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Ray Tracing Modelling of an Asymmetric Concentrating PVT

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ABSTRACT

Photovoltaic thermal hybrid collectors (PVT) are able to produce both heat and electricity from the same area. The studied PVT collector is an asymmetric Compound Parabolic Collector (CPC). The reflector design belongs to the MaReCo (Maximum Reflector Collector) family. The main advantages of this collector design are the reduction of material cost due to concentration and the increase cell efficiency by reducing its working temperature through active cooling.

Tonatiuh is a Monte Carlo ray tracing software that is able to simulate the interaction between the sunlight and a concentrating collector. A script was written to repeat the process and simulate the sun's movement over the year. The data was processed using Matlab and the annual received radiation on both receiver sides was obtained.

A collector model was drawn in Tonatiuh and its material properties were described. Incremental changes were used both to validate the models results and to assess the impact of each change. The first model had only the reflector geometry and the receiver with perfect properties while the final model had a very accurate description of the studied collector and its properties. The final model performed 21% worse than the initial with ideal properties. Additionally, the homogeneity of the solar radiation on the receiver was analyzed and the 3D effective solar radiation graph was plotted. Finally, it was found that over the year, the receiver under concentration produces 13% more energy than the flat side of the receiver, at the best tilt, for both 0º and 60º of latitudes.

Keywords: Asymmetric CPC PVT; Ray tracing; Tonatiuh simulation; Tilt influence; MaReCo; Homogeneity

1. Introduction

1.1. PVT solar collectors

The energy sector is in a state of evolution as conventional energy sources are challenged by the unquestionable need for new clean and sustainable energy sources that solve not only the global energy demand problem in the long term but also the pressing problem of climate change. Renewable energies respond to this increasing demand. Photovoltaic modules are experiencing a steady reduction in their production costs. It is needed that this trend continues. One way of reducing production costs is by using concentrators to increase the output of the photovoltaic cell. Another way, is to increase cell efficiency by reducing its working temperature through active cooling. These are the two of the main corner stones for concentrating photovoltaic thermal (PVT) collectors.

PVT solar collectors are able to produce both heat and electricity. According to Gomes et al (2013), the main benefits of PVT collectors when compared to photovoltaic (PV) and standard thermal solar collectors are listed below:

- The possibility to increase cell efficiency by reducing the cell operational temperature when the hot water is extracted at low temperatures. In a PVT collector, it is very important that the receiver can transfer enough energy to cool down the cells both efficiently and homogeneously.
- The production of one unit of PVT uses fewer raw materials than an equivalent area of thermal and photovoltaic panels. This is expected to enable a lower production cost per kWh of annual produced heat and electricity.
- Reduction of the installation area, which enables the deployment of more installed capacity per roof area and is also expected to lower the installation costs.

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The market for PVT collectors should be mainly the low temperature segment (under 100ºC). This is mainly due to two factors:

- On the electrical part, PV solar cells decrease their yield with the increase of operational temperature (Wenham et al, 2007).
- On the thermal part, PVT collectors cannot have the absorption area fully covered with selective surface which leads to poor thermal performance at higher temperatures.

In fact, both the electrical and thermal output from PVT collectors will be higher at lower operating temperatures.

1.2. Concentration in PVT solar collectors

The PVT concept can be combined with concentration in order to further reduce the usage of both PV cells and thermal absorber material. The goal is to reduce collector costs by reducing the amount of expensive components utilized (solar cells, receiver and/or selective surface). However, concentration carries the penalty of extra reflection losses on the reflector (normally ranging from 3% to 20% per bounce on the reflector).

Concentrating collectors can be tracking or stationary (non-tracking). Stationary collectors have an output penalty by having a lower Incident Angle Modifier (IAM) profile when compared to non-concentrating panels. Stationary collectors normally have small concentration factors (up to 5). Tracking collectors, on the other hand, can reach very high concentration factors and are able to receive more solar radiation over the year than non-tracking collectors but have the drawback a more complex and costly installation. Moreover, although not technically impossible, it is very rare to see tracking collectors on sloped roofs. This way, it should be mentioned that tracking collectors have a smaller market that conventional collectors.

Additionally, concentration also allows reaching higher temperatures which is useful for thermal collectors but does not constitute an advantage for PVT's since the PV cells operate at higher efficiencies under lower temperatures. In fact, this point can become a drawback since concentration normally raises the stagnation temperatures of the collector. Higher stagnation temperatures imply that either the collector is built with more resistant materials or the tracker is programmed to move away from the sun in the event of a malfunction such as a pump breaking.

In conclusion, stationary collectors will yield less energy per aperture area but they will also have a lower cost. Under the right conditions, the use of concentration is expected to enable a reduction in the price of the produced kWh. PVT should benefit more from concentration than standard thermal and PV panels because a PVT receiver is normally more expensive since it has both PV cells and the thermal absorber.

1.3. The impact of shading in PV panels and solar thermal collectors

According to Gomes et al (2013), shading has a considerably different impact on PV panels than on thermal collectors. In PV modules, the solar cells are often connected in series. This way, one fully shaded solar cell will reduce the output of the whole string to zero. Bypass diodes can be used to mitigate this effect by allowing current to flow in a different path at the expense of a minor fraction of the total power. However, the introduction of diodes increases both assembly time and material cost. On the other hand, diodes also prevent hotspots that can destroy PV panels.

