Study of the water dynamics into the CPVT system pipes

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November 2017

ABSTRACT

With the rising interest in the renewable energies, due to the rise in performances and the increasing need for more sustainable solution to power our societies, the studies on the topic have becomes more and more relevant with the passing of time. In addition to this the development of the virtual simulation programs are becoming more reliable and therefore are giving new and better tools to design and improve the products and systems. This thesis uses the technologies available at the moment to improve a concentrated photovoltaic-thermal (CPVT) collector produced by the company Solarus AB. After an introduction of the technologies used and a description of the physical phenomena that are involved in the system; this work studies the thermal effects and the temperature distribution in the receiver through the development of a simulation model. The model developed analyses the fluid flow mechanics and the heat transfer aiming to the optimization of the temperature in the PV cells and in the water conduct. Finally the study introduces time-dependent studies; to understand if the stationary conditions ever occurs during the normal functioning of the system and to give the basis for new future works like the analysis of shavings and fluid flow problems.

1) Introduction

Due to the increasing importance of the renewable energy, caused by the even more relevant negative impact that the human activities are having on the planet, the studies on the solar energy are continuously gaining more importance in the development of a sustainable society. The scientific community is so concerned with human development drawbacks that there is an increasing consensus in defining a new geological era called the Anthropocene. In fact, humans are the first specie on the planet able, with its behaviour, to influence the rhythms and the equilibrium of the life of the globe.[1]

Solar energy is crucial in the development of a better future. Its importance as a renewable energy source (RES) lays on several important aspects: the sun´s radiation is converted into heat and is available for heating domestic water or building; solar systems help the reduction of greenhouse gas emissions (GGE); the Sun can be considered as an inexhaustible source of energy; solar systems are an important alternative to fossil fuels, therefore an important tool which helps achiveing energetic independence; solar systems are more competitive on islands and rural areas, speeding up the process of reaching energetic independence.

With the increasing demand for energy all over the world, the solar energy is becoming more relevant for the production of thermal and electric energy.

The photovoltaic panels equiped with concentrators, generally referred as C-PVT collectors, are systems used to produce both thermal and electric energy at the same time: throughout the use of concentrators, the amount of collected energy is increased. The cooling effect introduced with the fluid circulation has a direct effect on the performance of the PV cells. Moreover, it partially recovers the heat produced by the radiation with the increase in the fluid temperature.

The main focuses of the research aim at the reduction of adverse effects in the collector caused by the shadings and the uneven distribution of the temperature. The bi-directional electric-thermal interactions will be important and will certainly lead to complex questions/problems due to the non-linearities involved. This thesis is mainly focused on the improvement of the collector thermal side, nevertheless, it is expected to contribute to future analysis on the interactions between the two systems.

2) Developments and key parameters for the technology

The use of solar energy to produce electricity is well known and its studies have been proceeding for more than a century. In facts, the first product capable of transforming the solar radiation into electricity, using the photoelectric effect discovered by Edmond Becquerel (1820-1891), is dated 1877 and had an efficiency of about 0.5%. From that moment to our days many things have changed and nowadays the efficiencies of the panels available in the market are close to the 22,5%, with some companies, such as Panasonic, that have already proclaimed they reached that levels, even though the panels are not yet available.[2][3][4]

Advantage of CPVT

Higher efficiencies in CPVT technologies, when compared to thermal collectors and PV panels, justify their recent developments. The most important gains are: a higher production of thermal an electric energy using the same technology; a higher efficiency throughout the day thanks to the solar concentration that permits to reach peaks bigger than the 80%;a higher power density (power per unit of area) that permit the reduction of the used area; fewer maintenance costs.

