Abstract — The work was developed in partnership with a Swedish company Solarus AB to study thermal effects and their influence on the energy efficiency of Solarus stationary solar concentrating photovoltaic-thermal (CPVT) collectors. Namely, thermal effects focused in how temperature distribution through the bottom layer of the solar panel, which receives the radiation reflected from the reflector, affect the electric efficiency. For this purpose, an electromagnetic-thermal finite element model in 2D and 3D, capable of computing the heat transfer occurring due to the presence of a moving fluid (usually air, water or oil) was developed. This analysis was crucial to the characterization of PV Solarus system since it allowed to determine the raise of temperature distribution occurred in the photovoltaic cells and water under given operation conditions. According to the variables of the system the model allowed us to map the temperature distribution through the different layers of the panel and verify the water temperature.

The distribution of photovoltaic cells in the panels of Solarus is made of an asymmetrical shape, since the non-uniformity of temperature and solar radiation occur in the back receiver caused by the reflector geometry. Hence, the simulations were realized to verify the influence of the flow, the losses in electric efficiency, the temperature variation in the panel, the shading effect in the back receiver of electrical efficiency in Portugal and Sweden and the relationship between the flow variation and electrical performance.

Index Terms — Cooling, CPVT, electrical efficiency, finite element program, photovoltaic cells.

I. INTRODUCTION

SIMPLE PV systems only produce electricity while CPVT systems can simultaneously produce electricity and thermal energy leading to lower cost of electricity production and greater overall use of solar energy.

In order to maximize efficiency levels, lower heat losses and obtain better solar radiation distribution it is important to understand the behavior of the CPVT. This may be achieved by performing a thermal analysis of the physical system, aided by a finite element software to simulate the natural phenomena that interact with the CPVT.

The thermal analysis should reveal the locations of greater heat losses, eventual hot spots and the different temperature levels throughout the layers and/or materials forming the CPVT collector.

II. CPVT COLLECTOR ANALYSIS

The CPVT analysis should take into account all system components, analyze the interactions between them and the atmospheric environment. A brief description of the CPVT system components will be made before proceeding to the thermal analysis. First, the object will be detailed and then will proceed to the thermal analysis by a software.

The CPVT system developed by the Solarus AB research center in Gavle, Sweden, is composed by 2 layers of photovoltaic cells, one on top of the receiver, one at the bottom of the receiver and in between these layers of photovoltaic cells exists 8 channels for water to flow in order to cool the cells and simultaneously absorb the excessive heat. The aluminum concentrator main function is to reflect solar radiation at the bottom of the receiver, as illustrated in the Fig. 1 [1].

To perform the simulation of the CPVT was used as working tool a finite element software to calculate the results of all physical phenomena that affect the dashboard.

A physical representation of a CPVT receiver is shown in Fig. 2, similar to the Solarus AB one, in which it is possible to distinguish an aluminum core and 8 elliptical water channels used to cool both photovoltaic cells layers.
A. Materials of the receiver

An amplified representation of a CPTV receiver is shown in Fig. 3 in which the different materials are highlighted.

Enumerating each of the layers, we have:
1 - Silicone; 2 - Photovoltaic cells (silicon); 3 - Aluminum; 4 - Channels for water; 5 - Electrical conductor.

![Fig. 3. Representation of all materials of the receiver.](image)

Each material has a specific function to enhance the overall performance. Photovoltaic cells are made of monocrystalline silicon and are responsible for the production of electricity. The silicone (not to confuse with silicon) main function is to guarantee electrical isolation of the photovoltaic cell layers (by preventing short circuit occurrences) and should possess a high light transmittance, which translates the effectiveness of the material in transmitting radiant energy vital for the photovoltaic effect at the photovoltaic cell. The heavier layer, aluminum, serves to facilitate the passage of heat between the silicone layer and the water channels. The electrical conductor is a piece of copper that makes the electrical connection between photovoltaic cells. As explained before the waters main function is the cooling of the photovoltaic cells and the use of that heat in the form of thermal energy [2].