In thermal collectors, the decrease in power produced due to shading is approximately proportional to the shaded area. Thus, shading clearly has a much bigger impact on PV panels than thermal collectors.

According to Gomes et al (2010), in concentrating collectors, an additional aspect to consider is that non uniform concentration is considerably more critical for PV panels than for solar thermal. This is due to the fact that non uniform radiation in one cell increases the series resistance losses. Non uniform radiation intensity in a string with series connected cells has even a larger negative impact. Non-uniform concentration is present in all compound parabolic concentrators (CPC).

2. The Model

2.1. Tonatiuh: A Monte Carlo ray tracer software

A Monte Carlo ray tracer software is a powerful tool in the design and analysis of solar concentrating systems. The Monte Carlo method is using the principles of geometrical optics as a statistical method to get a complete and statistically viable analysis of an optical system. All simulations detailed in this paper were performed using the software Tonatiuh which is an open-source software especially developed for optical simulation of solar concentrating systems. The rays are generated in a light source that simulates the sun and then these ray's intersections with system surfaces are calculated. The sun light is defined by the sun position, i.e. the elevation and the azimuth. These two parameters can also be calculated as a function of the day, the hour, the latitude and the longitude.

The main advantage of Tonatiuh resides in the possibility to write a script for parametrical simulations. This script allows launching several simulations and saving the results. For example, with a script, it is easy to simulate an entire year by using a few loops in the script. The disadvantage is that Tonatiuh is not able to do post-processing analysis of the results. Once a simulation is done the Tonatiuh software exports the results either as binary file (.dat) or as SqL database file (.sql). To extract these data Matlab can be used since it allows sorting and analyzing large amount of values rapidly.

2.2. Description of the studied collector

Figure 1 shows the studied PVT design, which is patented by a Swedish small scale solar manufacturer.
The solar radiation is concentrated onto an aluminum thermal absorber. A highly transparent and electrically insulating silicone is used to laminate the PV cells to the thermal absorber on both the upper and lower sides of the absorber. The upper side works practically as a standard PV module with very little concentration, while the lower side receives the concentrated solar radiation from the compound reflector (parabolic and circular). The collector also has glazed protection and a supporting structure made of plastic and metal.
The concentration factor of the studied PVT collector is low. At peak sun, the absorber side with the concentration is exposed to about 1.8 suns while the upper or flat side has no concentration. This gives 1.4 of average concentration for the whole collector. This way, the PV cells on the collector can reach higher temperatures than standard PV panels. Since mono-crystalline solar cells exhibit a reduction in power output at elevated temperatures (Wenham et al, 2007), cooling is necessary to maintain the electrical efficiency. Cooling is accomplished by running a fluid (normally water with or without glycol) through the channels of the thermal absorber. Thus, the PVT collector produces electricity and heat from the same area.
The reflector geometry of the studied PVT is shown in figure 1b. This reflector geometry is originating from a family of stationary reflector designs called Maximum Reflector Concentration (MaReCo) which is widely described by Karlsson et al (2000), Adsten et al (2004) and Diwan (2013). For the studied PVT, the optical axis for the reflector geometry is normal to the glass of the collector. This defines the acceptance angle; if the radiation falls outside this angle, the reflector does not redirect the incoming beam radiation to the lower side of the absorber and the optical efficiency of the collector is greatly reduced. The optics of the studied collector is further investigated by Bernardo et al (2012). This way, the optical efficiency of the collector changes throughout the year depending on the projected solar altitude. The tilt of the collector determines the amount of total annual irradiation kept within the acceptance interval (Bernardo et al, 2011a, 2011b).

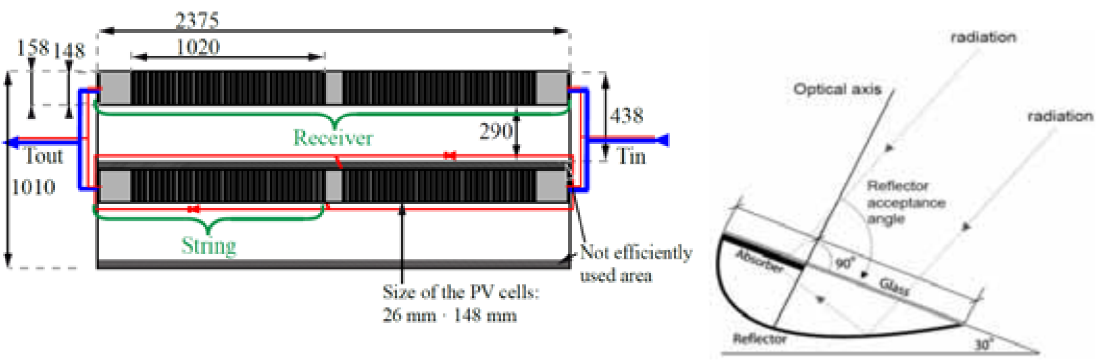

Fig. 1: a) Schematic view (from the top) with the water connection in blue and electrical in red; b) Reflector geometry of the studied concentrating PVT collector

Figure 1a shows the water connections for extracting the heat (in blue) and the electrical arrangements of the solar cells (in red) in the PVT collector, which has 2 troughs. Since the design of both troughs is exactly the same, only one trough is simulated and investigated. Figure 1a shows the collector plan view. The lower part of the receiver, i.e. the part that receives concentrated light, has exactly the same hydraulic and electrical configuration as the upper. The electrical part of each PVT collector consists of eight parallel-connected strings, each with 38 series-connected cells. The total number of PV cells is 152 cells per trough.

