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SOLAR RAY-TRACING SIMULATION AND THERMAL ANALYSIS OF A DISH STIRLING RECEIVER

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Abstract. *This work presents a computational simulation of the sun's rays to develop an optical analysis and a thermal analysis by mathematical modeling of a Dish Stirling receiver, with the purpose to evaluate the overall system performance for weather conditions of Itajubá City-MG, Brazil. Opto-geometric characteristic of the dish-Stirling's concentrator and receiver are considered. In this work, the configuration of the Dish Stirling system installed at NEST/UNIFEI Heliothermic Energy Laboratory, in Itajubá, is considered as a reference to define the parameters used in the simulations and analysis of the system operation, as such as receiver temperature, ambient temperature, wind speed, elevation angle, focal length, and geometric parameters. Weather information was also taken from the city of Itajubá. This system has a collector with a diameter of 3.75 m, the focal length of 2.3 m, receiver diameter 0.30 m and absorber diameter 0.10 m. In the thermal analysis, the highest thermal losses identified were the losses by radiation, which exceed the losses by natural and forced convection in 83% and 61% respectively. The optical-ray simulation identified the existence of spillage losses, which can be corrected by repositioning the receiver in its holder a few centimeters to the back side.*

Keywords: *Computational simulation, dish Stirling receiver, spillage losses, heat losses, ray-tracing.*

1. INTRODUCTION

The energy plays an important role in the economy of a country, providing support to various sectors such as manufacturing, mining, transportation, communication, and agriculture. Currently, it is known that there is a growing demand for energy in the world; this energy consumption is a result of factors such as technological progress and the development of socioeconomic parameters of humanity. Besides the energy demand, there is concern about the increase in the average temperature of the Earth in the last years. The scientific community is devoting efforts to research with renewable energies, including heliothermic energy to help reduce the emission of CO_2 into the atmosphere (Abdelaziz *et al.*, 2011).

In recent one hundred years, the temperature of the planet has increased by more than 1 ° C, which can be seen by the climatic changes that are occurring on the planet (NASA, 2018). These changes may take more than 80 million people to going hungry and 25 % of mammals and 12 % of birds at significant risk of extinction. The main reason for this warming is the increase in the level of CO2 obtained through the burning of fossil fuel, with these emissions resulting from the areas, 49 % transport, 30 % electricity, 11 % industrial, 7 % residential and 3 % commercial. Scientists have shown that there is a serious risk of severe weather disturbances if CO_2 emissions are not drastically reduced. , Such disturbances can trigger ecological, economic and social problems across the whole Earth. To brake the global warming it is required a 5 % to 10 % reduction in CO_2 emissions (stabilizing the amount of CO2 in the atmosphere), otherwise, it will continue until fossil fuel consumption decreases (Hejazi, 2017).

According to the Paris Agreement, climate change poses an urgent and potentially irreversible threat to humanity and the Earth, requiring cooperation from all countries to accelerate the reduction of Greenhouse Gases. In addition, the average global temperature increase should be kept below 2 ° C, seeking efforts to maintain the increase by 1.5 ° C. Such cooperation from all countries including the regional and international sectors provides access to sustainable energy for the developing countries (United Nations, 2015).

Heliothermic energy, the main object of this study, can be described as the conversion of the energy coming from the sun into electrical energy in an indirect way, using for this, thermal processes coupled to the solar energy concentrator systems. There are different types of heliothermic systems currently being studied, such as Fresnel linear collectors, Parabolic Trough, Solar Tower and Dish Stirling. The conversion of solar thermal energy into thermal energy and consequently into electrical energy is done through indirect processes of energy conversion that occurs, for example, in an ORC (Organic Rankine Cycle) system or in a Stirling Engine.

Dish Stirling systems consist of a concave surface covered by highly reflective material responsible for concentrating the solar radiation at the focal point where the receiver is located. The heat absorbed by the receiver is transmitted to the working fluid of the Stirling motor, which converts this thermal energy into mechanical energy by expansion and compression processes (Castellanos *et al.*, 2017). *Dish Stirling* system concentrate energy (solar radiation) on the receiver surface to increase its temperature to values around 1,000 C. This energy is transferred to a working fluid of the Stirling engine, which converts the thermal energy into mechanical energy and then, by means of a generator, into electric energy. The working fluid used in the Stirling engine is usually helium, hydrogen or air. This technology has efficiencies of up to 31.25 % of conversion of solar energy into electricity (Carrillo *et al*., 2017).