B. Channels formats

One of the main characteristics of the receiver, shown in Fig. 3, is the elliptical shape of the various water channels that transport energy (as heat) from the both photovoltaic cells. To evaluate the benefits of such shape it is useful to compare it to other possible geometries. Using the finite element software, 4 suitable geometries (square, rectangle, circle and ellipse) of water channels are evaluated and compared. To fairly compare the 4 shapes, they should all possess equal areas (70 mm²) and same heat source borders. The temperature distribution and temperature variations, obtained via simulation, for the different shapes is shown Fig. 4 and noted in Table 1.

![Fig. 4. Tests of the 4 forms of water channels.](image)

<table>
<thead>
<tr>
<th></th>
<th>Area (mm²)</th>
<th>Perimeter (mm)</th>
<th>T_min (°C)</th>
<th>T_max (°C)</th>
<th>AT (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ellipse</td>
<td>70.00</td>
<td>35.525</td>
<td>23.8</td>
<td>42.4</td>
<td>18.6</td>
</tr>
<tr>
<td>Rectangle</td>
<td>70.00</td>
<td>38.000</td>
<td>25.3</td>
<td>46.8</td>
<td>21.5</td>
</tr>
<tr>
<td>Circle</td>
<td>69.99</td>
<td>29.657</td>
<td>21.7</td>
<td>37.6</td>
<td>15.9</td>
</tr>
<tr>
<td>Square</td>
<td>70.00</td>
<td>33.468</td>
<td>22.0</td>
<td>46.5</td>
<td>24.5</td>
</tr>
</tbody>
</table>

By analyzing Fig. 4, it is notable the existence of hot spots (dark red color) on the square and rectangle shapes while lower temperatures (white color) where obtained by the circle and elliptical geometries. Hot spots should be avoided since the may damage the receiver.

In Table 1, it is noted that different shapes although having equal areas, do not have the equal perimeters. As known from the laws of thermodynamics, the greater the contact area, the greater the heat transfer. This means that the rectangle and ellipse as the better solutions for heat transfer (Table 1).

It is now possible to conclude and understand that the elliptical shape is the better solution since in manages to combine a greater contact area, which facilitates the transfer of heat and small temperature variation avoiding hot spots achieving a more uniform temperature.

C. Distribution of photovoltaic cells and bypass diodes

The organization of the CPVT photovoltaic cells of Solarus AB is developing, in order to achieve best results in terms of power produced. Each back receiver consists in 4 strings, of 8-11-11-8 photovoltaic cells [1].

In Fig. 5 can visualize the layout of photovoltaic cells with the bypass diodes, one for each set of photovoltaic cells. One of the major problems of the photovoltaic modules is exactly the shading, and in this case there are certain incidence angles of solar radiation that cause shading in the back receiver.

The use of these bypass diodes is essential to the shading cases, since the shaded cells cause a high resistance to current. Thus photovoltaic cells will cause hot spots in the receiver and reduce the performance of all photovoltaic cells in series. Once the bypass diodes have a lower resistance than the shaded photovoltaic cells, when part of set of photovoltaic cells is in shadow, the diode comes into conduction in order to not affect all photovoltaic cells which are in the other three strings [1], [3].

The major disadvantages of using bypass diodes are the assembly time, since there are more components to join the photovoltaic cells and the cost of this material [4].

With this scheme, developed by Solarus AB, is achieved reducing the negative effects of shading. However, new studies on the arrangement of photovoltaic cells are in place in order to further improve the performance of photovoltaic cells.

