 kg/s to 1 kg/s for different concentrations.

These results are in good agreement with those of Hegazy *et al.* [21]; since, according to their work, the electrical efficiency increases with increasing mass flow rate. In the best case, the conversion efficiency of photovoltaic modules does not exceed 16% according to Touafek *et al.* [22], but in our case the efficiency exceeds 30%. The use of CPV/T with air as the heat transfer fluid can be used to improve the cooling of photovoltaic cells compared with a PV module in isolated operation.

3.4.2. Thermal Efficiency

1) Thermal efficiency as a function of concentration

Figure 7 shows the thermal efficiency profile as a function of light concentration for different air mass flow rates.

Figure 7 shows that the thermal efficiency is a proportional function of the light concentration. The thermal efficiency of the solar cell increases as the light concentration increases, whatever the air flow rate used. For a concentration equal to 30 sun the thermal efficiency is 0.16 with an air flow rate equal to 0.005 kg/s; the thermal efficiency increases to 0.19 with an air flow rate equal to 0.1 kg/s at the same concentration. For a concentration equal to 100 suns, the thermal efficiency is 0.45 with an air flow rate equal to 0.005 kg/s; the thermal efficiency rises to 0.64 with an air flow rate equal to 0.1 kg/s at the same concentration. This increase in thermal efficiency is explained by the rise in temperature as the cell receives heat with the increase in solar concentration.

2) Thermal efficiency as a function of air flow rate

Figure 8 opposite shows the thermal efficiency profile as a function of air mass flow rate for different light concentrations.

Figure 8 shows that the thermal efficiency of the solar cell decreases for an air flow rate greater than 0.7 kg/s, whatever the value of the light concentration used.

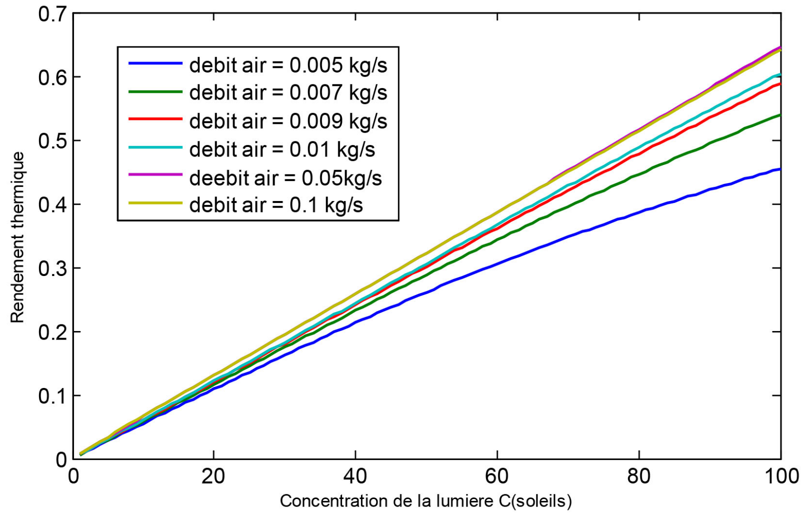

Figure 7. Thermal efficiency profile for C varying from 0 sun to 100 suns for different air mass flow rates.

