Operation of a Dish Stirling Heliothermic System with Directly Illuminated Tube Receiver

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Abstract. The generation of electricity from solar energy is one of the options within the renewable technologies that have gained much importance in recent years. Within this area, Dish Stirling systems stand out among solar concentration technologies, as they have the highest efficiency in converting thermal energy into electricity. Unfortunately, there are few publications and information on operating parameters of this type of technology. For this reason, this paper presents a methodology to characterize the behavior of this type of system, considering project parameters of a system installed in the city of Itajuba-MG Brazil. In the initial stage, a geometric and optical analysis is presented, which allows us to determine parameters such as the parabolic disk opening area and optical parameters that define the performance of this component. In the next stage, a thermal analysis is elaborated as a way to quantify the losses in the receiver system and to be able to calculate the energy supplied to the Stirling engine fluid. Finally, relationships are established to characterize the behavior of the Stirling engine working with a DIR type receiver. The results show that for speeds below 8 m/s, the heat loss due to radiation is higher than the loss due to convection, representing up to 90% of the total heat loss in the system, for solar irradiation of 1000 W/m², the maximum electrical power obtained by the system was 0.99 kW.

1. Introduction
The continuous development of society and the industrial sector has required the implementation of various technologies and processes based on the use of conventional energy sources. Throughout history, the use of these technologies has grown considerably due to their high potential to meet energy needs [1]. Unfortunately, this behavior has contributed to an increase in the level of pollutants, with harmful effects on the environment, human health, the deterioration of the ozone layer, and the greenhouse effect [2]. In this global scenario, renewable energies and technologies, besides gaining more importance as options to supply thermal energy or generate electricity, constitute new options for the diversification of the global energy matrix, with a positive impact on people's health and the environment [3]. We can highlight wind energy, biomass energy, geothermal energy, tidal and solar energy [4].

Emphasizing that, for regions with high intensity of solar irradiation, heliothermal or solar concentration technologies (Linear Fresnel, Parabolic Cylinder, Central Tower, Dish Stirling) represent one of the first options to generate electricity in a sustainable and friendly way [5]. In the case of Dish
Stirling systems, it is currently considered to be one of the most promising technologies, due to its high capacity to concentrate solar radiation, conversion efficiency, and compact configuration [6].

Some research on this type of system is presented below: Vahidi y Abbassi [7] introduced a dynamic analysis of a Dish Stirling system, using the TRNSYS simulation platform. For the conditions evaluated, the maximum efficiency obtained by the system was 24 % and electrical power of 2.1 kW, for an engine operating with helium as working fluid at a pressure of 50 bar. Sandoval et al. [8] developed a thermal analysis of a Dish Stirling system for climatic conditions in Natal, Brazil. As the main results of this system, system conversion efficiencies of 19% to 26% were obtained for the period April 14-15, 2015. Lai et al. [9] developed a mathematical model of a Stirling solar engine, which considers the climatic conditions and project parameters of this type of engine. For the conditions evaluated, the maximum power obtained was 25 k, at a conversion efficiency of 40 %. Shabanpour et al. [10] presented the analysis of a cogeneration system using a Dish Stirling system for electricity generation. The results obtained show that the implementation of this type of system allows considerable reductions in CO2 emissions to be achieved, and a period of return on investment suitable for the proposed method.

Because of the above and considering the global panorama, the chief scientific contribution of this work consists in the implementation of a methodology through a mathematical model to develop the analysis of the operation of a Dish Stirling system with a directly illuminated tube receiver, considering the project and operational parameters of a real system installed in the city of Itajubá-MG/Brazil, and the climate conditions of this city.

2. Analysis of the Dish Stirling system.

This section will present the stages implemented in this research work required to characterize the behavior of the Dish Stirling system. Figure 1 shows the calculation sequence defined in the methodology described in this paper.

![Figure 1. Dish Stirling system calculation algorithm](image)

It is essential to mention that the calculation sequence defined in figure 1, allowed to set the equations and considerations necessary to characterize this type of technology. And from these, a programming code was developed in Matlab, to determine and analyze iteratively the different calculations required to create the analysis proposed in this work.

The project parameters and the operating conditions of the system modeled in this work were defined from the TRINUM system installed in the NEST/UNIFEI Heliothermal Energy Laboratory, shown in figure 2.
As can be seen in figure 2, the main components of this type of technology include the concentrator disk and its support structure, the two-directional (elevation and azimuthal) solar tracking system, the receiver assembly, Stirling engine, an electric generator, the system's control panel and sensors, and the system's support pedestal.

