Modeling a Thermo - Electrical Concentrating Solar System for Heat and Electricity of a House

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Abstract— Thermoelectric generators are devices which collect solar radiation, they convert heat directly into electrical energy, using a phenomenon called the "Seebeck effect" and then transform it into electricity heat and they deliver it to a heat exchanger through the heat carrier. The purpose of this project is to examine the feasibility and efficiency of using solar energy in a house. Energy and thermal analyzes were evaluated, for a house using a concentrating solar system with TEG modules. The concentrator is composed of a Fresnel lens that focuses sunlight onto a plate of aluminum alloy coated with low emissivity paint, the absorber. From there the heat is transferred to the hot side of the module and part of it is transformed into electricity. The module transfers the remaining thermal energy to a water-cooling system. Therefore the concentrating system enables the harvest of electrical energy as well as thermal energy.

Keywords— renewable energy (RE), solar energy, TEG modules, photovoltaic, Seebeck effect, parabolic mirrors.

I. Introduction

Renewable energies are increasingly present in today because they fulfill a growing concern for the environment, and they represent inexhaustible sources of clean energy that may lead to the liberation of monopoly of oil economy. It is normal to say that solar energy is renewable, ever though the sun is not renewable.

Sun is a source of perpetual energy. It is said that power would have a perpetual existence for more than ten million years. (Nuclear energy is also considered perpetual).

The more it advances in this field of new technologies, as well as mass production, the cost of implementing a solar power system will fall and investment in this type of equipment will become more attractive.

Solar radiation reaching the earth surface is 6.33 107 W/m2 and about 51% absorbed by land and oceans, with 6% lost as radiation to space that atmosphere reflects, 20% reflected by the clouds, 4% reflected by the earth surface 16% absorbed by the atmosphere and 3% absorbed by the clouds [1].

For clear sky days the calculations of solar radiation are made by some methods using some software [2].

Studies about the effect of cloudless sky parameters over the complete global solar spectrum radiation are made in Malaysia at 0.3-1.1 μm [3]. For estimating global solar radiation on horizontal using sun hours are carried out on two weather stations from UAE, using a daily weather data recorded for 13 years [4]. There are used sensing for photovoltaic systems which planning and monitoring the solar radiation for a good efficiency, in order to expose a solar panel to maximum radiation [5].

Around the world population consumes 14 TW of energy per year, of which 4.5 TW are derived from fossil fuels (oil), 2.7 TW are derived from gas, 2.9 TW from coal and 1.2 TW derived from biomass [6]. One hour of sunlight is equivalent to all the energy we use on a year around the world [7]. The use of solar energy has been used all over the world and can be done in several ways: solar, photovoltaic, thermoelectric (steam turbine, Stirling engine or thermoelectric generators - TEG), and thermal (water heating), or new concepts such as artificial photosynthesis [8].

II. State of Art

The Seebeck effect was discovered by Thomas Seebeck in 1821 and was associated with the generation of electric power along a conductor to a temperature gradient [9]. He observed that when two electrically conducting materials are connected in a close loop and with the difference temperature between two junctions T1 and T2, in his measurements appear a deflection of a magnetic needle. The deflection was dependent on the temperature difference between the two junctions and the materials used for the conductors.

Twelve years later, a similar effect was discovered by Peltier, who observed that temperature changes near the junction of the dissimilar conductors when a current passed [10]. This effect was explained by Lenz in 1838 [11]. He said that depending upon of directions of the current flow, heat is absorbed or generated at a junction between two conductors.

But thermoelectricity enjoyed a temporary revival in 1850 with the development of thermodynamics when interest was directed to all forms of energy conversion. In 1851, William Thomson established a relationship between the Seebeck and Peltier coefficients and predicted the existence of a third thermoelectric effect called "Thomson effect" [12]. This effect refers to the heating or cooling process, when the current pass on the conductor in a presence of a gradient temperature.

In 1885 Rayleight calculated for the first time the efficiency of thermoelectric generator. In 1909 [13] and 1911 [14], Altenkirch gave an important theory of thermoelectric generation and refrigeration.