![Fig. 5. Circuit of the photovoltaic cells and the bypass diodes for each side of the receiver.](image)

III. EFFECTS OF TEMPERATURE ON PVT

The production of electrons from the photovoltaic cells is based on the incidence of solar radiation on a pn junction. The incident photons with an energy greater than the band gap of the material causes the generation of electron-hole pairs. An electric field is generated allowing the conversion of solar energy into electricity [5], [6].
As the photovoltaic cells are semiconductor devices, they are temperature sensitive, which influence the value of the band gap of the material. The temperature increase causes a lower value of the band gap and the energy of electrons in the material is greater. Thus, there is a greater probability of the electrons collide and fail to form an electron-hole pairs, back to the energy level down and only generates heat [6].

A. Electric efficiency

In relation to electrical performance, to obtain better performance, higher irradiance is not causes directly a higher performance. Let us analyze the importance of the irradiance in Fig. 6, given by (1) and (2) without the temperature variation.

\[
I = I_{sc} - I_0 \left( e^{\frac{V}{mV_T}} - 1 \right) 
\]

(1)

\[
I_{sc} = \frac{G}{G_{ref}} I_{sc_{ref}} 
\]

(2)

Where I represents the current in photovoltaic cell, \(I_{sc}\) is the short circuit current, \(I_{sc_{ref}}\) is the reference short circuit current, \(I_0\) is the reverse bias saturation current for the diode, \(V\) is the photovoltaic cell voltage, \(G\) is the solar irradiance, \(G_{ref}\) is the reference solar irradiance, \(V_T\) is the thermal potential and \(m\) is the diode ideality factor. It can be seen that at higher irradiance (1000 W/m² marked in red in Fig. 6) we obtain a high current and consequently a higher power output, in relation to the voltage, this is also affected by solar radiation but with a lower percentage in relation to the current. For lower irradiance (200 W/m² marked in blue in Fig. 6), was obtained a smaller current [5].

![Fig. 6. Current variation for different solar radiations and the same temperature.](image)

The temperature of a photovoltaic module, \(T_m\) depends not only on the ambient temperature \((T_{amb})\), as well as solar irradiance and the normal operating temperature of the photovoltaic cell (NOCT), shown by (3) [7]. The NOCT parameter is defined as the temperature reached open circuit by the photovoltaic cells under certain conditions STC, so that the module temperature is linear only in certain circumstances [8], [9]:

- Incident irradiance of 800 W/m²;
- Temperature ambient of 20 ºC;
- Speed of wind equal to 1m/s.

\[
T_m = T_{amb} + \frac{G(\text{NOCT} - 20)}{800} 
\]

(3)

Varying only the temperature of the photovoltaic cells simulating temperature variation of the different hours of a day with Sun, obtains Fig. 7. Resulting from (1), (3) and (4) is represent the characteristic I-V, with constant irradiance.

\[
I_0 = I_{0_{ref}} \left( \frac{T_m}{T_{ref}} \right)^3 e^{\left( \frac{eN_s}{m} \left( \frac{1}{V_{T_{ref}}} - \frac{1}{V_T} \right) \right)} 
\]

(4)

Where \(I_{0_{ref}}\) is the reference reverse bias saturation current for the diode, \(T_{ref}\) is the reference temperature, \(G\) is the band gap energy of 1.12 eV for silicon, \(N_s\) is the number of photovoltaic cells and \(V_{T_{ref}}\) is the reference thermal potential.

It is noted that increasing the temperature from 25 ºC (marked in blue in Fig. 7) to the temperature of 115 ºC (marked in red in Fig. 7), is obtained lower voltages and then lower output power of the photovoltaic cells.

![Fig. 7. Variation of the characteristic I-V for different temperatures.](image)

In Figure 8, there is shown the characteristic P-V, where \(P=V \times I\). It is noted that increasing the temperature from 25ºC cell (marked in blue in Fig. 8) up to 115 ºC (marked in red in Fig. 8) the power decreases about 50%. Proving that the increase in temperature in a PVT collector causes a direct reduction in electrical performance.