The solar collector manufacturer buys standard solar cells with 156mm by 156mm, which are laser cut into pieces of 26mm by 148mm. The objective is to increase the voltage and reduce the current at high irradiation levels and thus avoid any current capability constrains due to the increased concentration. Figure 1a also shows the most relevant dimensions in the collector. Active area (electrical or thermal) was defined as the area where the incident radiation can contribute to electricity or thermal production. The absorption area of the topside of the receiver (also called flat) is equal to 0.363m^2, the aperture area bottom side (also called concentrated) of the receiver is 0,670 m^2 while the aperture area of one through is equal to 1,033 m^2. The collectors' total area is 2,3 m^2.

2.3. Properties of the materials used in the PVT

The simulated solar collector uses reflector material made of anodized aluminum with a total solar reflectance of 95% (measured according to norm ASTM891-87) according Alanod, 2013. The glass cover of the collector is made of low iron glass with solar transmittance of 95% at normal incidence angle and the refractive index of 1.52 (measured according to the norm ISO9050 for solar thermal) according SunArc, 2013. The solar transmittance of the plastic gables is 91% and the refractive index is 1.492. Each material has been defined with a slope error of 2mrad (macroscopic defects). It was assumed that for the receivers the light is totally absorbed.

Tab. 1: Summary of the optical properties

Optical elements	Optical Properties
Reflector	Reflectance = 95%
Glass	Transmittance = 95% Refractive index = 1.52
Plastic gables	Transmittance = 91% Refractive index = 1.492

2.4. Model description and assumptions

The collector described in figure 1 was drawn and its material properties were described in Tonatiuh in full detail. Simulations were conducted using Tonatiuh. Each simulation consists of 10,000 solar rays that are sent in the direction of the collector and whose intersection points are calculated, in order to obtain the total power from the photons that is reaching each side of the receiver.

In order to enable repeating the process many times, a script has been written to launch several simulations and to save the results. Matlab was then used to extract the results exported from Tonatiuh in a binary file (.dat) and to do post-processing analysis of the results. For each yearly simulation, the power is calculated for each hour (i.e. in total 24 simulations per day, 8760 simulations per year) with an accuracy of 10,000 rays.

The sun shape follows a pillbox distribution, i.e. the solar intensity is the same on each point of the sun's disk, as shown in figure 2. The parameter of this flat distribution is the half-angle width of 4.65mrad. Additionally, the irradiance is always set at 1,000 W/m² and the weather is not considered. Simulations are made for the latitude and longitude of Gävle in Sweden (60,674°N, 17,142°E) and at the equator (0,000°N, 17,142°E).

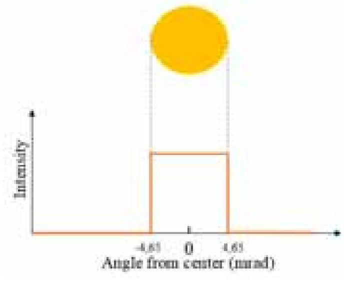

Fig. 2: Illustration of the pillbox sun shape

3. Analysis of Results

3.1. Step by step collector model and the impact of the different elements of the collector and its properties

In order to verify the newly created collector model, the simulation was started with a simplified version of the actual collector design that only featured the reflector design and the absorber. This is illustrated by the left drawing in figure 3, called Ideal.

After, several new collector models were done with small incremental steps in complexity level until reaching a very detailed copy of studied collectors that is described above in figure 1. The final version was called accurate and can be seen on the right side of figure 3. This allowed not only verifying the model used but also to assess the impact of the different incremental steps on an annual received energy basis.

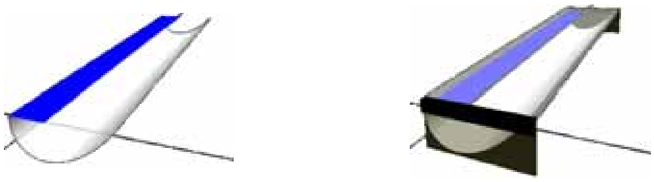

Fig. 3: The modelled solar collector. The initial simple model was called Ideal (on the left) and the complex complete model was called accurate (on the right). The bifacial receiver is drawn in blue while the frame and plastic gables are drawn in black.

Figure 4 shows the impact in the annual received energy of each incremental change. The selected collector tilt was 0°. The shape on the top of figure 3 shows the version that was modelled while the bars below describe the result.

The first shape is the simplest which was called ideal. The changes are then done in a gradual manner. The second shape includes an extension of the parabolic reflector while the third shape includes an extension of the circular reflector. The fourth shape includes the gap between the reflector and the absorber while the firth includes the thickness of the absorber. The sixth shape includes the collector frame and the shading that it causes on the receiver over the year. The seventh shape includes a more accurate representation of the sun rays. For all versions, except for the last, the optical properties of the materials were set as ideal (reflectivity 100%, transmittance 100% and no optical errors). The last version the collector has been simulated with all optical elements present.