He concluded that the thermoelectric materials should possess large Seebeck coefficients with low thermal conductivity.

A new interest of thermoelectricity appeared in 1930, accompanied by the development of semiconductors with Seebeck coefficients in excess of 100μV/K. In 1947 Telkes constructed a generator that operated with an efficiency of about 5% [15]. In 1949 Ioffe developed a theory of semiconductor thermo-elements [16] and in 1956 he along with his co-workers, have shown that the production rate may decrease if thermoelectric materials are alloyed with a composite or isomorph element [17].

Following the energy crisis occurred in 1970 with the increased by five times the price of oil in 1974, more attention was given in world for possibility of large-scale production of electricity by the thermoelectric effect in addition with possibility of obtaining power by waste heat. However concern over depletion of ozone layer in the late 1980s and the general public interest in environmentally sources of energy have led to increased renew interest in the thermo-electric generation as a potential source of electrical power using waste heat [18] [19].

Further years the development of thermoelectricity research continued in space projects, made by Americans. For entire spectrum of thermoelectric activities the Japanese involvement and interest are increased in the commercial exploitation of the unique energy conversion phenomenon.

A. Advantages and Disadvantages of Using Solar Energy

The solar energy is free, although there is a cost in the implementation and equipment to convert solar energy into electricity and/or heat. The solar energy is perpetual and does not cause pollution. However, the associated equipment and manufacturing process may have some associated pollutions.

Because there are certain geographical areas where the intensity of sunlight reaching the ground is small, or because of climate issues (like cloudy sky), this technology sometimes can be compromised.

Now the prices of equipment to capture and conversion the solar energy are still very expensive, although in future that could change. Also, a solar power station occupies large areas of land, changing the landscape, fauna and flora.

III. Case Study for an Average Size House

The purpose of this project was the development and assessment a simple solar concentrating system, in order to obtain both electricity and heat. Fresnel lenses were preferred for the concentration system, instead of parabolic mirrors, because they are an economical solution and offer a smaller set of clutter, less susceptible to strong winds.

The house was considered as a home for 4 people, with all the required appliances, such as electric devices (fridge, washing machine, air conditioning, TV, PC, lights, microwave, etc.) and central heating and water heater. Data on climate conditions is used in the modeling.

For the electricity production we used a Seebeck module RS code 6937116, which can withstand a high temperature and has the following specifications (Table I).

The results shown in this paper were carry out on Edp web page [20].

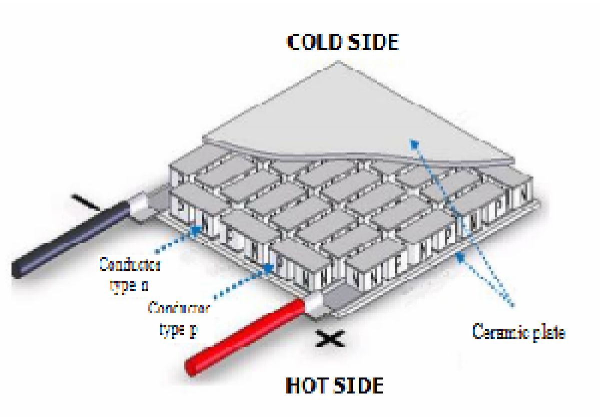

Fig. 1 Module Seebeck

The Seebeck module is formed by two junctions of semiconductor type p and n, which are intended to function as electrical generators producing electric current through the temperature difference between the sides, or used for cooling when the voltage at its terminals and heat is transferred from one side to the other. When is traversed by an electric current, this pass from a terminal (+), runs through all elements in series and exits by another terminal (-).

Thermal pairs are placed between two flat ceramic plates on the base of aluminum oxide or nitride that are used for thermal contact to remaining like a converter system. The principles of operation of these converters are based on Seebeck [9] and Peltier effect [10].