The operation of this type of technology starts when the irradiation reaches the surface of the collector disk, which is concentrated and directed on the surface of the system's receiver. This is a tube receiver, through which circulates a working fluid (can be air, helium, hydrogen), which is heated by the concentrated solar irradiation. When the fluid is heated, it expands and causes the pistons of the Stirling engine to move. This same working fluid, after this expansion stage, is subjected to a cooling process, so that the fluid is compressed, and in this way can cause an alternative movement of the pistons of the engine. In the final stage of this process, this reciprocating movement is used to drive the shaft of an electric generator[11].

During the operation of this technology, the control system, sensors, and solar tracking, are responsible for ensuring the monitoring of the regularly throughout the period of operation, or even are responsible for bringing the system to the safe position in the absence of solar radiation, presence of rain or high wind speed, as a way to protect the integrity of the system and its components [11].

Table 1 shows the main parameters of the two systems installed at the NEST/UNIFEI Heliothermal Energy Laboratory in the city of Itajubá, Brazil.

| System Operation | Electrical power [kW] | 1 |
|------------------|-----------------------|---|
| Overall efficiency [%] | 17.37 |

Concentrator

| The diameter of the | 3.75 |
|---------------------|------|
| Net reflective surface [m²] | 9.54 |
| Gross reflective surface [m²] | 11.23 |
| Focal distance [m] | 2.3 |
| Focal ratio f/d | 0.61 |
| Concentrator efficiency [%] | 76.9 |

Receiver

| Receiver Diameter [mm] | 230 |
|------------------------|-----|
| Receiver temperature [°C] | 525 |

Stirling Engine

| Electric power [kW] | 1 |
|---------------------|---|
| Gas temperature (high) [°C] | 497 |
| Stirling engine efficiency [%] | 22 |

The following will define some of the main equations used to characterize the operation of the system shown in Figure 2. The calculation sequences implemented in this work, the calculation algorithm presented in Figure 1.
2.1. Thermal analysis of the system

Once the solar radiation is captured by the collector disk, it is concentrated and directed on the system's receiver, located at the focal point. In the system's receiver, we have the main heat losses of this type of technology; for this reason we focus the energy balance of the order on this component, as shown in figure 3.

\[ Q_{\text{useful}} = Q_{\text{receiver}} - \left( Q_{\text{cov, w}} + Q_{\text{cov, aper}} + Q_{r, \text{em}} + Q_{r, \text{ref}} \right) \]  

(1)

Considering that all the concentrated energy reaches the surface of the system's receiver. Therefore the energy on the receiver can be determined with equation (2) [15]:

\[ Q_{\text{receiver}} = I A_{\text{DC, aper}} \rho \int_{\text{int}} \]  

(2)

to \( \rho = 0.94 \) according to [16] and is between 0.9-0.99, according to [15].

From the solar radiation on the receiver, a fraction is transferred to the environment, through the external wall of this component, this heat loss can be calculated with the equation (3) [17]:

\[ Q_{\text{cc}} = \frac{T_{\text{receiver}} - T_{\text{amb}}}{\frac{1}{K_{\text{pc}}} + \frac{1}{K_{\text{a}}} + \frac{1}{K_{\text{a}}} + \frac{1}{K_{\text{ec}}}} \]  

(3)

Additionally, in this component it is possible to identify a loss of heat by convection through the opening where the concentrated solar radiation enters the receiver. This type of heat loss can be determined with equation (4) [17]:

\[ Q_{\text{cov, aper}} = h_i A_{\text{ic}} (T_{\text{receiver}} - T_{\text{amb}}) \]  

(4)

In the case of heat losses by radiation, two main terms are identified, one for emitted and reflected radiation, which can be calculated with the equation (5) y (6) [18]:

\[ Q_{r, \text{em}} = \varepsilon A_{\text{car}} (T_{\text{receiver}}^4 - T_{\text{amb}}^4) \]  

(5)

\[ Q_{r, \text{ref}} = (1 - \alpha_{\text{ef}}) Q_{\text{receiver}} \]  

(6)

Once the useful energy of this type of system has been determined, it is possible to decide on the electrical power generated by this type of operation using the equation (7) [18]:

\[ W_{DS} = Q_{\text{useful}} \ast n_{DS} \]  

(7)

In equation (7) the term \( n_{DS} \), represents the overall efficiency of the system, calculated with the equation (8):
\[ n_{DS} = n_{con} \times n_{rec} \times n_{motor} \times n_{gen} \]  

(8)

3. Main results of the system's behavior

In order to determine the accuracy of the methodology presented, Figure 4 shows the comparative results of the behavior of the electrical power generated: in red by the system installed in the city of Itajuba/Brazil and in blue, the results obtained by the methodology proposed in this paper.

