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# MODELING OF A CAVITY RECEIVER OF A SOLAR DISH / STIRLING SYSTEM

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***Abstract.*** *The Dish/Stirling power system is the thermal generation technology with the greatest conversion efficiency of solar radiation into electricity. In this paper was made the study and characterization of the technology components, with the objective to evaluate the geometric parameters and analyze the thermal behavior of the losses related to the collector/receiver operation and finally the Stirling engine parameters. For a better representation of the model were quantified the thermal losses like convection, radiation, conduction and hydraulic losses, given in the interior of pipes and ducts. Finally it was performed a preliminary sizing DIR type absorber, regenerator and the Stirling engine cooling system.*

*The realization of mathematical modeling of the Dish / Stirling system was used Matlab, while for model validations were used different authors publications. The developed model allows to discribe the systems behavior, starting from the different parameters and influence the expected system power. These parameters are: The wind speed, the operating pressure, temperature operating, the engine rotational speed, internal diameter of the absorber tubes, etc. Is observed as the wind speed affects the heat transfer by convection, also is observed how the rotation speed and fluid pressure affects the power system output. The results show that the thermal efficiency of the Stirling engine is affected by the regenerator efficiency, however the power delivered by the engine is the same.*

***Keywords:*** *Dish/Stirling; Heat Transfer; absorber; Solar Energy; Losses.*

## 1. INTRODUCTION

Stirling engines have been regarded as a promising power generation technology since they have been successfully applied in a wide range of energy applications, including power plants (Petrescu, 2010). In solar thermal energy systems with high concentration, such as Dish/Stirling systems, the thermal losses of the solar receiver, including heat losses by convection, radiation for the environment and conduction losses through insulation are important parameters in the conversion of solar irradiation into electricity. The heat losses by radiation depend of the temperature on the cavity wall, emissivity and the absorptivity of the receiver walls. While the losses by conduction are dependent of the temperature in the receiver wall and the Insulation of the material. (Reis, 2003) says that the Dish /Stirling technology has some characteristics, which improves system efficiency, this has a modular collector and a receiver unit that can operate independently or as part of the system. In this system type, the proven efficiency for the conversion of solar irradiation into electricity is 28% for the Stirling cycle and 15% for the Organic Rankine Cycle, (Palz, 2002).

Dish-Stirling solar power generation has emerged as an efficient and reliable source of renewable energy. As the technology moves into commercialization, mathematical modeling becomes necessary to predict system behavior under various operating conditions (Howard, 2009).

In general, cavity receivers employed in the paraboloidal dish concentrators are subjected to various modes of heat loss, like conduction, convection and radiation. Among these, convection is the most complicated phenomenon. Hence, its characteristics need to be clarified such that losses can be effectively minimized for the improvement of system efficiency (Paitoonsurikarn, 2004).

ISSN 2176-5480



## 2 MATHEMATICAL MODEL

This paper presents a mathematical model that aims to analyze the behavior of a solar receiver and other Dish/Stirling system components. The concentrator calculation methodology proposed in this paper, is based on the work of Mendoza, (2012), who performed a preliminary opto-geometric and thermal sizing Concentrator/Receiver system. Completed the study of the concentrator, the next step was the modeling of the solar receiver, defining geometric parameters as: diameter of the cavity receiver, length, number and diameter of the Stirling engine heat exchanger tubes. Subsequently was quantified the different forms of heat loss in the cavity of receiver, to calculate the amount of heat that enters in the Stirling engine. Finally were calculated the parameters that define the behavior of the Stirling engine, the regenerator and the system in general.

### 2.1 Opto-geometric sizing of the concentrator / receiver

The concentrator is the dish Stirling component responsible for capturing solar irradiation, directing the incident rays to a receiver located at the focal point. Solar concentrators are characterized by being manufactured using highly reflective materials. The Fig. 1, shows, some of the calculated variables:

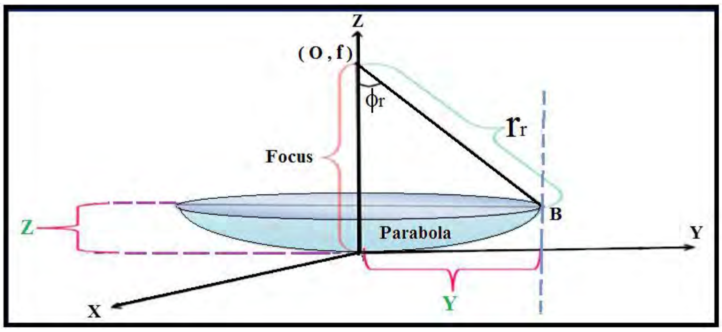

Figure 1. Paraboloid of revolution (Mendoza, 2012).