Table I Specific data about the TEG module

Dimensions	Width	Height	Depth
	62 (mm)	62 (mm)	6.3 (mm)
Max. current	Max. power	Max. temp.	Max. Voltage
1.96 (A)	9.2 (W)	250 (°C)	9.4 (V)
Number of pairs:		N=127	

We used the concentrating collector to convert heat into electricity, as we required high temperature (200ºC) on the modules hot surface. The other surface (cold) was cooled by water. Efficiency of this type of modules increases with temperature (Fig.2).

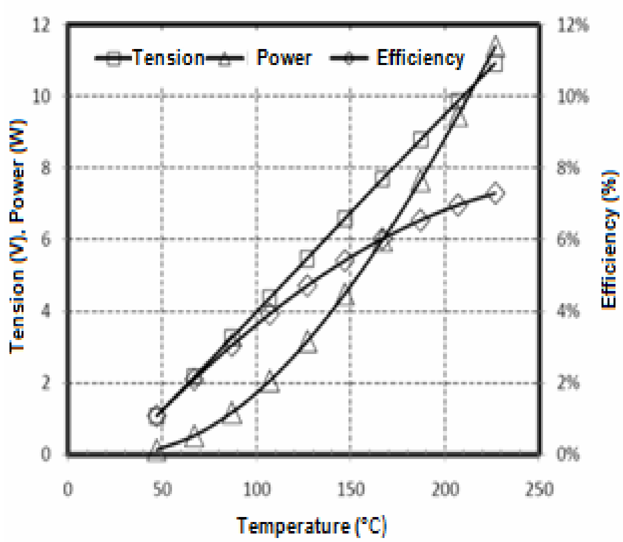

Fig. 2 Income module Seebeck (Antunes, 2011).

So an application should work as closely as possible the maximum temperature that the device supports, in order to get the best performance, as illustrated in Fig. 2.

A. The Design

The concentration level was determined by the calculation of the TEG surface temperature of 200ºC for average sun energy on of 750W/m². However, when the intensity of the sun is stronger, the temperature may rise above the maximum allowed by the module, and there must be a mechanism to reject this heat.

To solve this problem we decided to reduce the energy gain of the sun, by using a collector angle which would not maximize the energy received on the TEG, therefore reducing its temperature. This can be done, taking advantage of the existence of the actuators for positioning solar system, requiring only an additional control algorithm to get the desired effect.

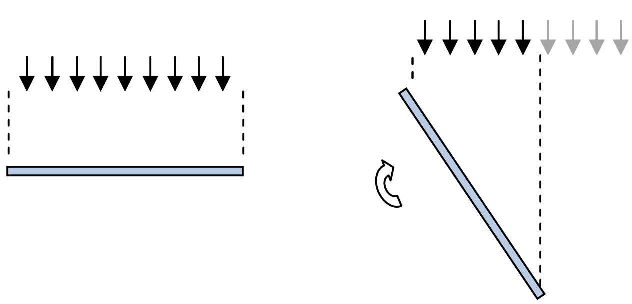

Fig. 3 Deviation from the collector to reject heat

The idea may be to combine the cooling requirement of the module itself, with the production of hot water. This can be implemented by decreasing the concentration in the module as shown in Fig. 3. In this figure the position of the TEG is changed, therefore altering the sun concentration.

This exposes the water pipe directly to the sun concentrated rays. The system response can be controlled electronically (with the aid of an actuator). As the thermal process is much more efficient than the process of conversion into electricity, the control algorithm should give priority to the needs of electricity.

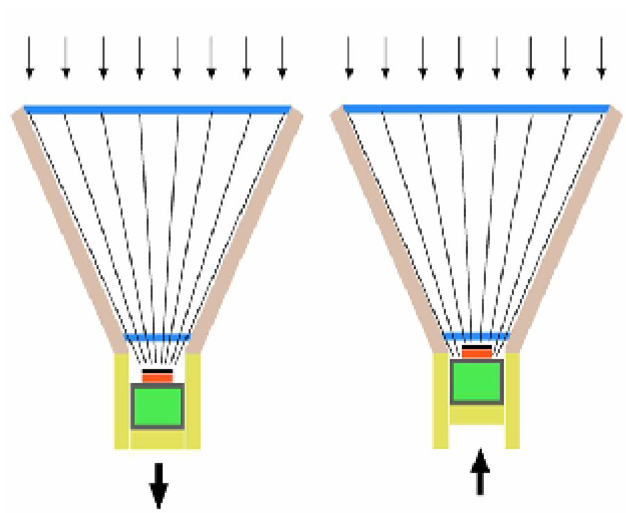

Fig. 4 System approach to the goal (one part of fluid gets out and other enters)