This study deals with an analysis of the receiver region of the dish Stirling system, conducting a survey of the thermal losses that occur in the receiver according to the operation of the system, by mathematical modeling, and evaluating the characteristics of the receiver's focal point and the spillage losses by computational simulation of the trajectories of the solar rays.

2. SYSTEM DESCRIPTION

Figure 1 shows the configuration and main components of the *Dish Stirling* system analyzed in this work. This system is installed at NEST/UNIFEI Heliothermic Energy Laboratory, in Itajubá (see Figure 2).

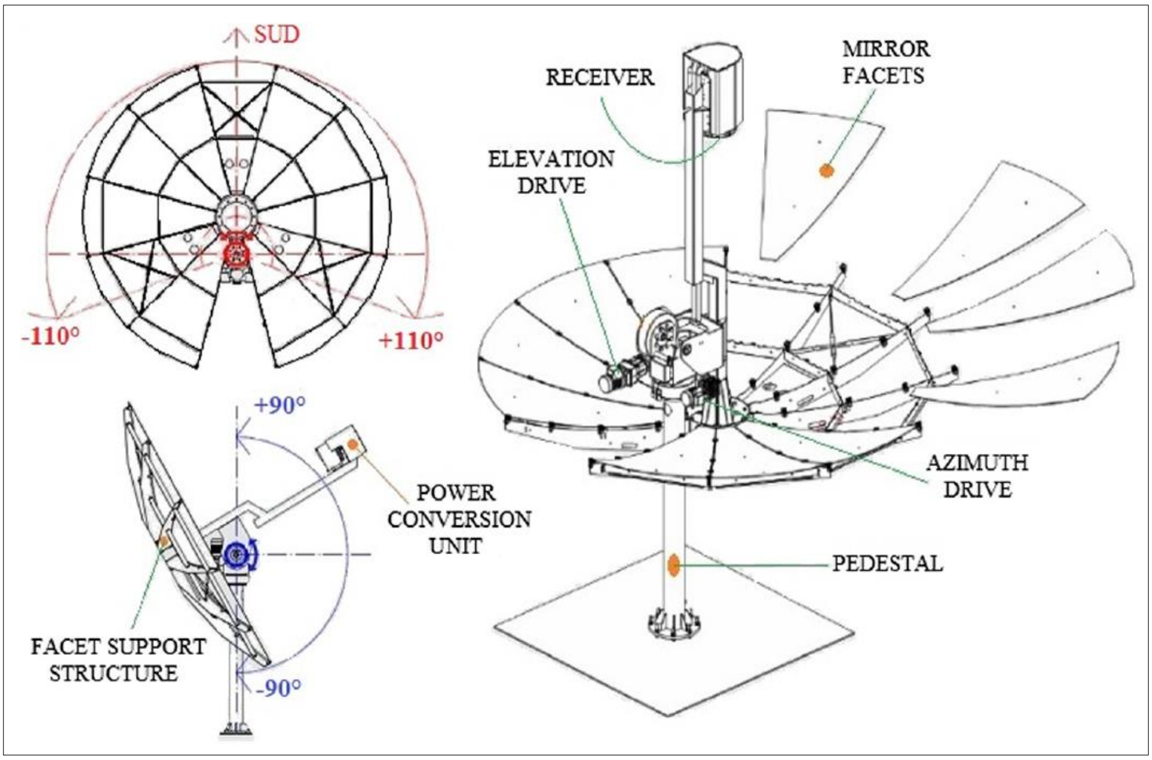

Figure 1. Most important components of the Dish Stirling system, (Carrillo et al., 2017).

The simulations and analysis developed in this work, use as a reference data available in scientific literature and the characteristic (material, diameters, height, geometry, and type of thermal insulation, etc.) of the system shown in Figure 2. The data acquisition system of the Dish Stirling system installed in Itajubá-MG was used to gather operational data and climatic conditions, which were used in the mathematical analysis, such: wind speed, receiver temperature, ambient temperature and system elevation.