Throughout this paper the back and top sides of the receiver are constantly compared. For simplicity and clarity, the bottom side was called concentrated side and the top side was called flat side since it behaves almost like a flat plate. The green line in figure 4 shows the received energy of both receivers and the numbers above show the variation to the shape called Ideal.

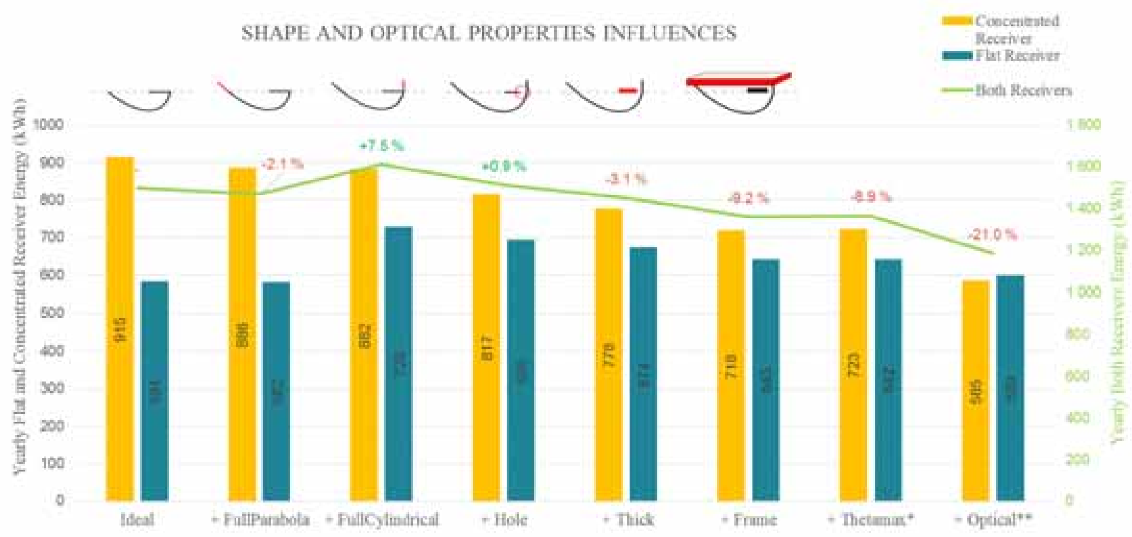

Fig. 4: Results of the presence of the optical elements and properties on the yearly energy for a tilt of 0° in Gävle, Sweden. (*This version corresponds to a sun shape is a pillbox distribution with $\theta_{max} = 4.56mrad$. **All the optical properties are taken into consideration, as well as the half-angle width of 4.65mrad for the sun.)

It was found that the small parabolic reflective extension leads to a small decrease (-2.1%) due to shading effects on the concentrated side of the receiver when the sun is low. This does not affect the flat receiver.

However, the same increase in collector thickness also gives space for the extension of the cylindrical reflector which allows the flat side of receiver to increase its yearly total power (+21%) and so the total power of the whole collector. Overall having the both extensions leads to an increase in power under these conditions (7.5%). The space between the reflector and the receiver is big enough to affect the total power received on each side, leading to a significant decrease (-6.1%) compared to the previous version. The firth change is adding the thickness of the absorber, which decreases the total power received in both surfaces in the same way. This decrease happens because some light hits the sides of the receiver and that light is not factored in by Tonatiuh.

Adding the collector frame had a smaller impact that it was initially foreseen. The total power received on both receivers was reduced comparing to the previous model. The concentrated side is, as expected, more affected by the reduction. It must also be mentioned that adding the frame presents a much larger reduction in the PV than in thermal part due to the series connection as discussed in chapter 1.3. The reduction in electricity production will be converted to heat.

Using a more accurate model of the sun increased slightly the total power received (seventh collector model). However, the biggest influence came when, on the last model, the optical properties of material were added. As expected, the concentrated side of the absorber is way much affected by these properties due to the reflectivity of the anodized aluminum and the fact that most of the time rays hit the reflector more than one time. The final difference between the first and last model is -21.0%.

3.2. Influence of the tilt

The final version of the collector model (named accurate) was then simulated for several tilt angles from 0° to 60°. The annual energy received was obtained and a power ratio power was establish as defined by equation (1) below:

$$\text{Ratio power} = \frac{\text{Energy}_{\text{Concentrated receiver}}\ [\text{kWh/year}]}{\text{Energy}_{\text{both receivers}}\ [\text{kWh/year}]} \qquad \text{(eq. 1)}$$

Whenever this ratio is above 50%, it means that the concentrated receiver is performing better than the flat receiver. Figure 5 shows the yearly energy received for each side of the receiver and a ratio power which is defined by equation (1).