![Fig. 8. Variation of P-V characteristic for different temperatures.](image)

Both variables, temperature and irradiance will vary over the day simulating the reality, represented in Fig. 9 [15]. Thus, as the module temperature on a day with high exposure to the sun, reaching 60ºC (without concentration), and the electrical performance decreases (by 13h) as already shown in Fig. 8.
B. Thermal efficiency

In relation to thermal efficiency, low temperature in the receiver can’t transmit as much solar energy to the fluid, but for best efficiency the fluid temperature should be similar to the ambient temperature as will be shown below.

Therefore, the thermal efficiency curve represented in Fig. 10 demonstrates the above statement. The thermal efficiency curve is obtained from the thermal efficiency as a function of \( (T_{\text{EXP}} - T_{\text{amb}})/G \) where \( T_{\text{EXP}} \) is the average temperature of the fluid in K.

To calculate the thermal efficiency is necessary to calculate the removal factor of PVT, \( F_R \), which is a factor that relates the actual amount of useful energy with the maximum amount of energy that can be absorbed, given by (5)

\[
F_R = \frac{m C_p (T_{\text{out}} - T_{\text{in}})}{A_{\text{total}} G_{\text{abs}} - U_L (T_{\text{in}} - T_{\text{amb}})}
\]

where \( m \) is the mass flow rate, \( U_L \) represents the energy loss coefficient of the collector, \( A_{\text{total}} \) is the area of the receiver, \( T_{\text{in}} \) is the inlet temperature of water, \( T_{\text{out}} \) is the outlet temperature of water and \( G_{\text{abs}} \) is the radiation absorbed by the receiver [10].

Finally arriving to (6) the thermal efficiency is affected by the correction coefficient \( (\tau \alpha) \) where \( \tau \) is the transmissivity and \( \alpha \) is the absorptivity [10], [11].

\[
\eta_{tr} = F_r \times (\tau \alpha) - F_r \times U_L \left( \frac{T_{\text{EXP}} - T_{\text{amb}}}{G} \right)
\]

For the thermal efficiency curve can be seen that the thermal efficiency is inversely proportional to the difference temperature. The increase in the difference between the temperatures \( T_{\text{EXP}} \) and \( T_{\text{amb}} \) decreases the thermal efficiency.

In Fig. 10 is possible distinguish the optical losses and the thermal losses. The optical losses is the light reflected from a surface and not absorbed by an object, depending of the transmittance and absorbance surface receptor. The thermal losses is the slope of the line represented in Fig. 10. The losses are mainly due to the increase temperature of water channels compared to the ambient temperature i.e., with a high temperature difference between receiver and the surroundings, the receiver loses thermal energy by conduction, convection and radiation [12], [13], [14].

IV. 2D RESULTS OF RECEIVER

The Finite Element Method (FEM) is a mathematical analysis that divides a large problem into smaller. FEM is the discretization of a continuous surface in small elements while maintaining the initial properties. Each analyzed surface of the element is associated with a partial differential equation and solved using mathematical models. Thus, the FEM use mathematical methods to calculate the surface properties and the higher the discretization of the surface elements smaller the calculation error [15]. The simulations were realized in stationary mode defined by (7) where \( k \) is the thermal conductivity and \( VT \) is the temperature gradient.

\[
\nabla \cdot (k \nabla T) = 0
\]

The mathematical models used in the simulation program are: the power transfer to the water defined by (8) and the power that occurs through the layers by conduction by (9).

\[
q_{\text{conv}} = -h A (T_{\text{PV}} - T_{\text{amb}})
\]

\[
Q = \rho C_p \frac{\partial T}{\partial t}
\]

Where \( q_{\text{conv}} \) is the heat flux by convection, \( h \) is the heat transfer coefficient, \( A \) is the area, \( T_{\text{EXP}} \) is the experimental temperature of water, \( Q \) is the heat source, \( \rho \) is the density and \( C_p \) is the specific heat capacity at constant pressure.

To conduct the thermal model CPVT resorted to a finite element program, in which an extra fine mesh was used to determine in greater detail the different temperatures that affect the entire receiver. The study of the CPVT collector model resulted in Fig. 11, which contains 23595 elements.
In order to demonstrate the importance of the cooling fluid in CPVT, were performed thermal simulations. With these simulations are intended to compare the different electrical efficiency and the importance of cooling.