Figure 2. *Dish Stirling* systems [Taken from: NEST/UNIFEI Heliothermic Energy Laboratory].

3. COMPUTATIONAL SIMULATION

The computational simulation to evaluate the behavior of the Dish Stirling system was performed using Comsol Multiphysics software. This software has several modules, for the most varied analyzes, such as CFD modules, Ray-Tracing Optics, AC/DC, Acoustic, Battery, and Fuel Cells, Chemical Reactions, Electrochemistry, Electrodeposition, Fatigue, Heat Transfer, Pipe Flow, Particle Trajectory, Structural Mechanics, among others.

The mesh used in the optical simulation of the concentrator was determined automatically by the software, based on the type of phenomenon analyzed; in the case of absorber the mesh used was defined by the user. In both cases, the geometric of mesh elements was triangular with a maximum size of $5e^{-4}$ and minimum size of $2e^{-4}$ for the absorber, and a maximum size of $7.5e^{-2}$ and minimum size of $7.5e^{-4}$ for the concentrator. Figure 3 shows the mesh configuration for the concentrator and the absorber.

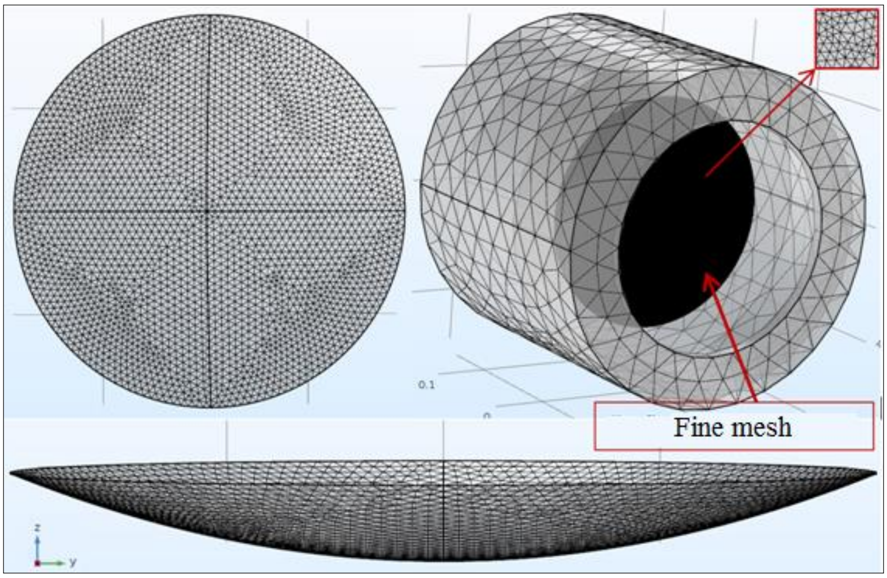

Figure 3. Optical simulation mesh.

4. RESULTS

The main objective of this work is to develop a ray-tracing simulation and thermal analysis of the Dish Stirling receiver to determine system performance. Therefore, it was necessary developed a detailed analysis of the operational condition of the system installed in Itajubá-MG, using the information collected from its data acquisition system and the information supplied by INNOVA (the Dish-Stirling system manufacturer).

4.1 Ray tracing simulation

Figure 4 shows the front view of the Dish Stirling receiver, where is possible to observed burn marks on the metal surface of the absorber, and out of the receiver, near its aperture. These marks are caused by: The Sun's rays concentrated, which hitting aperture surface, due to, for example, misalignment of the receiver-collector; in the absorber surface by the concentration of the sun's rays in a small area of the absorber.

Figure 4. Dish Stirling receiver [Taken from: NEST/UNIFEI Heliothermic Energy Laboratory].

According to Stine and Diver (1994), the focus is normally placed in the aperture of the receiver cavity so that the highly concentrated irradiation flux enters through the cavity and spreads, covering the largest possible area of the absorber, this scattering reduces the rate of energy per unit area, avoiding the metal stress of the absorber due to overheating.