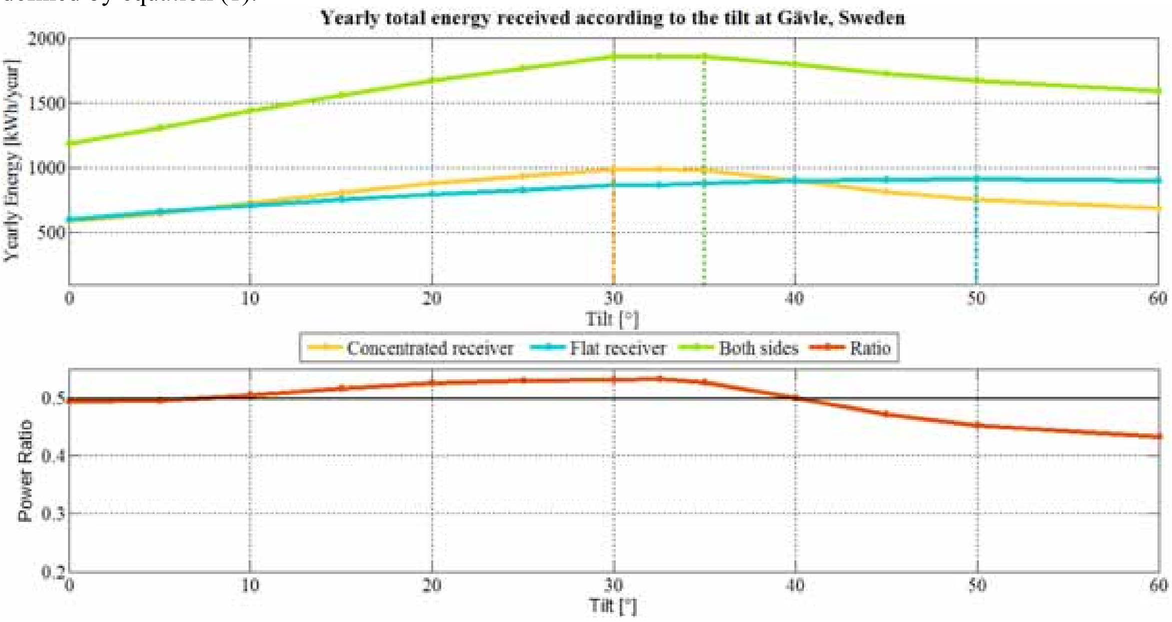

Fig. 5: Influence of the tilt on the yearly energy received for each side of the receiver, in Gävle, Sweden

The most important observation from figure 5 is that on an annual basis, the total energy received by the concentrated side of the receiver is only 13% above the front side, even for the best tilt for the concentrated side.

As expected, tilting the collector leads to a considerable increase on the total energy received on the receiver. Changing from a tilt of 0º to 35º, increases the power of both sides to 56% compared to 0° tilt. Regarding the tilt that allows reaching the best performances, the two sides of the bifacial receiver behave differently: 30° for the concentrated side while the flat (or top) side performs best at 50°. The tilt that maximizes the annual received solar radiation for the whole receiver is 35º. This is because the concentrated side is much more sensitive to the tilt variation than the flat side.

The ratio shows that between the tilts of 10° and 40°, the concentrated side receives more energy from the sun than the flat receiver. At tilts higher than 35°, the daily average power of the concentrated side starts to show large reductions during the summer days in relation to what would be expected. This effect is clearly shown in figure 6. Indeed, a more detailed observation, we were able to see that the concentrated side receives sunlight only during a fraction of the day which greatly affects the daily average power in summer. For example, on the summer solstice with a tilt of 30º, the concentrated receiver sees sunlight between 9AM and 15PM when the length of the day is 19h. This happens because of the reflector acceptance angle, as described in figure 1b.

Figure 6 below shows both the daily maximum and average power that is received in each side of the receiver. At tilt 30º, the average power of the concentrated is already showing the cut-off of the collector around the summer solstice. At a tilt of 45º, this cut-off is even more evident with the concentrated side of the receiver producing any power during the summer solstice due to the acceptance angle of the reflector geometry.