Even if C-PVT collectors present the advantages described above, PVT and CPVT markets are still a small percentage of the photovoltaic and thermal totals. This is also a consequence of an inexistence certification or definition of quality to evaluate test and performances. This situation creates an obstacle to the adoption and the diffusion of the technology in the market. [5][6]

Temperature and irradiance in the different places

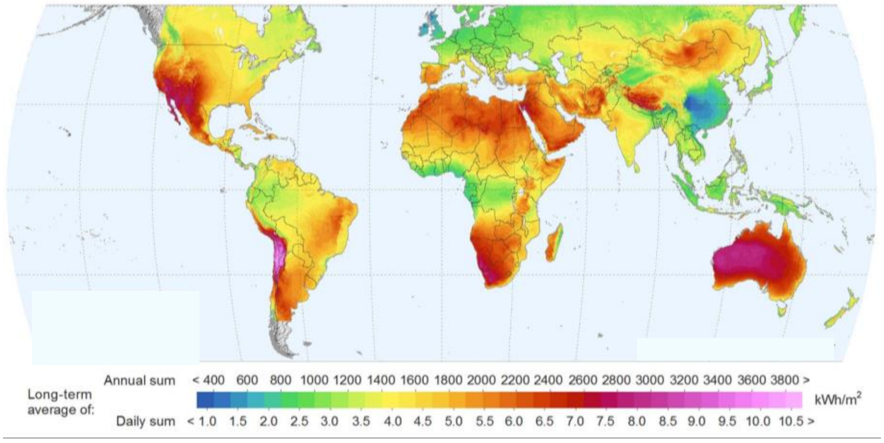

Figure 1 Irradiation in the world [kWh/m2] [7]

Since the solar radiation is one of the more critical parameters to evaluate the harvested energy, it is always necessary to analyse the local characteristics. In Figure 1 above it is shown the global solar irradiation in the world and underlined the differences in the different regions of the world. From the map we can also see how the irradiation does not depend only on the latitude.[7]

3) Physical theory

Heat transfer

To perform the study of the temperature in the CPVT it is necessary to understand the phenomena that govern the heat transfer.

Therefore, in order to describe the formulas that regulate this physical phenomenon we have to start from the analysis of the internal energy of a system that is not stable. In order to do that we will analyze the local heat balance equation in its spatial frame. The equation is reported below:

$$\rho \frac{\delta E}{\delta t} + \rho \boldsymbol{u} \cdot \nabla E + \nabla \cdot (\boldsymbol{q_{cond}} + \boldsymbol{q_r}) = -(\sigma : \boldsymbol{D}) + Q \qquad \text{(eq 1)}$$

Where ρ is the density, *E* is the internal energy, *t* is the time, *u* is the velocity field, q_{cond} is the heat flux by conduction, q_r is the heat flux by radiation, σ:*D* is an expression for the stress power where σ is the Cauchy stress tensor, the term ":" is an operator (that can be written like a:b=$\sum_n \sum_m a_{nm} b_{nm}$) and *Q* is the additional volumetric heat source.

When the heat transfer takes place in a solid in addition to the adjustment of equation 1, shown in the complete thesis, the Fourier's law shown in equation 2 regulate heat transfer.

$$q = -k\nabla T \qquad \text{(eq 2)}$$

where $\vec{q}$ is the local heat flux density, expressed in [W.m^{-2}], k is the material's thermal conductivity, expressed in [W. m^{-1}K^{-1}], and ∇T is the temperature gradient, expressed in [K].

In case of heat transfer in fluid the adjustment of the first equation include the consideration of the viscous dissipation and the work done by pressure as shown in the complete work.

In any case of heat transfer it can happen in three ways: by conduction, by convection and by radiation. The first method can occurs only when there is a contacts between the two domains that are transferring the heat and is described by the Fourier's law previously shown. In the convection case one of the two domain need to be a fluid in order to move while transferring heat; it is described by the equation 3. The last method of heat transfer is by irradiation, described in equation 4,and it does not require the contacts between the two domains and its obtained with an exchange of photons.

$$q_{conv} = h(T_{ext} - T) \quad \text{(eq 3)}$$

In the equation above it's clearly visible how the flux depends on the heat transfer coefficient, h, and on the difference between the external temperature, T_{ext}, and the one of the element analyzed, T. However, in many cases it is not easy to define the heat transfer coefficient, which is influenced by the geometry, the fluid material properties and the surface temperature.

$$q = \varepsilon\sigma(T_2^4 - T^4) \quad \text{(eq 4)}$$

In the equation above ε is the emissivity (defined in the complete work), σ is the Stefan-Boltzmann constant (5.670367×10^{-8} W/(m^2·K^4)) and T_2 and T are the temperatures of the two objects. If the exchange of heat is with the environment, T_2 is equal to the ambient temperature, T_{amb}.[8]