Aiming to diminish the problem of spillage losses, it was performed in this work a ray-tracing simulation to predict and analyze the sun's ray's trajectory in the focal plane, of the dish Stirling receiver.

Figure 5 shows the sun's rays trajectories considering the design parameters of the system installed in Itajubá-MG. It is possible observed that a fraction of the reflected sun's rays hit the outer surface of the receiver, consequently, they do not enter the cavity aperture, resulting in an energy loss.

From sensitivity analysis developed in this work, it was possible to determine that, moving the receiver to backside for around 5 cm, there is an increase in the amount of sun's rays cross the cavity aperture and consequently hit the absorber.

Rays-tracing simulation also allows determining the solar radiation concentrated on the absorber surface of the Dish Stirling system, installed in Itajubá, as shown in Figure 6. Considering this figure, it is possible to observe that the most of the concentrated radiation is located in the center of the absorber. Outside the center, it is observed a significant decrease of the concentrated radiation, with the values decreasing to approximately 0 W/m^2.

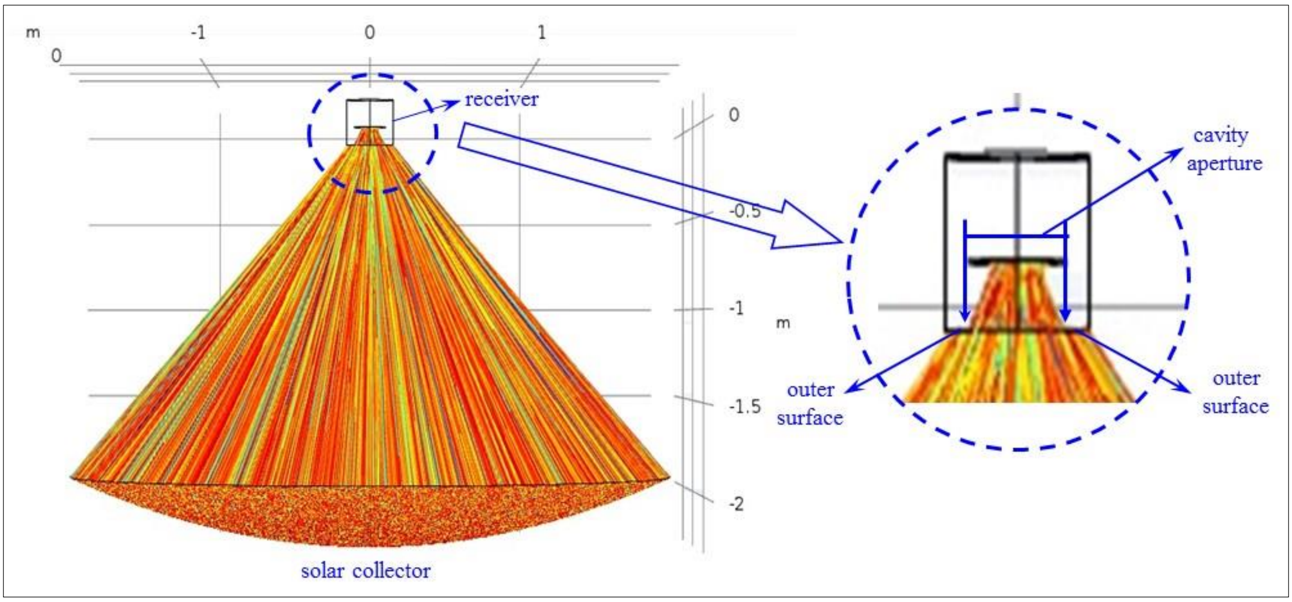

Figure 5. Trajectories of reflected rays leaving the solar collector and hitting the Dish Stirling receiver.