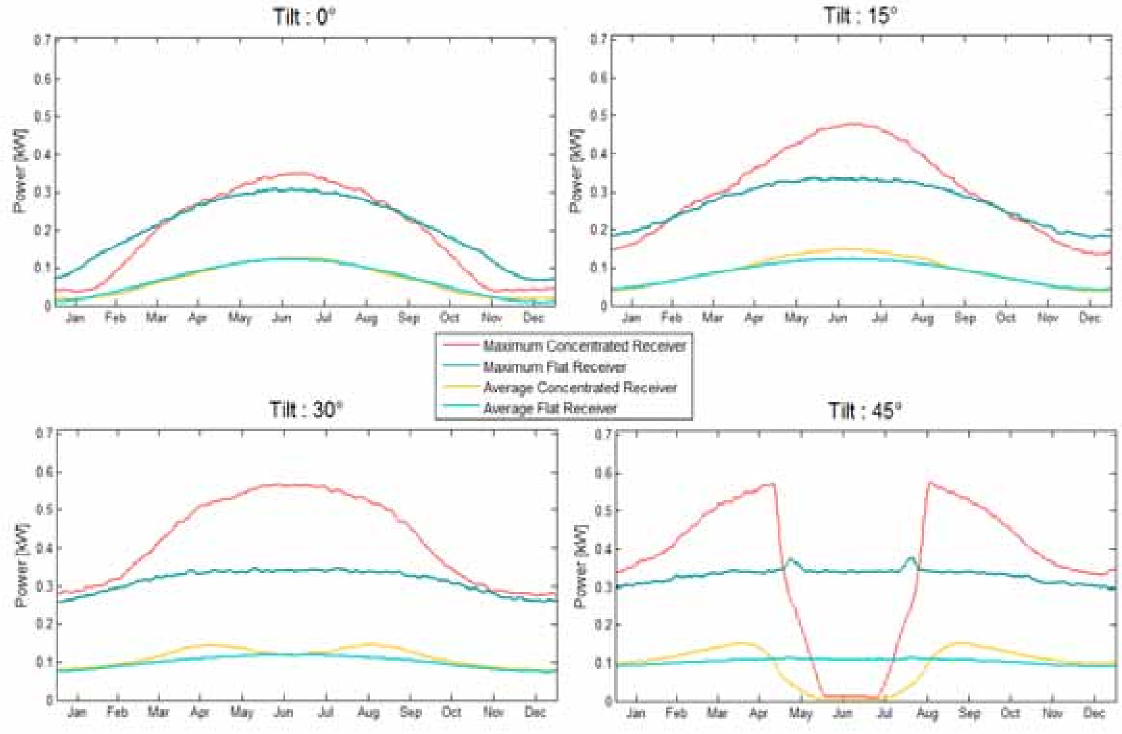

Fig. 6: Daily maximum and average power received on each receiver side

Figure 7 below is showing the same as figure 5 but for the equator. On an annual basis, the total energy received by the concentrated side of the receiver is only 13% above the front side, just like for latitude 60º. One of the reasons for this is that in summer at 60° of latitude, despite the fact that the sun light lasts for 20hours, the collector can only see a maximum 12hours because during the other 8 others hours the sun is behind the collector. It is important to note that working with this reflector geometry at low latitudes will imply that the concentrated side of the receiver will not accept a large part of the incoming solar radiation either during summer or winter.

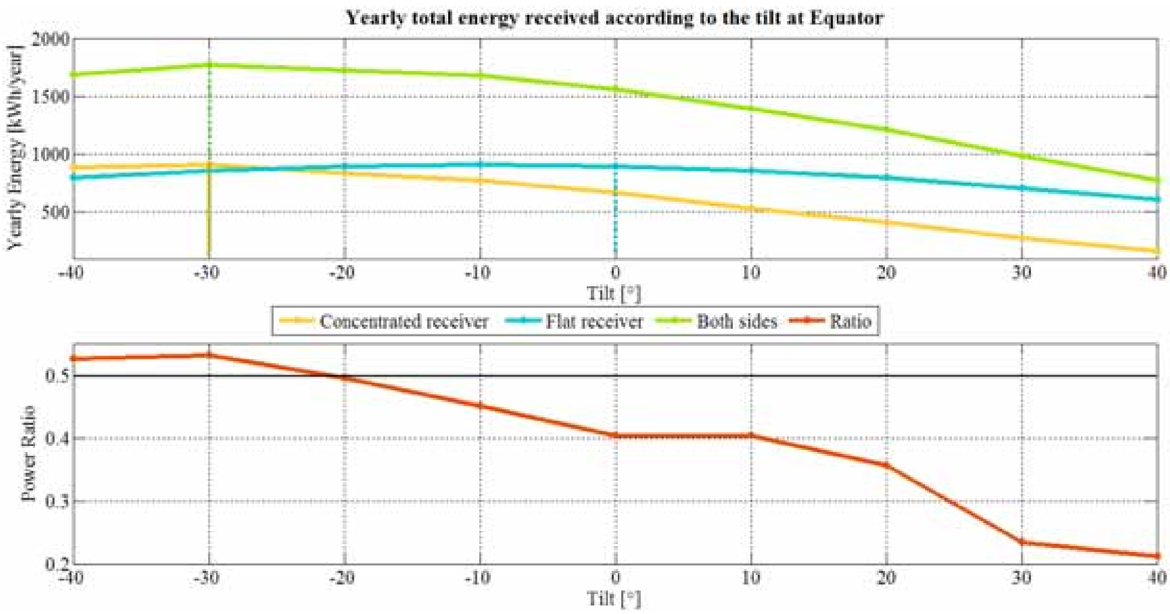

Fig. 7: Influence of the tilt on the yearly energy received in each side of the receiver, in Equator

3.3. Flux Homogeneity

As described by Coventry et al (2004), obtaining homogeneous flux intensity on a receiver and on solar cells can improve the lifespan of the material. Additionally, non-homogenous light can reduce the collector performance, as described by Gomes et al (2013). In this way, it becomes important to characterize how the light is distributed in the receiver.

Figure 8 shows how the sunlight is distributed on each side of the receiver while figure 9 shows the collector model and the sun rays in different times of the year. It must be noted that, in figure 8, the surfaces plotted below are normalized in a 50x50 mesh for an easier reading of the results