Was neglected in calculates of the design of solar concentrator the reflectivity of the glass, which is about 5%, which is reflected in the lens about 5% and arrived to target where passes through the glass again, like an infinite loop, as shown in Fig. 5.

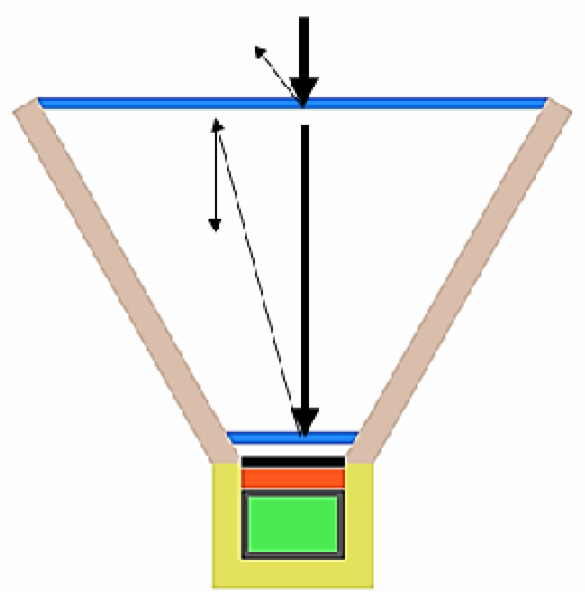

Fig. 5 The reflectivity between glass and lens

The transfer of heat between the glass and the lens through the hole takes place by convection, as illustrated in Fig. 6.

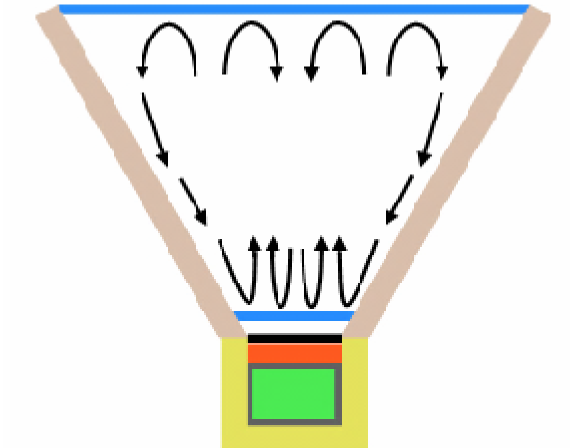

Fig. 6 Heat transfer between the cavity and the outside air

As for this study the Rayleigh number was Ra>1708, means that from this value there are significant convection currents.

Convection between the glass and the inside of the cavity may be considered an area of convection for a less heated.

After a few designs a relatively simple configuration (Fig. 7) was chosen. In this configuration the Fresnel lens concentrates the solar energy into a target, which is an aluminium alloy plate, with high absorption and low emissivity. The concentrated heat passes through the module that converts electrical energy and is dissipated by a water pipe. The system is entirely isolated, even around the air cavity of the tube, to minimize thermal losses.