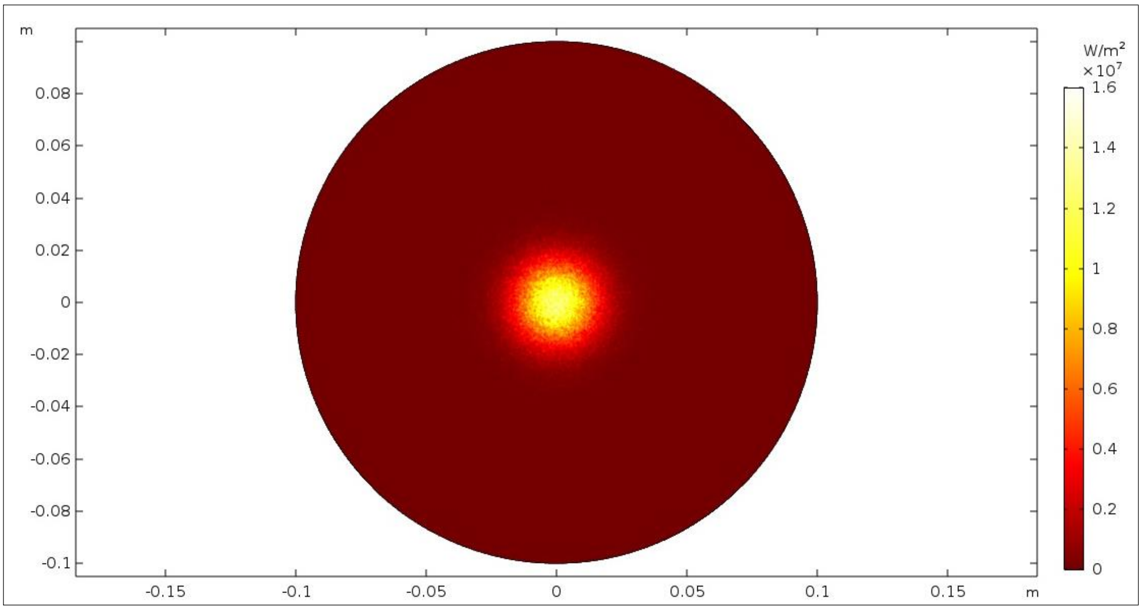

Figure 6. Solar radiation distribution on receiver surface.

Figure 7 shows the solar ray tracing simulation, performed for the focal distance of 2.35m, where it is possible to observe that spillage losses are minimal. The concentrated rays, cross the aperture of the receiver cavity and reach the absorber, no longer hit the surface of the aperture cavity. And also, we can see that the energy concentrated now reaches a larger area of the absorber, thus avoiding the metal stress of the absorber due to overheating, visualized in the focal length of 2.30m.

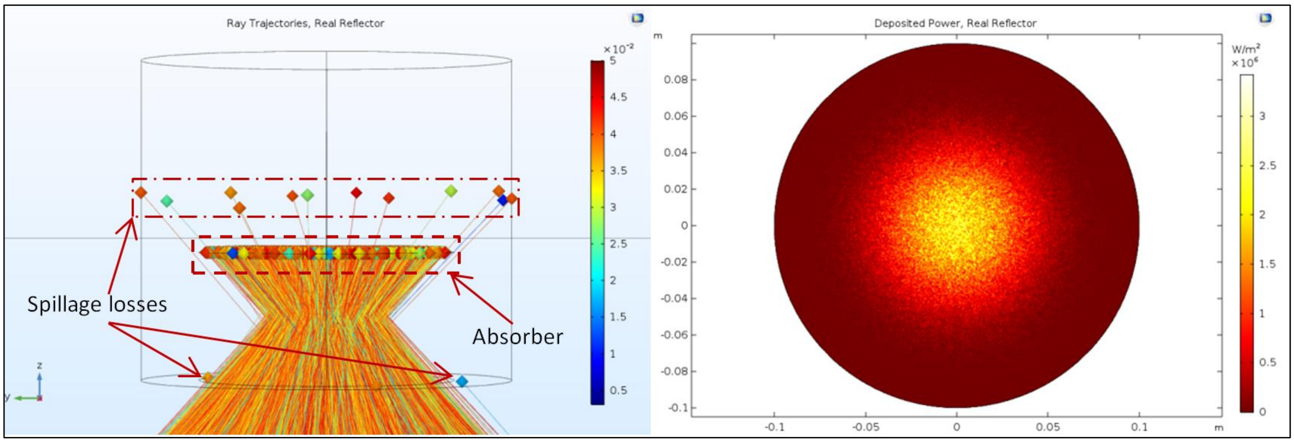

Figure 7. Ray Tracing Simulation to 2.35m of focal length.