This stage defines the parameters of the model used for the geometric dimensioning of the concentrator/receiver that allows to analyze the behavior of the system for different geometrical dimensions (Mendoza, 2012):

$$Y^2 = 4fZ \tag{1}$$

The Calculation of the edge radius is given by:

$$r_r = \frac{2f}{1+\cos(\phi_r)} \tag{2}$$

Where:

$f$: Focal distance (m)
$\phi_r$ : Edge angle (°)

The focal length is given by:

$$f = \frac{D_P}{4\tan\left(\frac{\phi_r}{2}\right)} \tag{3}$$

Where:
$D_p$: Collector diameter (m)

The concentration ratio is given by:

$$C_{geometrica} = \frac{A_{Aperture}}{A_{receiver}} \tag{4}$$

Where:

$A_{Aperture}$: Concentrator aperture area ($m^2$)
$A_{receiver}$: Area of the receiver ($m^2$)

Optical efficiency of the concentrator

$$\eta_{op} = f_S * Cos(\theta_i) * \tau * \alpha * \rho * \phi \quad (6)$$

$f_S$: Shaded fraction area of the concentrator
$\theta_i$ : Angle of incidence (°)
$\rho$ : Reflectance
$\phi$ : Interception factor
$\tau$ : Transmittance

Concentrated solar irradiation

$$Q_C = \eta_{op} * A_{apeture} * I \quad (7)$$

$I$: Incident direct radiation on the concentrator (W/m$^2$)

## 2.2 Thermal analysis of the behavior of the system's receiver

The receiver is the Dish Stirling system component that presented the greatest thermal losses. For a steady-state condition, the useful heat reflected by the mirror collector is equal to the energy absorbed by the heat transfer fluid, which is inside the Stirling engine heat exchanger. The useful heat of the Stirling engine is determined as the energy reflected by the concentrator, less the receiver cavity losses (Wu et al, 2009). The Eq.8 represents the engine usable heat:

$$Q_r = Q_C - Q_{Loss} = Q_C - (Q_{cond} + Q_{conv} + Q_{rad}) \quad (8)$$

Where $Q_{Loss}$ is the total heat loss of the receiver. It consists of radiative, convective and conductive losses of the cavity and radiative and convective losses of the external absorbing surface (Kaushika, 1993).Another type of losses presented in the receiver, is caused by the solar irradiation overflow on the cavity aperture of the receiver, irradiation that does not reach to impact all the surface where is the working fluid, as shown in Fig. 2, this phenomenon results in the decrease of temperature in the work area (Nepveu, 2009).

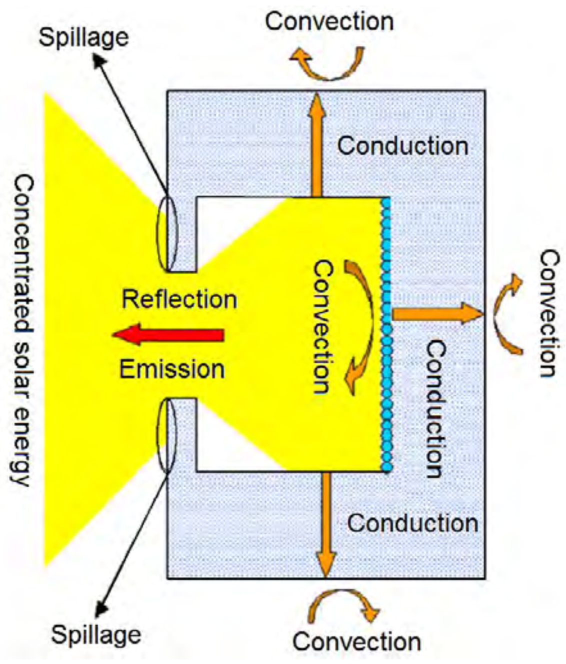


Figure 2. Cross-section of a receiver with the main causes of system losses (Nepveu, 2009).