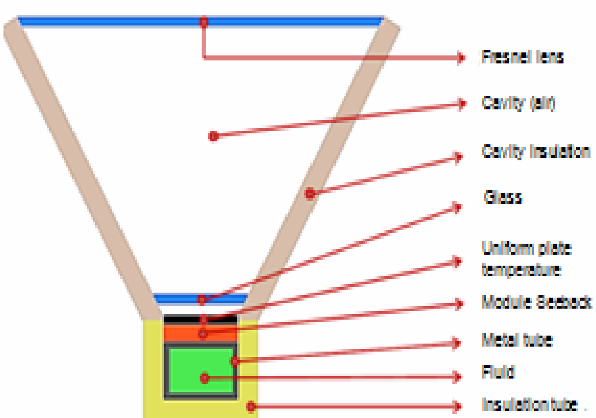

Fig. 7 Components of the solar concentrator

This solution still requires a system with a fluid circuit and an insulated container. The heat passes from the module to the water until it reached a temperature of about 50 ° C, above which the heat would be rejected by opening a valve connected to a heat exchanger with the environment, this would happen when there is no need for hot water.

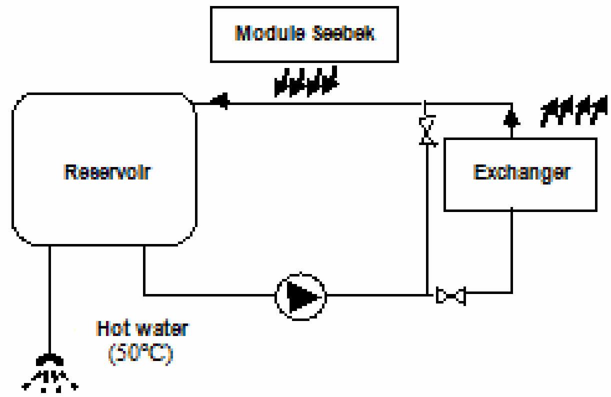

Fig. 8 Schematic of the flow water

To calculate the various temperatures, concentrator efficiency, electricity and hot water production we used the system described in Fig. 8.

The heat dissipation module is provided through the cooling fluid (water) that has the function of maintaining a low temperature in the cold face of the module.

With the increased water flow, the efficiency of the module has a rapid growth and then tends to a constant value, as can be seen in Fig. 9. The ideal is for the establishment of a compromise between the temperature of hot water (for domestic use) and module efficiency.

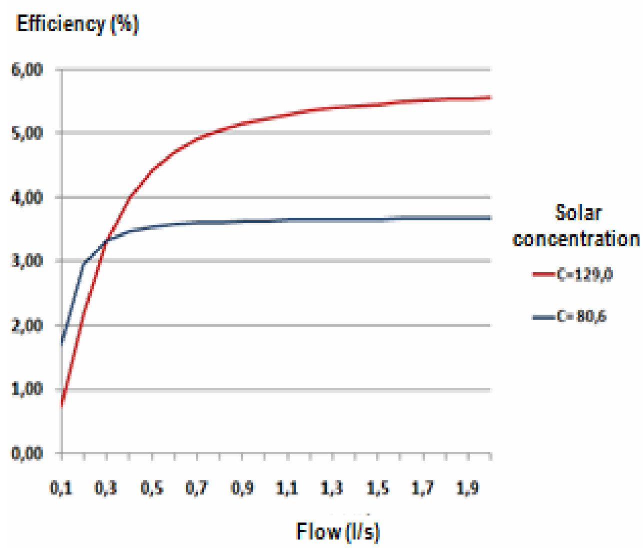

Fig. 9 Influence of water flow variation in system efficiency

This system can supply up to about 200 W/m² (of Fresnel lens) of electricity. The Seebeck module efficiency, applied to this system fall from 5% to 4,5% when the cooling water passes from 30°C to 50°C.

A flow rate of one liter of water per second per square meter of the exposed lens to the sun is more than sufficient in terms of hot water needs for a home, which is considered as 150 m2 for four persons.

B. *Data on building*

The building is at ground level and has three bedrooms, two bathrooms, a living room, a kitchen and one hall.

Table II The home area

Accommodations	Area A [m²]	High [m]
Hall	18,41	
Bathroom 1	7,63	
Bathroom 2	6,27	
Kitchen	27	2,6
Bedroom 1	15,05	
Bedroom 2	15,05	
Bedroom 3	13,11	
Living room	46,58	
Total living area	150 [m²]	

Total requirement of hot water for the peoples who live in this home, using the utilities like washing machine, washing dishes, or for bath is N= 266 l/day, and specific flow for a person in one day is:

$$q_s = 66.5\ l/person\ on\ a\ \ day$$

We considered that the hot water has average temperature of 450C.