4.2 Mathematical Modeling

Figure 8 shows wind speed behavior for a typical day in Itajubá. This information was directly collect from the data acquisition system of the *Dish Stirling* system. For the day considered in fig. 7 (June 15, 2016) it is possible to observe a random variation of wind speed with a maximum value of 10.1 m/s and a minimum value of 2 m/s. These variations of wind speed have a direct effect on the convection heat losses of the receiver. Therefore, simulations were performed aiming to understand and determine the parameters with more influence convective heat loss in the receiver, and consequently on r the performance of this type of technology.

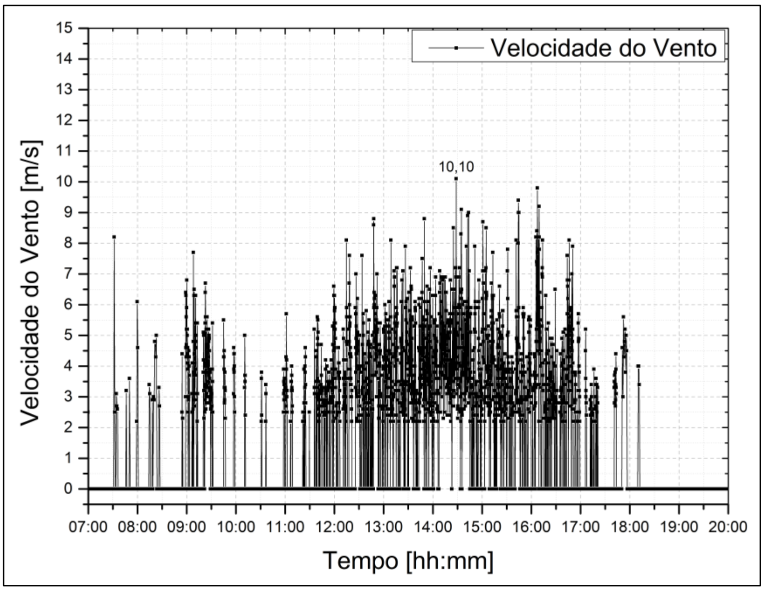

Figure 8. Wind speed behavior for a day in Itajubá-MG.

Figure 9 shows the behavior of the elevation of the Dish Stirling system, during the period its operation in June 15, 2016. It was observed that the lower elevation occurs in the morning and afternoon, reaching values around 10°, and the greater elevation occurs around midday, reaching values around 44°.

Figure 10 and Figure 11 show natural and forced convection heat loss behavior for the *Dish Stirling* receiver system installed in Itajubá-MG. From these figures, it is possible to determine that the behavior of convection heat losses follows the behavior of the elevation of the system described in Fig. 9 and the wind speed described in Fig. 8. For the conditions presented it possible to observe determined that the forced convection has more influence on the system performance in comparison to the natural convection heat losses. The maximum value obtained for forced convection losses, was 157.59 W, while for natural convection losses, the maximum value was 59.72 W.

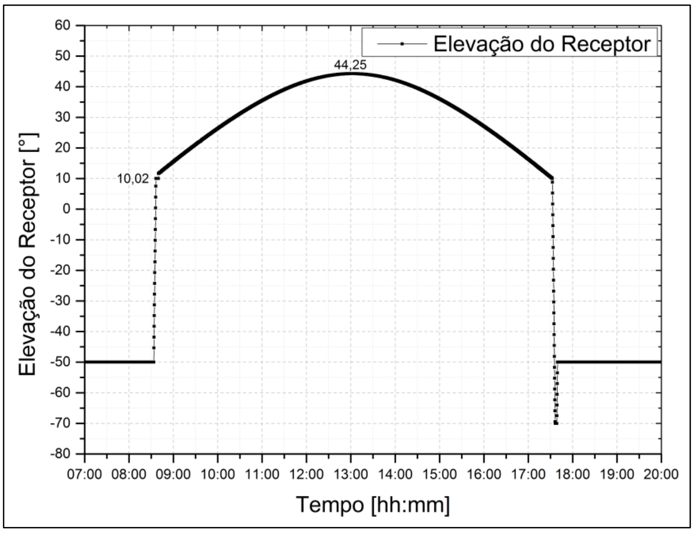

Figure 9. The behavior of the Dish Stirling system elevation for the June 15 in Itajubá-MG.