**Figure 4.** Comparative analysis of the electrical power generated by the Dish Stirling system.

In table 1, some of the leading project parameters of the Dish Stirling system, used to develop the analysis presented in figure 4, are described. It is essential to mention that for these analyses, it was necessary to assume the value of some parameters of the system, once these were not provided by the company that sold this technology, and likewise they could not be measured directly on the network. Some of these parameters and their values assumed in this work are collector disc reluctance (90%), receiver absorbance (96%), and the receiver tilt angle (80°).

In order to make these simulations, data of the behavior of the climatic conditions of the city of Itajubá MG, of day 06 of June of 2017, were used. These data were obtained from the meteorological station installed at UNIFEI University. For this day analyzed, it was possible to determine through the methodology implemented in this work, minimum electrical power of 0.3 kW, obtained for a solar irradiation value of 450 W/m², and a maximum value of 0.99 kW, for solar irradiation of 1000 W/m².

When analyzing the experimental values and those obtained with the methodology proposed in this work, it is possible to identify the differences between the compared value at an irradiation value of 450-525 W/m². For values of solar irradiation higher than 525 W/m², minimum differences of the compared values are observed, with values close to 5 %. This behavior can be explained by the fact that at low solar radiation values, the Dish Stirling system has to use energy to overcome the inertia of the system and its components. This behavior cannot be replicated in the mathematical model proposed in this work. In addition to the system parameters that are not known or could not be determined.

Figure 5 shows the behavior of heat losses, present in the system's receiver, for which some parameters were considered as, a tilt angle of the receiver of 80 °, a value of solar irradiation of 906 W/m2, interception factor of 92%.
From the results shown in figure 5, it is possible to observe that for the conditions evaluated, the heat loss by reflected radiation is observed to remain constant. In the case of the heat loss emitted, it is possible to keep a small variation for the different evaluated. Presenting a minimum difference of 4 % and a maximum difference of 36 %. For the loss of heat by convection, it is possible to observe a considerable increase with the increase of the wind speed. For the low-speed values, this heat loss has the best impact on the performance of the system. It is changing behavior, from a wind speed higher than 8 m/s, where the value of convection heat loss exceeds the values of radiation heat loss.

Figure 6 shows the behavior of heat loss by convection, by emitted and reflected radiation as a function of the system's operating temperature behavior, considering a wind speed of 5 m/s, an ambient temperature of 298.15 K and a receiver inclination angle of 80 °.

For the evaluated conditions and operating temperatures between 879.6 and 1108 K, it is possible to observe that the heat loss by reflected radiation has a more significant impact on the operating behavior of the Dish Stirling technology. In some of the conditions evaluated, up to a maximum difference of 55 % in relation to the other forms of heat loss. In the case of low operating temperatures, heat loss by convection shows higher values than the radiation emitted. For a temperature of 876.8 K, the heat loss by convection exceeds the maximum difference in relation to the radiation emitted, in a proportion of 27 %. In this analysis, it is observed that as the temperature increases, the emitted radiation increases. From the values of 1001 K, the heat loss exceeds the values of heat loss by convection.

Conclusions
The results obtained in this work allow us to conclude that the performance of Dish Stirling systems for cities or places with conditions similar to those of Itajubá/Brazil are affected to a greater extent by heat losses due to radiation. Once the data obtained by the weather station (June 06, 2017), the low values of wind speed present in this region of Brazil.
The analyses carried out in this research also allowed to determine that for some operating conditions, heat losses by radiation, considering the UNIFEI project parameters, can represent up to 90-95% of the heat losses present in the system's receiver. From the comparison of the electrical power of the experimental system and that obtained in this work, it is possible to observe that there is a functional characterization of the behavior of this type of technology. For this reason, it can be concluded that the methodology implemented in this work can be used as a useful tool, which helps to have a better understanding of this type of technology and its operating parameters. And from which it is possible to make decisions on the system parameters that contribute to the improvement of its performance. In the particular case of Itajubá, the analysis shows that efforts should be made to investigate and invest in strategies to reduce the effects of heat loss from radiation.

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