To compare different simulations of water flows all climacteric aspects (wind, ambient temperature and solar radiation) and physical aspects (dimensions, material characteristics) must be equal. The only difference being only the water circulation in the water channels. For the simulation with flow was imposed a flow in liters per second, and the simulation without flow, the water flow is zero, i.e. there is water inside the channels but this does not circulate (simulation of stagnation temperature).

A. Receiver with cooling

In Fig. 12, the water flowing in the channels between the layers of photovoltaic cells reached 28 °C. However, the water temperature values are lower than the temperatures registered over the silicone layers. It is with this cooling technique which can reduce the excessive temperature which affects the performance of photovoltaic cells and at the same time remove heat from the receiver through the water flow.

Comparing the maximum temperature of the two simulations, it is observed that there is a difference of more than 100 °C. The advantages of the use of water flows into the receiver are notorious in terms of temperatures that are obtained at the photovoltaic cells.

C. Electric efficiency of CPVT

The reflector has a key role in the capturing and distribution of solar radiation to the back receiver. A bad distribution of solar radiation has a high impact on the efficiency of photovoltaic cells. Once the photovoltaic cells become shaded creates a resistance to the generated electron flow, resulting in hot spots. For the case where the solar radiation is too concentrated, the temperature will also be higher, causing a lower efficiency in the photovoltaic cells. For the best efficiency, the reflector should distribute the incident radiation as best as possible while concentrating it at the receiver without losses.

Analyzing the CPVT solar incidence of Solarus AB with 18 sections, a very accurate geometry, as shown in Fig. 14. The analysis was performed to Lisbon and Gävle, where temperatures and solar radiation are different.

After the distribution of solar radiation that focuses in the reflector and after the back receiver, was simulated the temperature distribution in the different regions of the back receiver to finally can get the efficiency of photovoltaic cells. The values used in the current and voltage of the photovoltaic cells in standard condition for testing are: reference short-circuit current, \( I_{sc\_ref} = 3.53 \) A; reference open circuit voltage, \( V_{oc\_ref} = 24.03 \) V; reference maximum power voltage, \( V_{mp\_ref} = 19.49 \) V; reference maximum power current, \( I_{mp\_ref} = 3.22 \) A.

\(^1\) By kind permission of Catarina Barata.
Knowing the distribution of solar radiation and the different temperatures after the simulation, it is possible obtain the different efficiencies ($\eta_{PV}$) of photovoltaic cells by the maximum power voltage, the maximum power current, the solar radiation and the area of photovoltaic cells ($A_{cell}$) by (10)

$$\eta_{PV} = \frac{P}{G \times A_{cell}} = \frac{V_{mp} \times I_{mp}}{G \times A_{cell}}$$ (10)

where $V_{mp}$ is obtained through iterations by (11) and $I_{mp}$ is obtained by (12) that utilize the values of voltage determined by (11) [3], [8].

$$V_{mp}^{k+1} = m \cdot V_T \cdot \ln \left( \frac{I_{sc}}{I_0} \left( \frac{V_{mp}^k}{m \cdot V_T} + 1 \right) \right)$$ (11)

$$I_{mp} = I_{sc} - I_0 \left( e^{\frac{V_{mp}}{m \cdot V_T}} - 1 \right)$$ (12)

Comparing the optimal case (solar radiation fully distributed by the reflector) with the real case for the two regions presented in Fig. 15 and 16.

In ideal cases all simulated monthly electric efficiencies are higher, for Portugal and for Sweden. In January and November for both cases exist some regions in shadow and the electrical efficiency drops about 2.5% in relation to the annual average.

With a better distribution of solar radiation at the receiver the temperatures distribution becomes more uniform too. The elimination of hot spots caused by shading and/or excessive solar concentration results in high and uniform electric efficiencies over the year for Portugal and Sweden.