For energy consumption, we use a program that simulates the potential of electricity in every part of the building.

So in the table below we present the main electronics that are used for four persons with their power consumptions:

Table III The main electronics and appliances, along with their power

Nr. Crt.	The name of the device	Nr. of devices	Nominal power [W]
1.	Fluorescent lamps	9	75
2.	TV	4	90
3.	PC	1	250
4.	Printer	1	90
5.	Scanner	1	70
6.	Washing machine	1	1600
7.	Refrigerator	1	100
8.	Electric oven	1	2500
9.	Hood	1	150
10.	Microwave	1	1000
11.	Toaster	1	750
12.	Air Conditioning	1	1800
13.	Telefon	1	5
14.	Iron	1	300
15.	Vacuum cleaner	1	1250
16.	Other home appliances (blender, juicer, hair drying, exchanger...)	1	1330

During the winter and summer seasons, we schedule the time of using the consumers for electricity in every day used in every room of the house, as can be seen in Fig. 10.

We can see that in some days the consume is higher than the others days.

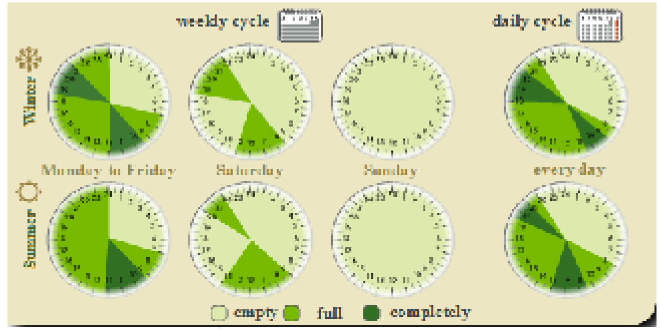

Fig. 10 Schedule of using electricity for the consumers, in summer and winter

For the house we considered all the equipment's required, as electric device like TV, PC, light, fridge, washing machine, air conditioning etc.

Fig. 11 Total consumption of the home per one month for kitchen

Fig. 12 Total consumption of the home per one month for bathrooms

We can see that the house consume is 85.74 kWh in a month by using the utilities with a power of 16330 W. The price of energy may vary depending on the way it is used. But for home we use the simple cost.

C. *Results*

After inserting all the inherent properties of the fluids and materials of the module Seebeck, presented in green sells, are introduced the following input parameters presented in the Table IV.

The consumption of the house it is divided by each room.

Table IV Parameters of the module Seebeck

Width mod Seebek 0,062 (m)	Dist focal (f) 5,000 (m)	Rad. sun media 750 (W/m²)
Fresnel lens width 5,00 (m)	Dist. of the modul (f*) 4,938 (m)	Concentration 80,645 %
Temp. module 147,73 (ºC)	Thermo dule efficiency 3,08 %	
No. of modules (m linear) 16,129	Flow 1,10 (l/s) = 0,0011 (m³/s)	

To know the total value of losses, was calculated each part of thermal resistances in the scheme below, where it made an analogy with the resistance of an electric circuit. In order to facilitate the implementation of the calculation, the water flow was transformed into a thermal resistance.

The average thermal resistance of the modul is R = 0.6667 K/W and is the inverse of the average thermal conductance (≈ 1.5 W/K), which has been experimentally measured during a master's thesis by Joaquim Antunes in Minho University. These values are charted in Fig. 13.