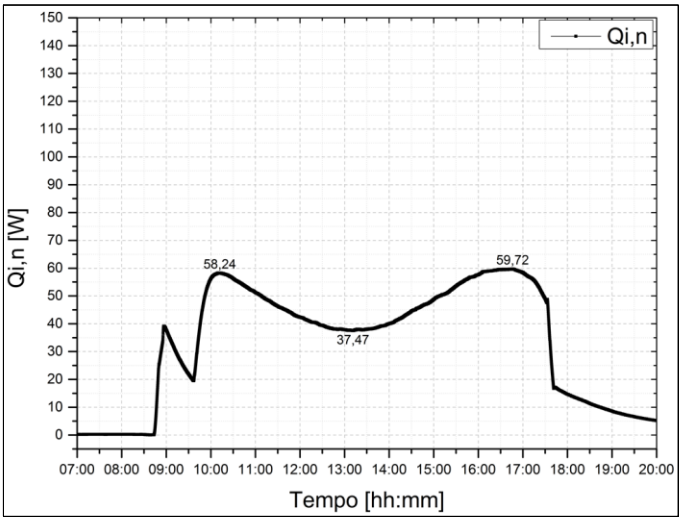

Figure 10. Natural convection heat losses behavior.

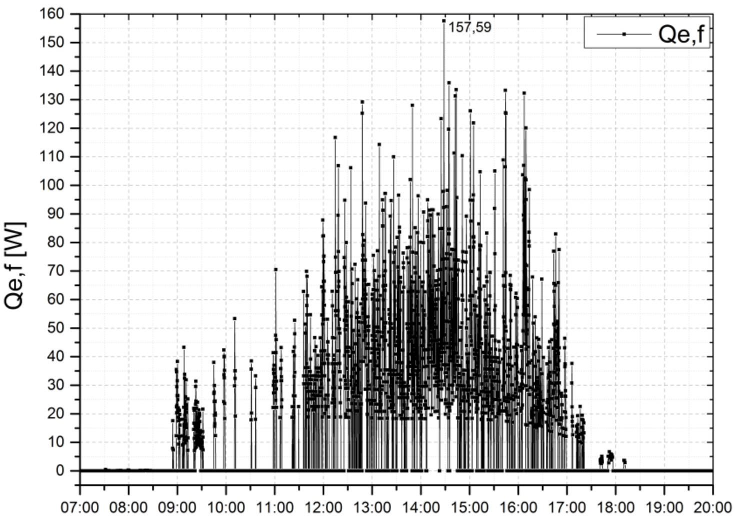

Figure 11. Forced convection heat losses behavior.

Figure 12 shows the thermal losses by radiation occurring in the absorber region of the *Dish Stirling* receiver. Due to its direct relation to the surface temperature, the radiation losses presents a curve with the same shape of the temperature curve (Fig. 13), reaching the highest radiation loss at the point of higher receiver surface temperature. The maximum radiation loss obtained was 391.10 W, what happened when the maximum temperature reached 489.5 ° C by midday.

The radiation heat loss which is the highest thermal losses occurring in the receiver, exceeding the maximum losses by natural and forced convection in 83.73% and 61.43%, respectively. The Figure 13 also shows a decrease in the receiver temperature from 255 ° C to 170 ° C in the period between 08:30 hours and 10:00 hours, due to a failure in positioning system of the Dish Stirling, which lost the reference of the GPS signal and moved the system out of focus for safety.