The heat loss by conduction in the Dish Stirling receiver depends on the temperature of the receiver and the temperature on the topped of the insulating material and is easily analytically determined (Holman, 1997). As follows:

$$Q_{cond} = \frac{T_{\sup,ext-abs} - T_{amb}}{\dfrac{L}{K_{aisl} A_{cav}}} \tag{9}$$

Now, another heat transfer mechanisms presented in the receiver is the convection heat loss, determining this is rather complicated due to the complexity of the temperature and velocity fields around the cavity; generally, this calculation depends on semi-empirical models. There are many factors which influence the convection heat losses in the receiver of the Dish Stirling systems and the external geometry of the cavity (Shuang-Ying, 2010). In the case of natural convection, the local coefficient of heat transfer in the cavity can be calculated as (Wu, 2011):

$$Nu_{\text{int},nat} = 0.088 * Gr^{1/3} \left( \frac{T_{cav}}{T_{amb}} \right)^{0.18} * \left( \frac{D_{aper}}{L_c} \right)^{s} \tag{10}$$

$$s = 1.12 - 0.98 * \left( \frac{D_{aper}}{L_c} \right); \qquad para: 0° =< \theta =< 90° \tag{11}$$

Where:
$L_c$: Average length of the cavity (m)
Gr: Grashof number
ϴ: Tilt angle of the cavity (°)
$D_{aper}$: Aperture diameter of the cavity receiver (m)
Nu: Nusselt number

For the outside of the cavity the heat transfer coefficient can be determined as (Incropera, 2003):

$$Nu_{ext,nat} = \frac{h * x}{k} = 0.664 * \mathrm{Re}^{1/2} * \mathrm{Pr}^{1/2}; \quad For: \mathrm{Pr} >= 0.6 \tag{12}$$

Where:
Pr: Prandlt Number

In the case of forced convection for the cavity of the receiver, it can be studied as surface heated from the bottom or as a surface cooled by the top (Incropera, 2003):

$$Nu_{for,ext} = 0.27 * Ra^{1/4}; \quad para: 10^5 =< Ra =< 10^{10} \tag{13}$$

Where:
Ra: Rayleigh number

Once the Nusselt number is known, for each of the above situations, the heat transfer coefficient is determined, as:

$$h = \frac{Nu * h}{x} \tag{14}$$

And finally the convection heat loss can be determined through the following equation:

$$Q_{conv} = h_{total} A_{amb} (T_{cav} - T_{amb}) \tag{15}$$

The losses by radiation contribute with a significant fraction of the total losses of Dish/Stirling system receiver. In contrast with the heat transfer by conduction and convection, the radiation heat transfer does not need a fluid. This type of heat loss, contributes to the heat losses in the receiver in two ways (Fraser, 2008).

Radiation emission, the general equation for this is:

$$Q_{rad,emi} = \varepsilon_{cav} \sigma A_{rec} \left( T^4{}_{cav} - T^4{}_{amb} \right) \tag{16}$$

ISSN 2176-5480



Where:
$\varepsilon_{cav}$ : Emissivity
$\sigma$ : Stefan Boltzmann constant (5.67 x 10 -8 W/m$^2$K$^4$)
$T^4_{cav}$: External temperature of the receiver (K)
$T^4_{amb}$: Ambient temperature (K)
$A_{rec}$: Area of the radiation-emitting surface, assumed to be the receiver opening area (m$^2$)

The other radiation type present is the heat loss by radiation reflected, which is defined as:

$$\alpha_{eff} = \frac{\alpha_{cav}}{\alpha_{cav} + (1-\alpha_{cav}) * \left(\frac{A_{aper}}{A_{cav}}\right)} \tag{17}$$

Where:
$\alpha_{ef}$ : Effective absorbance
$\alpha_{cav}$: Absorbance of the cavity
$A_{aper}$: Opening area of the cavity receiver (m$^2$)
$A_{cav}$: Total area of the inner cavity surface (m$^2$)

$$Q_{rad,ref} = (1-\alpha_{ef})Q_C \tag{18}$$

Solar irradiation has a high thermodynamic quality, which is reduced when it reached the earth's surface, due to the reduction in heat flux density. This problem is directly reflected in the efficiency of concentrator systems, since as the flux density decreases the degree of the system heat concentration and the receiver performance. This can be improved using punctual concentration systems, which increase the density of heat flux over an area, achieving an improvement in receiver performance (CIEMAT, 2009). The receiver efficiency is then defined as:

$$\eta_{rec} = \tau\alpha_{abs} + \frac{\alpha_{abs}\varepsilon\sigma T^4{}_{rec}}{C_{geo}G_b} - \frac{\varepsilon\rho\sigma T^4{}_{amb}}{C_{geo}G_b} - \frac{h(T_{rec}-T_{amb})}{C_{geo}G_b} \tag{19}$$

$\tau\alpha_{abs}$: Input due to the energy coming to the receiver and capable of absorbing, increased heat across the surface.