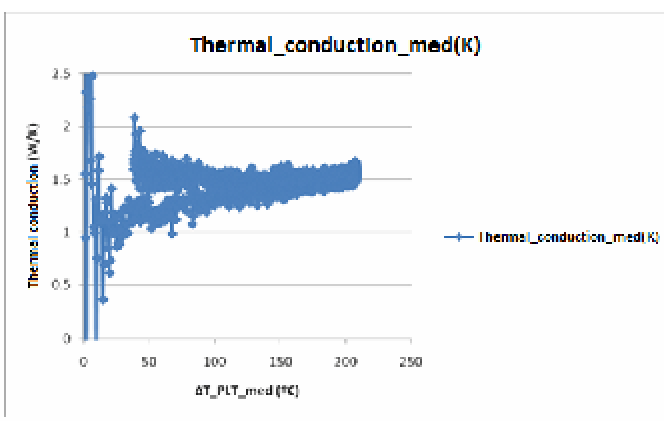

Fig. 13 Thermal Conductance of Seebeck module [21]

One aluminums plate receipts the Sun's rays and can be called the target. This board in contact with the Seebeck module it has also the function of uniform temperature peaks, and for possible precaution which perhaps might occur due to the behavior of the Fresnel lens.

Through the width of the lens L_1, the focal length (f) and Thales theorem, we can know the distance to the target f*. The target is square and has a width equal to L_2, so the module focal area (target area) is at a distance of lens.

The calculation was designed for an average radiation of the Sun in Portugal of 750W/m². This energy passes through the lens and the glass and has a transmittance of 0.92 and 0.90 respectively, reaching target board with energy of 621W/m^2.

Table V Resistence of the system

R air(small)	0,009648	R metal	9,11E 05
R vacuum	0,069124	R contact	8,06E-05
R med. cavity	0,063377	R module	0,041333
R lat. cavity	0,011261	R contact	8,06E-05
R insulation	0,072453	R pipe	0,000182
R conv. (air)	0,031809	R fluid	0,008767
R high cavity	0,032081	R flow	0,000217
R lens	0,006	R pipe(ext.)	6,07E-05
R conv. (air)	0,070245	R insulation	4,301075
		R conv. (air)	1,888304

Starting with the face painted black on the top of the target board as the heat source, which focuses the Sun's energy (after multiplied the losses due to lens transmittance coefficient and glass), disregarding the lateral losses because it is a thin plate and for this is isolated in tops, the heat flow has two possible pathways represented in figure below per Q1 and Q4. Once in Q1 can seep flow sideways through Q2 or over isolation through the lens Q3. The flow Q4 also has two alternatives, or seeps into the fluid flow or exits to the walls Q6 tube and isolation to Q5.

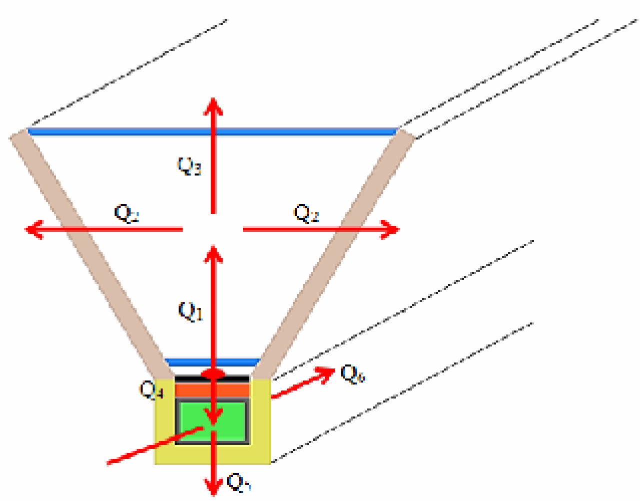

Fig. 14 Heat flows of the solar concentrator

The heat is represented in [W], where Q1, Q2, Q3, Q4, Q5 and Q6, are showed in table 5. These powers are matched with the calculation of resistance that were showed earlier in Table V.

Table VI: Heat dissipated

Q (total)=	3172,441808
Q 1=	647,1334
Q 2=	313,1650
Q 3=	333,9683
Q 4=	2525,3084
Q 5=	0,9801
Q 6=	2524,3284

In the Fig.15 we can see all temperatures calculated.