Thermal efficiency and electric efficiency

In the traditional panels, thermal and photovoltaic, in order to evaluate the performance of the different types of collector the energy output is measured and is put in relation with the energy received from the irradiance. For the thermal panels the thermal efficiency of the system, η_T, defined in the following formula.

$$\eta_T = \frac{P_{fluid}}{P_{in}} \quad \text{(eq 4)}$$

The energy that is entering into the panel, E_{in}, and E_{fluid} is the energy of the fluid.
The electric efficiency of a photovoltaic panel is defined with the Equation 5 below.

$$\eta_{PV} = \frac{P}{G \times A_{pan}} \quad \text{(eq 5)}$$

In the formula above G is the Irradiance measured in W/m^2, P is the power produced by the panel in W and A_{pan} is the area of the panel.[9]
The variation of electric efficiency caused by the temperature variation can be calculated using the equation 6 that follows

$$\eta_C = \eta_{ref} + b(T_c - T_{ref}) \quad \text{(eq 6)}$$

Where the terms with the subscript c are valid at the analysed temperature, the terms with the subscript ref are those calculated at the reference temperature and b is the temperature coefficient that is a parameter typical of each panel. It is important to underline that the second addend is always negative when the temperature considered is higher than the reference one. [10]

4) Virtual simulation of a physical problem

To study and design a new product very often are used simulation programs to study the performance of the goods reducing the costs related to prototyping and lab simulations. To conduct the studies described in this thesis one of these programs has been used. In particular, the finite element method has been used.

The finite elements method consists in a study of many smaller sub-systems that together create the complete object of the study. Every sub-system is an element of the study and is associated with a partial differential equation which is solved using mathematical methods. The use of computers, to execute this analysis can make the process faster and more valuable, can permit to increase the numbers of elements studied and therefore obtain a more loyal and careful reproduction of the physical phenomena.[11]

Steady-state simulations

To evaluate and progress with the simulation on the collector, produced by the Swedish company Solarus AB, the first simulations were performed with steady state conditions like in the thesis produced by Pedro Alves [12]. The steady-state simulation was performed to compare the situation already studied in the previous work with a new possible solution to refrigerate the collector, the counter flow direction of the water in the conducts. In particular the counterflow studied considered a alternate direction of the flow in the adiacent pipes. The Figure 2 that follows show the temperature in the receiver top side with the flow in cocurrent (a) and in counterflow (b).

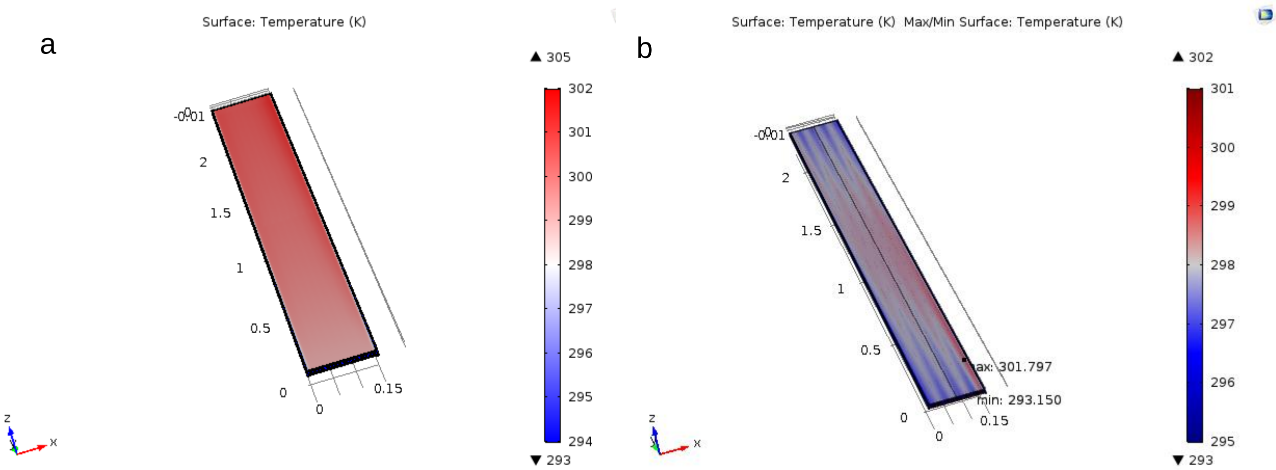

Figure 2 Temperature on the top of the receiver with the fluid in one direction (a) and counterflow (b)

In the image above is clearly visible how the counterflow is more performing having lower temperature. Moreover, in the image of the receiver with counterflow is clear the effects of the alternated inlet in fact the points were the inlets are situated are surrounded by a blue area that indicates a colder area. The final consideration that can be made, observing the images of the top part, is that the right side of the panel reaches higher temperature than the left side. This can be explained considering that the right side receives also the radiation from the vertical face.