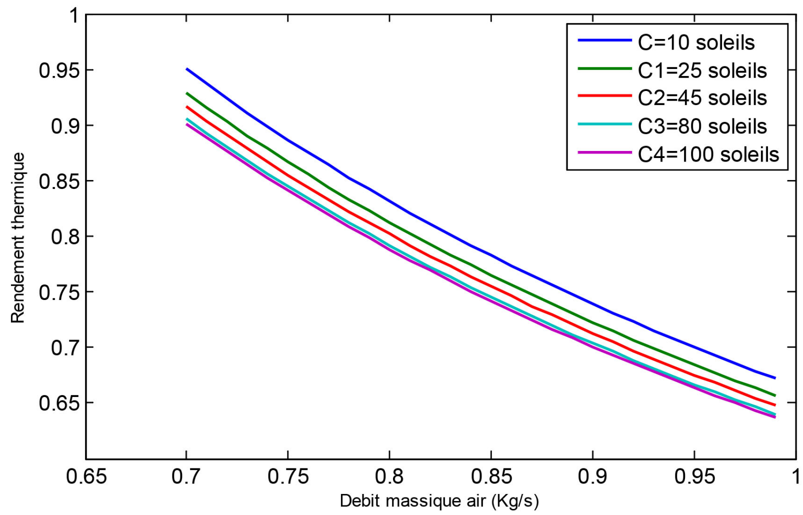

Figure 8. Thermal efficiency profile for $\dot{m}$ varying from 0.65 kg/s to 1 kg/s for different concentrations.

As the air mass flow rate increases, the thermal efficiency of the solar cell decreases. For an air flow rate equal to 0.7 kg/s, the thermal efficiency of the cell is 0.95 at a concentration of 10 suns. At an air flow rate of 0.9 kg/s, the cell's thermal efficiency falls to 0.73 at the same concentration. Under a concentration equal to 80 soleils the thermal efficiency is 0.90 for a mass flow equal to 0.7 kg/s. The thermal efficiency drops to 0.70 for a flow rate equal to 0.9 kg/s at the same concentration. The greater the air mass flow rate, the more the cell cools and the cell temperature is lower, so the thermal efficiency of the cell decreases.

In the work on the performance of hybrid collectors carried out by Sopian *et al.* [23], the thermal efficiency of these PV/T systems was in the range 45% to 65%, but with the cooling of the solar cell in our case we observe a drop in thermal efficiency as a function of air flow.

4. Conclusions

The theoretical study of the thermal efficiency of a hybrid concentrated photovoltaic-thermal system using air as the heat transfer fluid has enabled us to evaluate the thermal and electrical performance, such as cell temperature, electrical and thermal efficiency, for different values of mass flow rate and different values of solar concentration of a solar cell.

We established the heat balance for our model, which enabled us to draw up the equation as a function of cell temperature.

By solving this equation numerically using Matlab software, we were able to plot the temperature profile, the thermal efficiency profile and the thermal efficiency profile of the photovoltaic cell as a function of light concentration, temperature and surface area for different air mass flow rates.

The results showed an improvement in electrical efficiency and a decrease in temperature as the air mass flow rate increased. It was also observed that under light concentration, the increase in air mass flow rate led to a decrease in thermal efficiency. However, an increase in light concentration leads to an increase in temperature, which in turn leads to an increase in thermal efficiency and a decrease in electrical efficiency.

The results also show an improvement in electrical efficiency and a decrease in thermal efficiency with increasing air speed. However, increasing the surface area of the cell leads to an increase in thermal efficiency. The cooling system (air) placed at the back of the cell transports the heat not absorbed by the solar cell to cool it, which has the effect of lowering the cell temperature and therefore reducing thermal efficiency.

Following this work, new areas for study have emerged. These are as follows:

• A comparative study of the performance of the CPV/T hybrid system with different types of heat transfer fluids.

• Study of a two-fluid CPV/T hybrid system.

• A 3D study of the CPV/T hybrid system.

Also, a practical implementation and testing could be carried out in an experimental study of the model.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Nomenclature

τ_0	Concentrator transmissivity
α_0	Absorption coefficient of solar cell surface
A_0	Surface area of the solar cell (m^2)
P_{ecl}	Power density of solar irradiance (W/m^2)
C	Light concentration
A_{ray}	Radiative surface ($A_{ray} = A_0$) (m^2)
σ	Stephan-Boltzmann coefficient (5.67×10^{-8} $w/m^2 K^4$)
ε	Emissivity of the solar cell surface
T_0	Ambient temperature
$A_c = A_0$	Convective surface (m^2)
h	Heat exchange coefficient
v	Air velocity (m/s)
$\dot{m}$	Air mass flow rate (kg/s)
c_p	Air specific heat ($J \cdot kg^{-1} \cdot K^{-1}$)