$\frac{\alpha_{abs}\varepsilon\sigma T^4{}_{rec}}{C_{geo}G_b}$ : Input due to the coverage from the cavity receiver, due to the efficiency of the material.

$-\frac{\varepsilon\rho\sigma T^4{}_{amb}}{C_{geo}G_b}$ : Losses by radiation from the receiver due to the emissivity of the material and the reflectivity of the material.

$-\frac{h(T_{rec}-T_{amb})}{C_{geo}G_b}$ : Losses by convection between the absorber and the environment.

## 3. RESULTS-DISCUSSION

The computational tool used to model the Dish Stirling system behavior was *MATLAB*. The algorithm is sequential and has as input parameters, climatic factors such as (wind speed, ambient temperature and solar irradiation), and geometric parameters as the diameter of the collector, solar angle, edge angle, etc. Finally the inputs for the receiver thermal balance are: receiver temperature, material properties, working fluid properties, etc. With these variables and according to a convergence criterion implemented in the algorithm, is evaluated the inlet temperature and its validity in the thermal analysis of the system, allowing, to calculate heat loss in the cavity of the receiver, the heat input to the Stirling engine, the receiver efficiency, Stirling engine efficiency, the regenerator efficiency, output power, etc. Also was performed a sensitivity analysis to determine the influence of the variation of the input parameters on the overall system behavior.

Figure 3, shows the variation of the *Dish/Stirling* overall system efficiency related to the diameter of the solar collector. It is observed that the increasing of the collector diameter contributes to increase the efficiency, for diameters greater than 18 m, it was noticed that the system efficiency has minimum changes. At this stage, we have as input parameter, the direct irradiation, equal to 906 w/m$^2$.

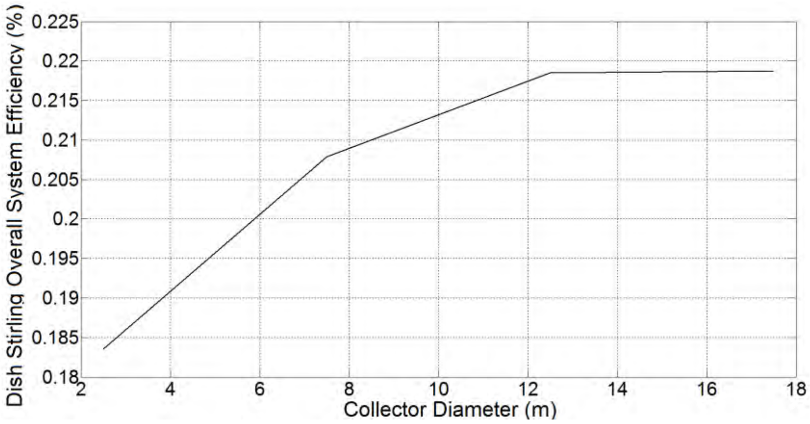


Figure 3. Overall efficiency in function of the collector diameter.

The mathematical model allows to calculate the power output of the system for different values of collector diameter. The Fig .4, describes the behavior of the electrical power with the increasing of the collector diameter.

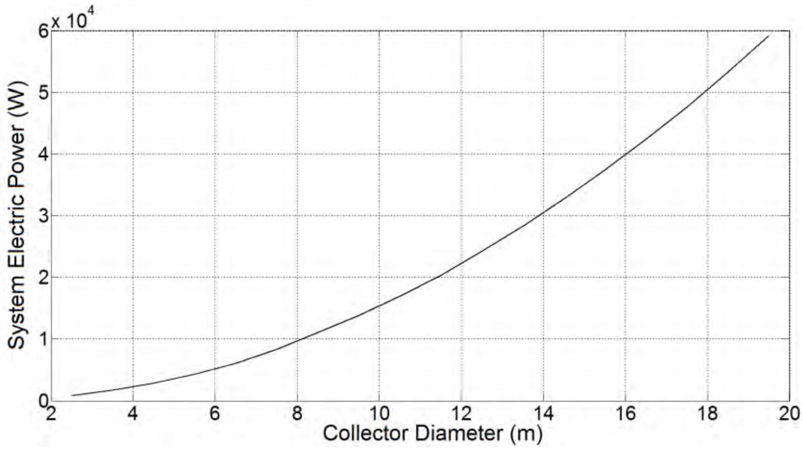


Figure 4. Variation of the system output power in function of the collector diameter.