On the thermal side the thermal efficiency is dependent on the temperature of the fluid that is shown in Figure 3 for the single direction fluid, in case a, and the counterflow, in case b.

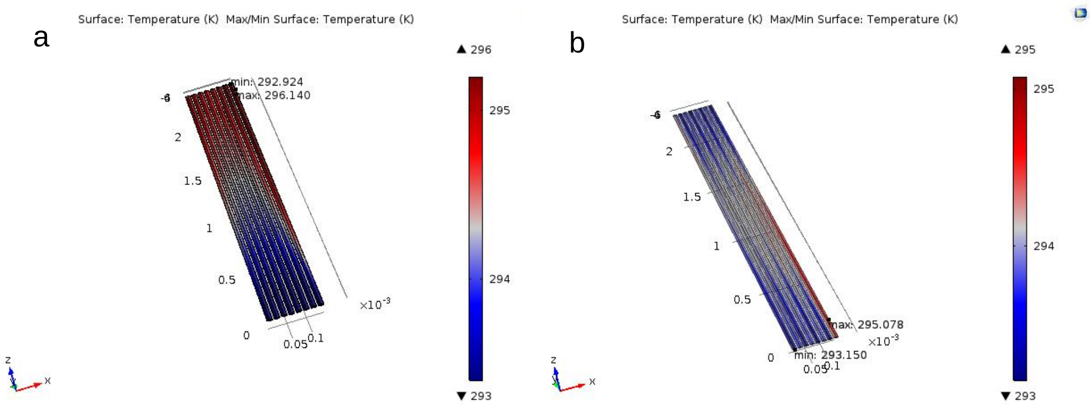

Figure 3 Fluid temperature in the receiver for the single direction flow (a) and for the counterflow case (b)

In the image can be seen how the difference and not uniform temperature is more characteristic of the single direction flow. However, even if this difference in temperature is reflected in the surface and gives a worse electric efficiency, the thermal energy collected in the water is higher in the single direction flow. The bigger difference in temperature between the inlet and outlet in the cocurrent flow (visible in the picture above) has a direct influence on the thermal efficiency that, as explained in the previous part of the thesis, depends on this variation. These results underline how, many times, the improvements in the energy gained in form of heat and the energy obtained in for of electricity are competing. In fact, the increase of one can decrease the performances of the other aspect. The water needs higher temperature in the receiver to increase its performances but the efficiency of the solar cells decrease with this increase. Therefore the compromise between thermal and electric energy have to be decided according to the needs of the location where the collectors are installed considering in which form the energy is more useful.

Time-dependent studies

In order to study if the stationary study ever occurs in the real functioning of the panel and to learn how to introduce time-dependent variable (that can be used also in other studies to study temporary phenomena); the previous simulation were repeated with a irradiance variable with time.

The irradiance studied was equal to the one considered in the stationary studies only in one instant, considered the peak. The time evolution of the irradiance was defined as a Gaussian curve to simulated the movement of the Sun during the day; at the peak the irradiance has the same value of 900 W/m^2 as the irradiance used in the previous studies. The Gaussian equation is generally defined with the following formula.

$$f(t) = ae^{-\frac{(t-b)^2}{2c^2}} \qquad \text{(eq 7)}$$

Where a, b and c are real constant and t is the time in minutes. The constant a indicates the value of the maximum, the constant b the position of the peak and c controls the standard deviation and so the width of the curve. In the simulations conducted a was equal to 1, because then the function was multiplied by the value of the stationary irradiance, b was 360 (the peak was imposed after 6 hours, 360