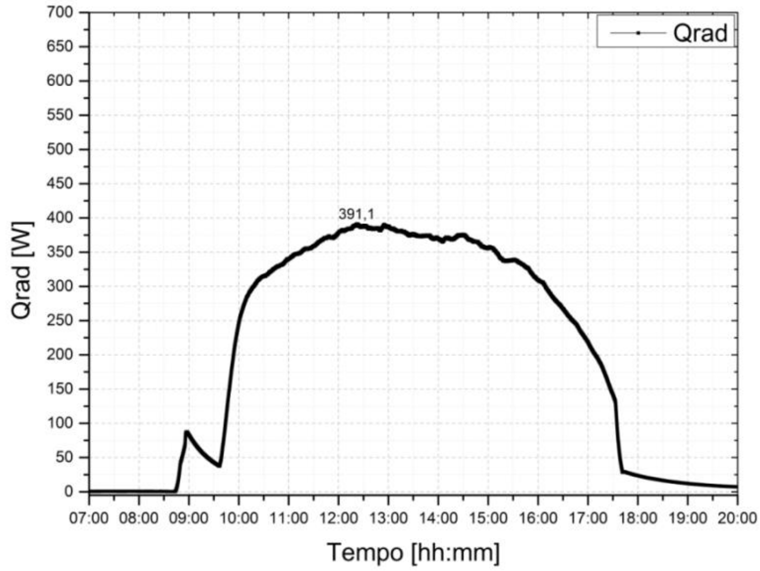

Figure 12. Thermal losses by radiation in the receiver.

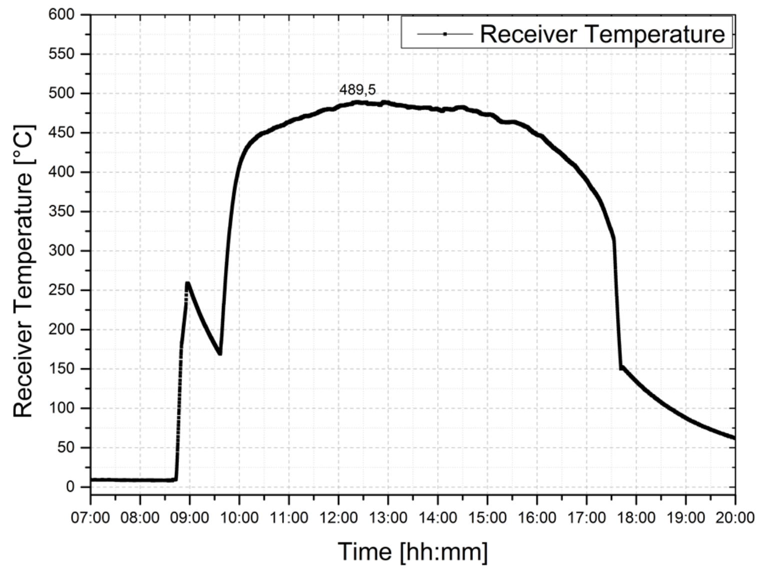

Figure 13. The temperature on the receiver surface.

5. CONCLUSIONS

Results show, that it is possible to improve system performance by change the actual focal position on the receiver of the Dish Stirling system installed at NEST/UNIFEI Heliothermic Energy Laboratory. It is concluded that the current configuration of the Dish Stirling Trinum system presents spillage losses of 6.53% that can be reduced to 0.01% with the repositioning of the receiver to a focal distance of 2.35m.

By means of the mathematical modeling, it is concluded that for the wind speeds greater than 10 m/s (15 m/s and 16 m/s), the highest thermal losses occur at 90 ° inclination and at wind speeds of 10 m/s (5 m/s and 1 m/s), the highest losses occur at slopes below 40 ° (30 °, 20 °, and 0 ° respectively). Among the thermal losses examined, the ones that occur by radiation were identified as the ones that most impact the performance of the system, followed by the convection losses (forced and natural, summed) and finally the losses by conduction. Of the accumulated losses during the day (June 15, 2016) analyzed, the losses by radiation represent 75.12%, the losses by convection 17.44% and the losses by driving 7.44%.

Considering the results obtained in the present work, it is possible concluded that future efforts should be directed to study the optical performance of concentrator and thermal performance of the receiver, aiming to decrease the values of heat losses, mostly in case of heat losses by radiation.

6. ACKNOWLEDGMENTS

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