The observed increasing behavior of the *Dish/stirling* system efficiency and the power , shown in the Fig. 3 and 4, is justifiable, since the energy available for the receiver is directly proportional to the concentrator area, the value of the solar irradiation and parameters dependent of the reflector material, therefore with the increase in the collector area, increases the opening area of the receiver's cavity , the energy available on the receptor and as a result, the efficiency and the power. For the model developed, the values of geometric concentration estimated for each collector diameter, can be categorize as satisfactory in relation to existing systems and tested.

Another parameter to be analyzed in the mathematical model is the influence of the temperature on the *Dish/Stirling* system receiver performance. The parameters compared at this stage were: the output power, the efficiency and heat losses present in the cavity of the receiver and the general *Dish/Stirling* system.

Figure 5, describes the heat losses present in the cavity of the receiver (DIR receiver) as a function of the temperature in the receiver. It is observed that at high temperatures the heat losses by radiation are more representative than the convective heat loss on the receiver. For temperatures above 800K this behavior is more evident, whereas for temperatures below 800K, the convection effects dominated are the radiation effect.

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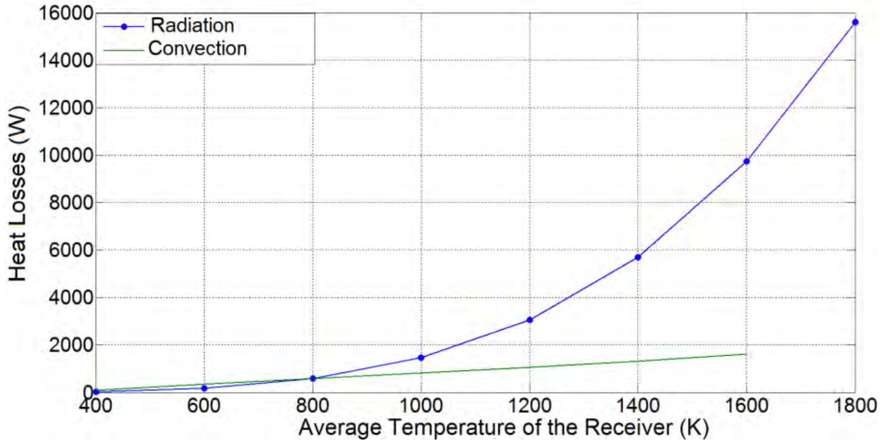


Figure 5. Temperature influence of the receptor on the heat loss by convection and radiation.

Several authors consider that the conduction heat losses in the receiver of the *Dish/Stirling* system are negligible (), however in this model these losses are calculated. In the Fig. 6, is shown the variation of this parameter for different temperatures of the receiver. Comparing the values obtained for the conduction heat loss, with the values obtained for the heat loss by radiation and convection, shown in the Fig.5, for the same temperature, is appreciated that the conduction loss has less impact.

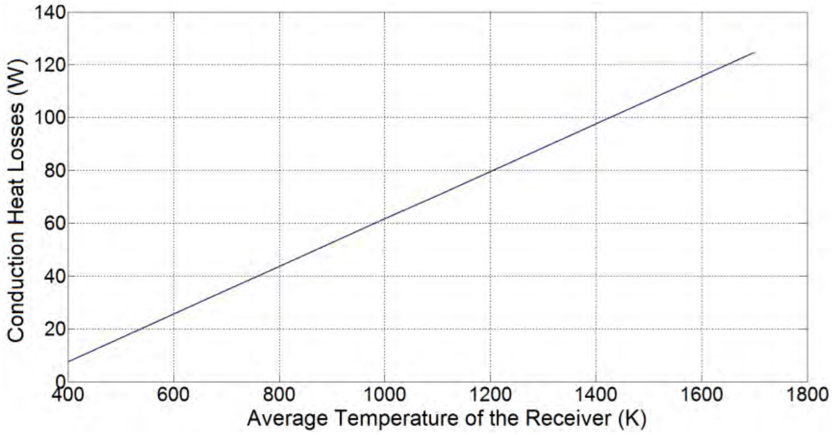


Figure 6.Temperature influence of the receptor on the heat losses by conduction.

Once calculated the system losses, it possible to quantify the Stirling engine input heat and to analyzed the variation in relation to the receiver temperature. The curve shown in the Fig.7 represents the variation of the useful heat in the Stirling engine as a function of the receiver temperature. It is observed that as the receiver temperature increases, the useful heat in the engine decreases, this phenomenon is reflected by the increase in heat losses (for temperatures above 1100K) and in the Stirling engine power decreasing.