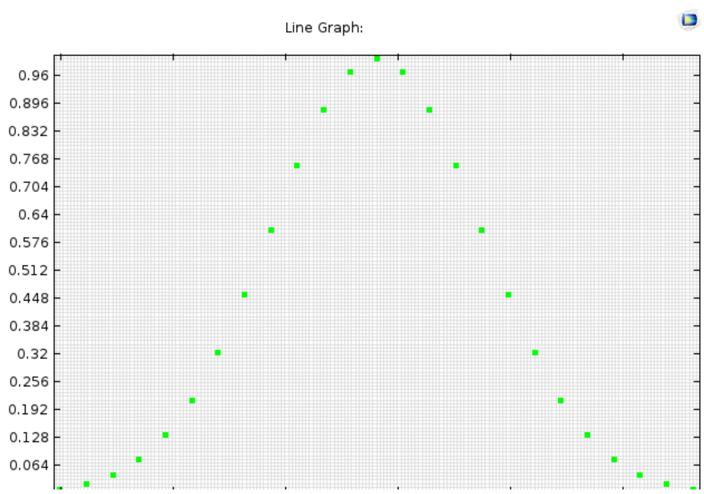

Figure 4 Gaussian distribution as function of the time

minutes) and c was 120 (that means that is supposed that the 68% of the radiation is sent in 240 minutes, 4 hours). The Figure 4 above shows the obtained gaussian distribution as function of the time.[13]

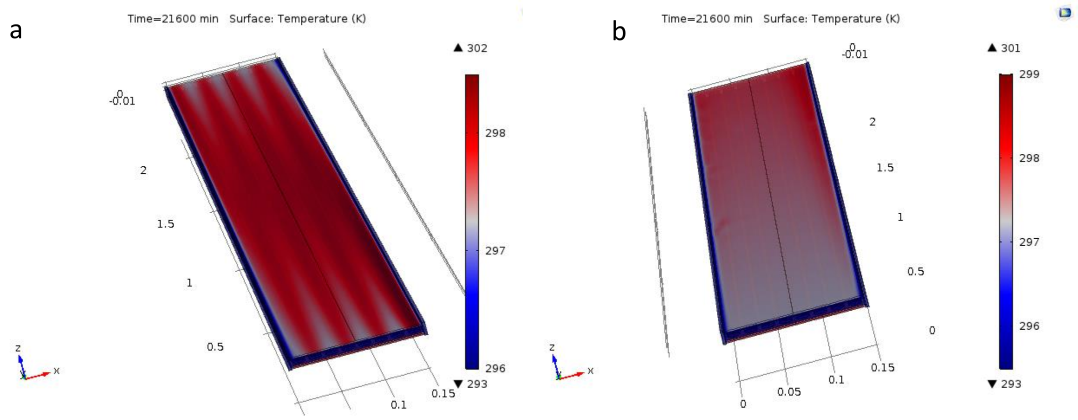

Figure 5 Temperature distribution in the receiver after 360 minutes for the conterflow (a) and the cocurrent solution (b)

Comparing the results of the counterflow and of the cocurrent solution it is possible to see that the obtained images are not in line with the expectation produced in the stationary case. In facts, the distribution of temperature obtained is similar to the one of the stationary case, but the values of the cocurrent remain lower than those of the counterflow. One of the supposition that can explain these results is that the response of the system to the variation of the irradiance is not fast enough to reach the configuration obtained in the stationary case. However, at the moment of the end of the thesis the cause of this problem was still not solved.

If the supposed reasons of the surprising results will be confirmed, the speed of the change in the different phenomena becomes a crucial parameter to identify the relevant perturbation in the functioning of the panel during its lifespan.

5) Conclusions and possible future developments

This study demonstrate the advantages of the virtual simulation permitting to obtain new developments without changing the geometry of the receiver saving time and reducing the costs.

These studies could be the introduction of the shadings in the time-dependent mode to discover possible critical situation. One of this shading studies would be the study of the shading that the structure produces on the receiver in the firsts and lasts minutes of the day. Other interesting studies could involve a time-dependent variation of the fluid flow that could balance the variation of irradiation during the day. However, this studies should also consider that a variation of the fluid speed produces also a variation in the costs that need to be taken into account.

Other more simple studies can involve a variation of the materials that create the receiver. To study the different compromises between the costs of production and the performances obtained with the different characteristics of the different material.

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