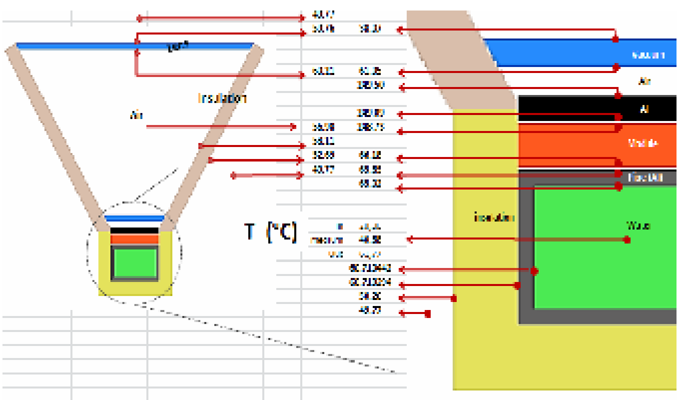

Fig. 15 Different temperatures on the system

In Fig. 16 we can see the relation between the variables: water flow, outlet temperature of the water, energy produced by the concentrator, energy used for pumping and module efficiency.

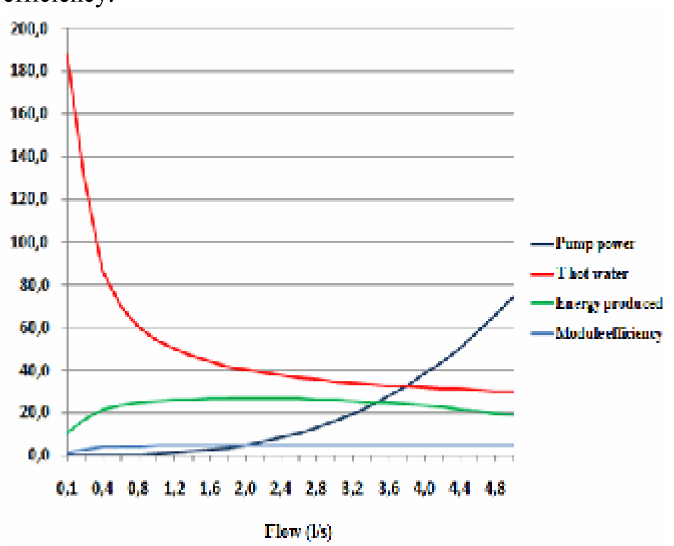

Fig. 16 Comparison chart of harvest of electrical energy as well as thermal energy produced by the Seebek module

As the water flow increases, the outlet temperature drops and the energy extended when pump increase.

The energy produced by concentrator increase rapidly to a value and this is because the flow is increased for to cool the cold face of the module (dark blue line). Once stabilized, because from a certain flow, the water comes out near the temperature at which entered and can't cool more than that (red line).

If the flow continues to grow, pumping losses increase exponentially and justify this loss of energy produced (green line).

Obviously, the module efficiency is not affected by pumping losses and its line (blue line) tends to be horizontal.

IV. Conclusions

It was noted that a solar power station, occupies large areas of land, changing the landscape, fauna and flora. This impact can be reduced by using smaller plants, which collect the energy into small points.

Major limit of this project is mainly Seebeck module efficiency (currently about 5% of potential), but this technology is developing, and the future evolution of modules will make the system more efficient.

To obtain a reasonable efficiency of the module with a solar incidence medium (750 W/m²), in intervals of high incidence, so the module does not exceed the allowable temperature, water flow would be so great as to involve a very high speed, and therefore greater pressure drops in the tube. The pressure drop increases exponentially with speed liquid, so the energy consumption for pumping would not justify the gain in efficiency. You will need to make a commitment.

This problem can be resolved with the approach system of the target (or fall in the set, with the fixed target), shown in Fig. 4.

This system is easy to implement, obtain two types of energies (electrical and thermal energy), being more efficient than other systems and representing a good solution for future.

Acknowledgments

The work of this paper was supported by Project SOP HRD – EFICIENT 61445/2009, Romania and by University of Minho, Guimarães, Portugal.

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