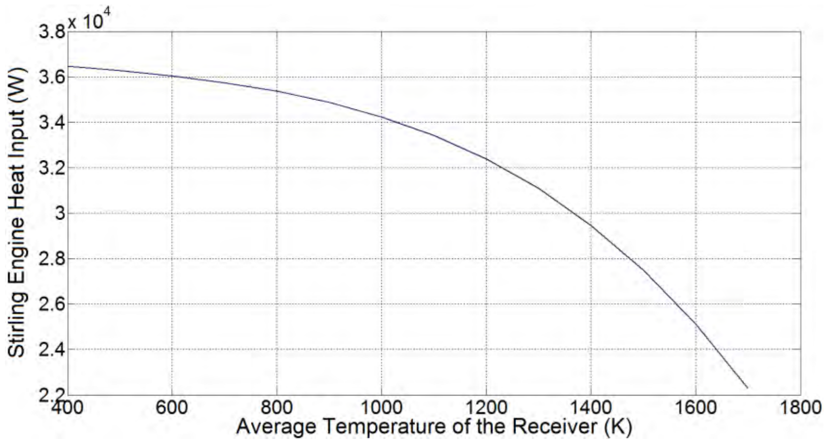


Figure 7. Variation of the heat input to the Stirling engine in dependence on the temperature of receiver.

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The receiver is the system component, where occurs the transformation of solar irradiation into useful heat that is transferred to the engine. With the calculation methodology developed in this work, it was determined that any variation in the geometrical parameters of the receiver affects the system thermal balance, as described in the Fig. 8 y 9 where is observed that, for an excess number of tubes in the absorber (greater than 36), generates a drop in overall system efficiency affecting Stirling engine power, this drop corresponds to the inflection point of the graphs.

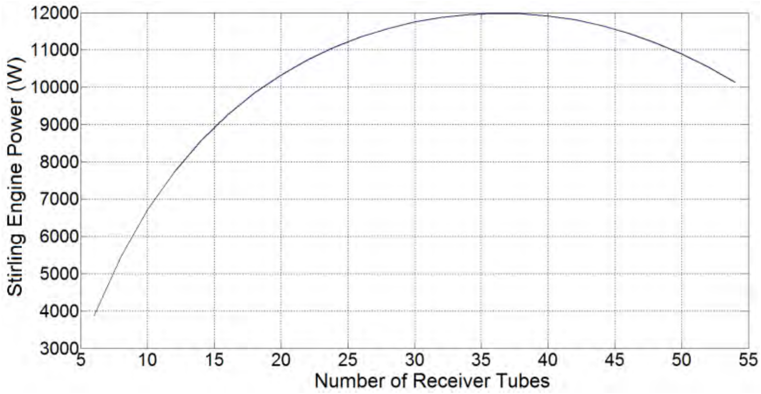


Figure 8. Dependence of the Stirling engine power on the number of receiver tubes.

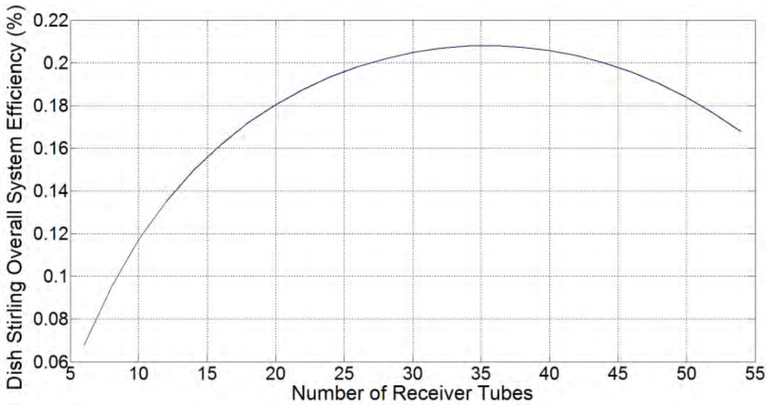


Figure 9. Dependence of the Dish/Stirling system efficiency in dependence on the number of the receiver tubes.

The curves shown in the Fig. 10, described the behavior of the Stirling engine efficiency and the overall efficiency of the dish Stirling system and it dependence on the diameter of the tubes of the receiver. For this studied condition, was observed that the increased in the cross-sectional area change the fluid turbulence intensity, causing a decrease in the heat transfer and consequently in the work that the Stirling engine is capable to perform.