V. 3D RESULTS OF RECEIVER

After the 2D simulations with a cross-section of the receiver, it proceeded to 3D simulations, which provide data from temperature variation of water channels, temperature variation of photovoltaic cells, temperature variation over the silicone layer and the temperature variation since the top receiver to the back receiver. Only 1 of 2 receivers existing in collector will be analyzed once both are equal.

A. Initial conditions of simulations

For the new simulation in 3D it was created a new object in finite element program and a new and more complex mesh. In comparison to the 2D model, the model in 3D has much more elements (552628 elements) what takes a lot of time to run one simulation.

Some normalizations about the collector and the surrounding environment have been assumed to perform this study about the PVT receiver, such as:

1. A solar irradiance of 900 W/m² with an ambient temperature of 305 K (summer values for Portugal);
2. The reflector has a concentration factor of 1.7 and all irradiance is distributed over the receiver uniformly;
3. The wind speed is null;
4. There is no dust or any other object to make shading on the receiver;
5. The heat transfer coefficient from the receiver to the surrounding environment is 6 W/(m²·K);
6. The water circuit is open i.e., is placed an initial temperature when the water enters the receiver and that due the surrounding conditions simulates an outlet water temperature;
7. The water flows with a constant pressure and velocity over the receiver.

The finite element program performed the simulations in stationary mode and the physical models used were the heat transfer in solids and the heat transfer in liquids.

B. Simulation without shading

With the normalizations at the receiver and the surrounding environment was performed a simulation illustrated in Fig. 17 to better understand the temperature variations in the upper and lower layers of receiver. All dimensions considered in the simulations are in millimeters, the range of temperature are in degrees Celsius and for this case the water flow is 2 l/min i.e., the velocity of water is 0.867 m/s.
To be more rigorous and better understand how to varies the temperatures on the receiver was performed the charts represented in Fig. 18 and 19.

In Fig. 18 are represented the temperature variations over the receiver, in back receiver (continuous line) and top receiver (dashed line) i.e., from the location of the inlet water to the outlet water.

In Fig. 19 are illustrated the temperature variations from the top of the receiver to the bottom, at the inlet water site (dashed line) and the outlet water site (continuous line). The inlet water has a constant temperature, but when it reaches the silicone layer the temperature changes. The variation of temperature in the outlet water verifies from the point 4.5 mm to 8 mm.

Illustrating the simulation has in Fig. 20, the shaded area (region 1), the area with a lower irradiance (region 2), the area of irradiance with a concentration factor of 1.7 (region 3), and finally the area with direct irradiance in the top receiver (region 4).

All other variables, such as the wind, the velocity of the fluid, etc., remained constant compared with the simulation without shading. However, the influence of the distribution of the irradiance in the bottom of the receiver is significant, changing the linear temperature variation which has been verify in Fig. 17.

As in the previous simulation direct irradiance not changed (G=900 W/m²). The part 1 of receiver is shaded (irradiance G=0 W/m²), the part 2 of receiver had only a percentage direct irradiance (irradiance G=360 W/m²), the part 3 of receiver is under concentration (irradiance G=1530 W/m²), making it the part with higher temperature in receiver.

Analyzing the temperature in the silicon over the receiver illustrated in Fig. 21, can be seen a large difference between this figure and Fig. 18. Since there is a shaded part in receiver this part will not heat like the others parts. However, such photovoltaic cells are shaded could create hot spots at the receiver, but the existence of bypass diodes avoids this problem. Thus, the decrease of output power of the photovoltaic cells is inevitable and the set of photovoltaic cells that are shaded produces a null output. The parts receiving a lower irradiance produces electrical energy, however, since the irradiance is significantly lower the efficiency is not as high as desired.

C. Simulation with shading

After the simulation with a perfect distribution of the irradiance in the back receiver, it proceeded to a simulation with a shaded part, a part with lower irradiance in relation to direct irradiance and other with concentrated solar radiation. This simulation with shading not only tries to simulate the non-uniformity of the solar radiation from the concentrator as well as the shading effect of the support structure around the CPVT [4].