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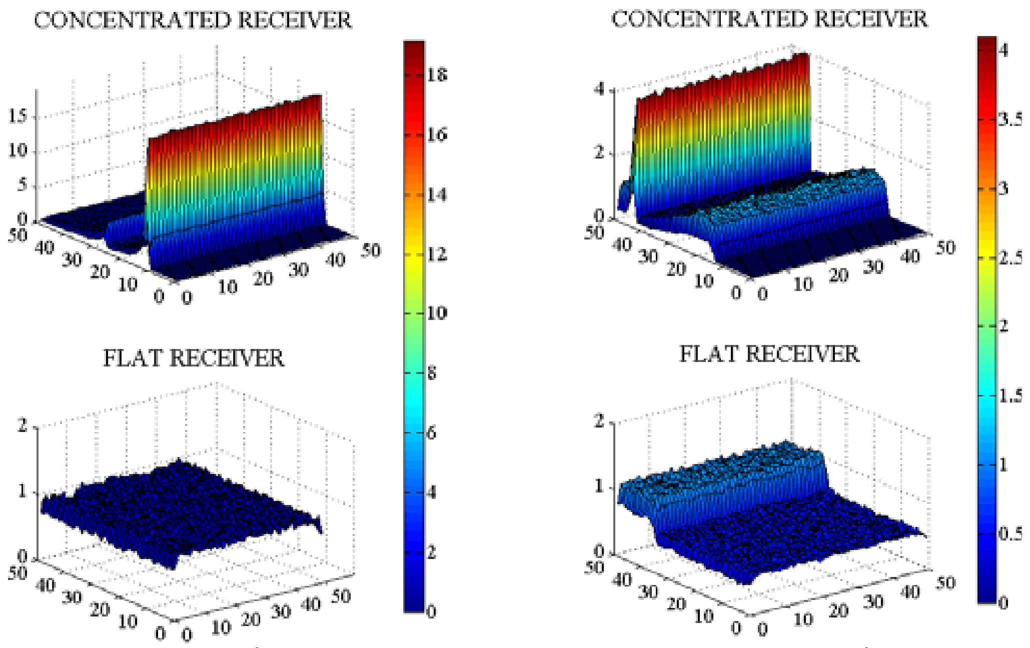
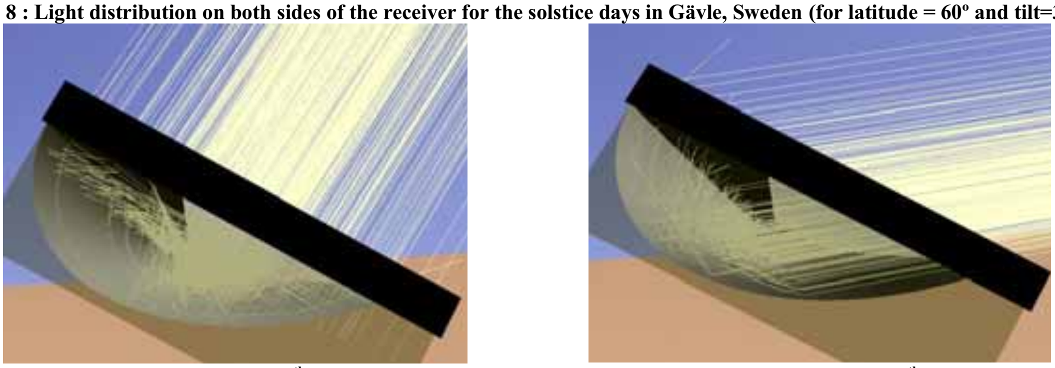


a) June 21th at 12:00 **b) December 21th at 12:00**

Fig. 8 : Light distribution on both sides of the receiver for the solstice days in Gävle, Sweden (for latitude = 60º and tilt=30°)



a) June 2th at 12:00 **b) December 21th at 12:00**

Fig. 9: Illustrations from Tonatiuh showing the solar rays reaching the receiver (for latitude = 60º and tilt=30°)

As expected, the flat side has an almost homogenous solar radiation distribution. Only the small extension of circular reflector creates a small disruption of the homogeneity mainly around the winter solstice, when the sun is low.

On the other hand, the reflector does not distribute light homogeneously on the concentrated side of the receiver. In fact, very high concentration levels can be reached in some parts of the absorber (around the parabola focus). Since the absorber is considerably larger than the focus area, at certain angles, there will be shading on parts of the concentrated receiver. The highest concentration factor that has been simulated for this geometry was 22 for a small duration of the day in a very small percentage of the area of the receiver. This is a very large concentration factor can potentially create lifespan issues and affect power production as detailed below:

- Temperature on the concentrated line raises and thus reduces cells efficiency as a whole;
- High light lead to high current in one of the 3 busbar of the cells which will lead to higher capacity and may be above the total capacity of the busbar;
- Higher solar radiation intensity can, without considering other factors, improve the efficiency of the PV cells causing a higher field factor in the IV curves.

3.4. 3D Effective solar radiation

Performance measurements are generally taken with an exposure to sun perpendicular to the collector plane. However when the suns' rays reach the collector from a different angle, the performance can change considerably. This can be explained by angular effects such as decrease of transmission in the glazing (see Figure 10), decrease of absorption of the receiver at high incidence angles, shading effects caused by collectors' frame, increase width of the solar image on the receiver, etc. (Duffie et al, 1974 and Bernardo et al, 2012)

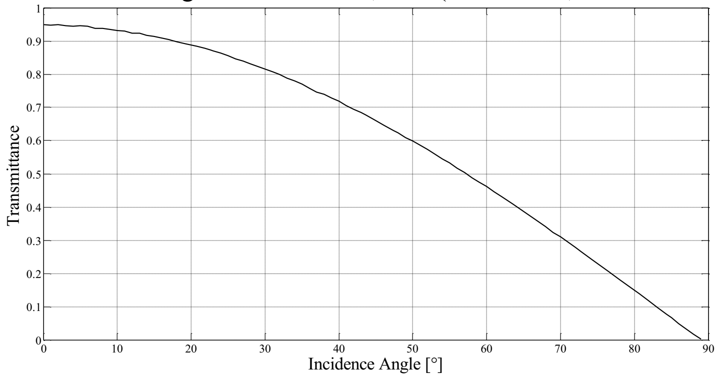


Fig. 10: Transmittance variation of the glass cover (index of refraction of 1.52) according to the incident angle

The PVT collector incident angle is characterized by two angles: Transversal angle (θt) and longitudinal angle (θl), as can be seen in figure below. Figure 11 (a) illustrates the transverse angle and the longitudinal angles of the collector and helps to understand how the Figure 11 (b) is obtained. Figure 11 (b) represents the 3D effective solar radiation which corresponds to the the coefficient of solar power for a given angle. In order to be able to measure this coefficient for different transversal and longitudinal angles, the collector was kept in the same position in one axis, while the sun was moving around the other axis.