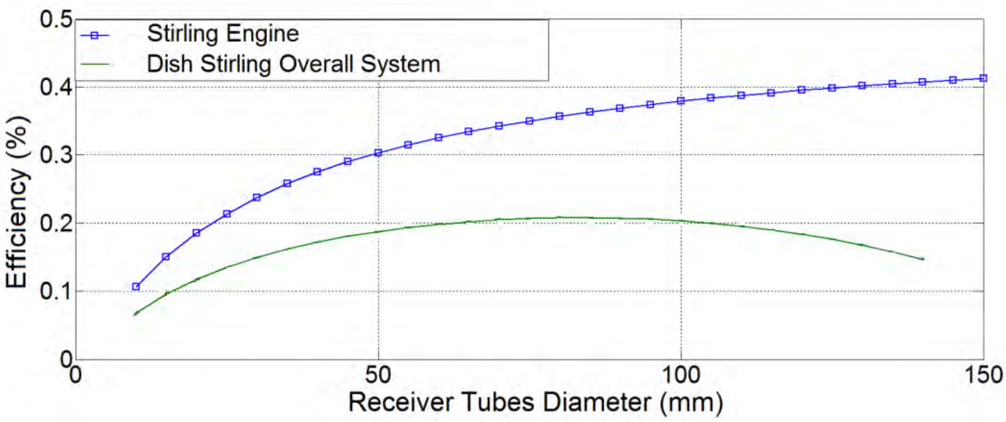


Figure 10. Dependence of the Dish/Stirling system efficiency on the receiver tubes diameter.

For the developed model and in specific in the study of the stirling engine's regenerator, was used the characteristics of a commercial regenerative mesh, using parameters such as: The mesh's porosity, equal to 0.607, the wire diameter of the mesh 0.02mm and the hydraulic radius equal to 0.008 mm. Considering the operating parameters of the system, was possible to analyze, the variation in the effectiveness of the regenerator as a function of rotational speed of the Stirling engine, as shown in the Fig. 11, which shows that with the increase in the speed, the efficiency of the regenerator decreases. Despite this, the power of the system is unaffected. The regenerative thermal capacity is constant and when the engine rotates at some angular velocity, the thermal load which carries the working fluid is accumulated on the mesh. The increased speed cause that the working fluid remains less time in contact with the mesh and therefore the opportunity to achieve heat storage inside the regenerator decreases. This results in a lower overall thermal efficiency, despite having a high power output.

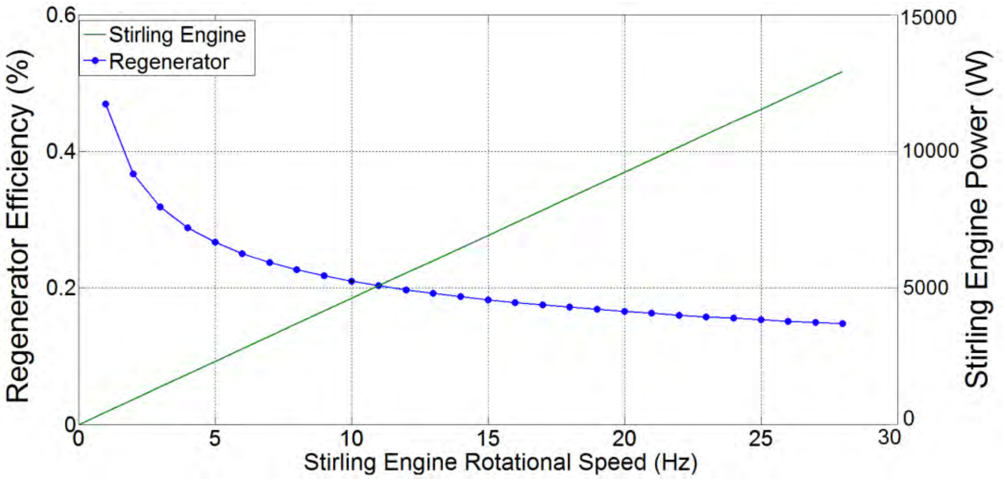


Figure 11. Variation of the regenerator efficiency as a function of the Stirling engine rotational speed.

## 4. VALIDATION

The development of this mathematical model was based, on scientific literature and specialized periodicals in the subject. The objective was to develop a model to describe the Dish Stirling's operation for actual conditions, with acceptable uncertainty values. To validate the model, were used papers, as: W. Reinalter, called Detailed Performance Analysis of a 10 kW Dish/Stirling System and Compendium Solar (Stine, 1994).