The Figure 22 shows the variations of the transversal temperature (from the top to the back receiver) for entry and exit of the receiver. There is a loss of temperature in the back receiver output (shaded site, 9.5 to 12.5 mm).
The temperature variation of the output water channel, it is illustrated in Fig. 23 where it finds a positive variation of the temperature from the ellipse center to border. With this, we can say that there is a laminar flow of the fluid.

The main fluid flow is the laminar and the turbulent. The laminar flow is characterized by low agitation of the layers fluid. In order to define the type of flow it is necessary to calculate the dimensionless Reynolds number (Re) which is given by

\[ Re = \frac{\rho \cdot u^2}{\mu \cdot L} \frac{u \cdot L}{v} \]  

(13)

Where: \( \rho \) = density (kg/m\(^3\)); \( u \) = Velocity of water in channel (m/s); \( \mu \) = Dynamic viscosity (Ns/m\(^2\)); \( L \) = Channel length (m); \( v \) = \( \mu / \rho \) = Kinematic viscosity (m\(^2\)/s).

Determining the value of Reynolds number can be determined the type of flow even without having done any simulation or experience. Fluid water circulating in channels/pipes has the following flows [16]:
- Laminar flow – \( Re < 2300 \)
- Transitional flow – \( 2300 < Re < 4000 \)
- Turbulent flow – \( Re > 4000 \).

D. Simulation Portugal versus Sweden

In order to compare the CPVT performance of the Solarus AB to different locations, two simulations were performed for 2 different locations, Sweden and Portugal. These countries have temperatures, radiations and solar altitudes very different. For a more real simulation was considered the existence of shading in back receiver caused by the reflector and the support structure.

Depending on the altitude of the sun the support structure causes more or less shading in the back receiver. In Fig. 24, is demonstrated as the shading of photovoltaic cells is caused by support structure through the movement of the sun. I.e. for low solar altitudes structure causes a stronger shading in the receiver and as the sun increases its solar altitude shading decreases [4].

The simulation used values for the month of June for Portugal and Sweden. Portugal have an ambient temperature of 30\(^\circ\)C and a direct irradiance of 767 W/m\(^2\). Sweden have an ambient temperature of 20\(^\circ\)C and a direct irradiance of 491 W/m\(^2\) [18].

The distribution of solar radiation is effected by the aluminum reflector with a high reflection factor. In order to facilitate and to determine more precisely the calculations was discretized the back receiver in 6 sections with less complexity. Thus, were obtained the irradiances for Portugal and for Sweden with a distribution by 6 sections described in Table 2.

<table>
<thead>
<tr>
<th>Section of back receiver</th>
<th>Irradiances in Portugal [W/m(^2)]</th>
<th>Irradiances in Sweden [W/m(^2)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>391.56</td>
<td>2041.11</td>
</tr>
<tr>
<td>2</td>
<td>1686.12</td>
<td>1058.92</td>
</tr>
<tr>
<td>3</td>
<td>2037.73</td>
<td>828.72</td>
</tr>
<tr>
<td>4</td>
<td>1790.10</td>
<td>332.51</td>
</tr>
<tr>
<td>5</td>
<td>1510.32</td>
<td>414.36</td>
</tr>
<tr>
<td>6</td>
<td>103.88</td>
<td>1588.58</td>
</tr>
</tbody>
</table>

Using a slope of zero degrees in CPVT and a fixed flow of 2 l/min for both simulations were obtained Fig. 25 and 26 for Sweden and Portugal respectively, where highlights the back receivers.

\(^2\) Values assigned by permission of Catarina Barata.
Once the 2 countries are at different latitudes, and the inclination of the CPVT is the same (zero degrees) the distribution of solar radiation is different, resulting in different temperature distributions over the receiver. For the simulation of Sweden an average temperature was obtained in the back receiver surface of 34.10°C and an electric efficiency of 19.14% whereas for Portugal the average temperature in the back receiver surface was 37.57°C and the electric efficiency was 18.86%.