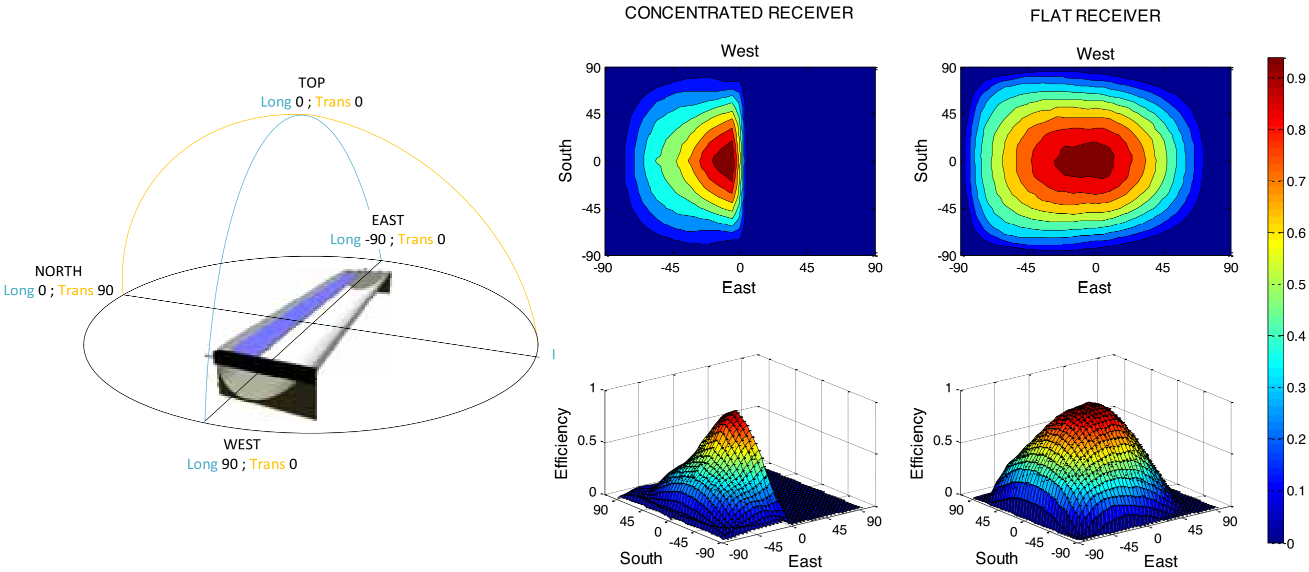


Fig. 11: (a) Representation of the longitudinal and transversal directions. (b) 3D effective solar radiation for the concentrated and flat receiver

The drop in the concentrated receiver around 0º is due to the acceptance angle of the reflector and is the most significant drop in this collector.

Since light is reflected on the cylindrical extension to the flat receiver between -90° to 0° in transversal, the effective solar radiation is not symmetrical. This cylindrical extension also shades a part of the receiver whenever the sun is between 0° and 90° in transversal.

4. Main Conclusions

A numerical model that was created that allows performing simulations which show the annual distribution of the light, in both the flat and the concentrated sides of the receiver. This analysis is fundamental to evaluate the merits of the current reflector geometry. One of the advantages of using simulation is that obtaining with different parameters (localization, tilt …) is both faster and cheaper.

The main conclusions are listed below:

- The optical properties of the components affect significantly the performance of the collector. The concentrated side of the receiver is more affected because it is affected by one more property, the reflective of the reflector;
- Finding the best tilt allows reaching the optimum production;
- The final model performed 21% worse than the initial with ideal properties.
- Large concentration factors were discovered for certain angles on the concentrated side. This can potentially create lifespan issues and affect the power production of the collector.
- The effective 3D solar power performance was characterized. For the concentrated side, a very large cut-off around 0º was found due to the reflectors acceptance angle. The small contribute of the cylindrical extensive has a small impact on the homogeneity,
- Due to the acceptance angle, on an annual basis, the total energy received by the concentrated side of the receiver is only 13% above the flat side, even at the best angle for the concentrated side; this value is the same at latitude 0º or 60º. It is important to note that this value is reached for a perfect weather (assuming that all days are sunny). However, in real conditions the weather is not perfect and clouds exist. The performance of concentrating collectors is more affected by clouds than non-concentrating collectors. This is because beam light is fully reflector concentrated by reflectors but only 1/C of the total light is reflected. If the weather would be taken into account, it is expected that the flat part would produce more energy than the concentrated over the year. However, it is also important to note that there is some concentration on the flat side at least for low angles. This reduced the value of the ratio.

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