Then, the obtained results in the present work are compared, with the results obtained for the Eurodish system (Reinalter, 2007) and the results given by the compendium Solar.

Table 1. Validation of the results obtained by the model.

| | ***Reference (Compendiun Solar)*** | ***Modelo (NEST 2013)*** | ***% Error*** |
|---|---|---|---|
| ***Collector Diameter(m)*** | 7,5 | 7,5 | |
| ***Collector Efficiency(%)*** | 78 | 80 | 2,56 |
| ***Concentration*** | 1670 | 1411,2 | 15,50 |
| | | | |
| ***Working Fluid*** | Helio | Helio | |
| ***Working Temperature(K)*** | 902 | 902 | |
| ***Receiver Diameter(cm)*** | 18 | 17,68 | 1,78 |
| ***Receiver Efficiencia (%)*** | 86 | 83,57 | 2,83 |
| | | | |
| ***Operation Pressure(bar)*** | 40,8 | 40,8 | |
| ***Engine Power (KW)*** | 10,85 | 10,98 | 1,20 |
| ***Engine Efficiency(%)*** | 33 | 33,33 | 1 |
| ***System Efficiency(%)*** | 20,3 | 21,05 | 3,69 |

The table 1, shows the comparison between the results obtained from the model (Nest-2013) and the compendium solar. The percentages of errors calculated or deviations, are within allowable values, between (1 y 4%), concluding that the model represents adequately the system Dish/Stirling, in the case of solar concentration, the deviation was 15%, because the system has a geometric configuration that is not fully detailed.

Finally are described some Eurodish system parameters, that were used for the simulations and for the comparison of the mathematical model developed, results shown in the Tab.2, some of the parameters that were taken into account are: direct irradiation on the concentrator equal to 906 W/m$^2$, receiver temperature 850 K, wind speed 1 m/s, Stirling engine working pressure 40 bar, concentrator diameter 8 m, ambient temperature, equal to 315 K.

Table 2. Validation of the results obtained by the model.

| | *% Variación permitida* | *Reference (Reinalter, 2007)* | *Modelo (NEST 2013)* | *% Error* |
|---|---|---|---|---|
| ***Conduction Heat loss(KW)*** | | not available | 0,34 | |
| ***Convection Heat Loss(KW)*** | ***(-+25)*** | 1 | 0,63 | 37,00 |
| ***Radiation heat loss Emitted(KW)*** | ***(-+16)*** | 2,59 | 2,1 | 18,92 |
| ***Heat Loss Reflected Radiation(KW)*** | ***(-+25)*** | 1,71 | 1,6931 | 0,99 |
| ***Energy Intercepted*** | ***(-+3,1)*** | 37,75 | 38,52 | 2,04 |
| ***Engine Input Heat*** | ***(-+4,3)*** | 31,67 | 32,6 | 2,94 |
| ***Electrical Output*** | ***(-+1)*** | 10,85 | 11,05 | 1,84 |

Other parameters used to validate the model, are shown in the Tab. 2 where it observed that most of the parameters analyzed have a low deviation, except for the value obtained for the convective heat loss, which obtained a deviation of 37%. For some authors, it is difficult to calculate the losses by convection, due to the complexity to study the effect of the temperature and velocity fields, about this type of heat loss, however this atypical behavior does not greatly affect the thermal analysis of the system.

## 5. CONCLUSIONS

The Dish/Stirling system, are an option within the solar technologies for electricity generation, however with the model developed, was determined that at high operating temperatures, the heat loss by radiation present in the cavity of the receiver are the most representative. It was observed that for temperatures above 1100K, the losses in the system are considerable.

The results obtained in this model allowed to demonstrate that for temperatures below 800K, the convective heat loss was the more representative, while the conduction losses presented the lowest values in all cases studied.

The error data obtained, shows that the mathematical characterization performed for this technology is similar to the operation of some actual systems found in the scientific literature. The difficulty of finding in detail necessary parameters as: type of collector receiver material, geometric configuration, variations in the velocity field and the temperature field in the receiver, etc., does not allowed to present more accurate performance in the final results of the mathematical model.

Model results show that for a receptor with a number of tubes greater than 36the engine power losses and the overall losses system efficiency are increased. By increasing the number of tubes, the behavior of the working fluid is changed from turbulent to laminar, affecting the heat transfer. The values for the heat transfer coefficients obtained, for laminar flow are much smaller than for turbulent flows, consequently the change in the fluid behavior affects system performance Dish / Stirling.

## 6. ACKNOWLEDGEMENTS

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