Once the CPVT, more specifically the reflector is designed for latitudes equal to Sweden, this will give better results at these latitudes. Although there is a higher irradiance in Portugal relatively to Sweden, does not mean that the photovoltaic cells reach higher efficiencies. Thus, to obtain the maximum efficiency of CPVT is necessary to adapt the collector slope depending on its location, since the production of a reflector for each latitude is economically expensive. The control of water flow to optimize the temperature of photovoltaic cells is also an important factor in the overall efficiency.

**E. Electric performance in function of flux**

In order to take full advantage of the incident solar energy in CPVT, is required a control of the water flow in the receiver in order to cooling it. If there were not this water flow, the temperature receiver reached high values (stagnation temperature) as already proved in chapter IV-B and illustrated in three dimensions in Fig. 27, where the receiver reaches temperatures of the order of 190°C.

Since it becomes important to use a coolant must also be important quantify the best water flow values. Increasing the water flow rate increases the amount of power on the water pump, however, an increased water flow is obtained by removing more heat from the receiver, reducing the temperature of the photovoltaic cells and increasing their efficiency.

The Fig. 28 was obtained for Portugal values used in chapter V-D and associates electrical efficiency to the cooling fluid flow in liters per minute. It is possible highlight 3 areas of high importance. The first region is situated near the flow values from zero liters per minute, this region expresses the necessity of a cooling fluid even if it is a low water flow. The second region is from 0.5 l/min to 2 l/min water flows, this region reveals the best flow for this case, since it is able to obtain almost the maximum possible electrical efficiency and at the same time using low values of water flow, reducing electricity cost. The third region is registered from 4 l/min, this is not beneficial, since they require high flow rates and obtain small positive variations (comparing to the region 2) in electrical efficiency.

Since there is current technology that can vary the water flow to optimize the temperature of the photovoltaic cells and the temperature of the water that crossing the receiver, so it is necessary determine the minimum working flow that does not damage any material, in particular photovoltaic cells (equipment more expensive and more sensitive of CPVT).

The maximum work temperature of monocrystalline photovoltaic cells is around 85°C, so the least flow rate for Portugal is 0.025 l/min. However, wind and other factors can influence the temperature of the receiver, thus using a 20%
safety margin to never reach the maximum work temperature of the photovoltaic cells has a threshold for the water flow of 0.03 l/min [19], [20].

VI. CONCLUSIONS

The environmental influences determine completely all the performance of a hybrid solar collector. Thus, studies and adaptation to the environment are essential to be able to take advantage to solar energy with the best efficiencies.

In relation to the shapes of the water channels, they were tested 4 different forms, all having the same area: square, rectangle, circle and ellipse. Of these forms, the ellipse that was highlighted in a general way. It was the shape that show better uniformity of fluid temperature and had a greater contact area, i.e., it has a larger area that facilitates the transfer of heat.

In the simulation in 3 dimensions the main goal was to visualize the temperature variations over and across the receiver. To a simulation with uniform distributed solar radiation, temperature values are uniformly increased as water moves through the receiver. However, the temperature distribution is very different in the cases of shading and/or non-uniform solar radiation. With the different solar radiations in the lower receiver the performance of photovoltaic cells is completely modified. If there is no such irradiance efficiency decreases as previously shown, and for cases in which there is no irradiance (G=0 W/m²), the bypass diodes enter into conduction and all the strings that are affected by shading stop producing, decreasing the output power of the entire receiver.

The coolant is a vital component in this CPVT, however, it is necessary optimize the fluid flow for the best performance. For the case of Portugal, under test conditions described above, the flow should be between 0.5 l/min and 2 l/min and never should enable flows below 0.03 l/min once the photovoltaic cells reached their maximum working temperature (85 ºC).

REFERENCES