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ANALYSIS OF A SOLAR PARABOLIC DISH STIRLING ENGINE USING BRAZILIAN NORTHEAST SOLARIMETRIC DATA

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Abstract. *One of the most significant systems that use the sun heat as a source of generating electricity by concentrating the sun heat is the parabolic solar dish. The solar dish tracks the sun direction to focus the heat on the receiver, which drives a Stirling engine-generator unit. This technology has many applications in relatively small capacity applications due to the size and the weight of available Stirling engines and wind loads effects on the dish reflector. In addition to this, among the Brazilian regions, the Northeast presents the greatest potential of solar radiation in the country, result from the semi-arid climate added to the low precipitation and cloud cover. Thus, the objective of this work is to simulate the performance of a solar parabolic dish Stirling engine, Alpha type, using solarimetric data from Natal-RN (Brazilian northeast city), in order to evaluate the feasibility of its implementation. For this, Direct Normal Irradiance (DNI) data were treated to obtain the temperature at the focal point throughout the day, which was used to simulate the engine operation, using Adiabatic analysis. The power and efficiency curves were obtained for one day, which, as expected, followed the curve of DNI. The maximum power and efficiency obtained were, respectively, 129.88 W and 57.8%. The power curve was adjusted and, from the function obtained, the energy generated over a month by the system was obtained, which is equal to 29.04 kWh.*

Keywords: *Stirling engine, parabolic solar dish, CSP, Brazilian northeast*

1. INTRODUCTION

Stirling technology powered by solar energy is one of the most promising solutions among the available technologies since they associate a well-known and available renewable energy resource with a simple and efficient thermal cycle (Barreto, 2017). The Stirling technology has many conveniences, among them it is possible to point out a high theoretical efficiency, equivalent to the Carnot one, and the capability of using any source of energy as fuel, since it has external combustion, i.e., it occurs in a separate system, this flexibility is not only restricted to the fuel type but also to its quality, with the possibility of using so called "dirty" combustibles like biomass, firewood and landfill gas without the need of pretreatment or cleaning (Stirling Engine Assessment, 2002). That allows the usage of locally available fuels as, for instance, agricultural waste. Apart from that, there is also the aptitude of being less pollutant than conventional engines, furthermore, presents low level of noise. These are reasons that explained the cause it has received the attention of researchers of different areas in the last years such as modelling, optimization and application studies (Ni, 2016; Wang, 2016; Babaelahi, 2015; Valenti, 2014; García, 2014). This solution is mainly feasible for small or medium scale solar power plants (Balcombe, 2015) and its combination with thermal energy storage and the hybridization with other energy sources still are open fields of research to explore (Monné, 2014).

The parabolic solar dish is one of the most important methods that use the sun heat as a source of generating electricity by concentrating the sun heat. Also in the current status, different thermal power technologies such as (a) parabolic trough systems, (b) solar tower systems, (c) solar dish systems and (d) linear Fresnel systems are used in solar power generation (Hafez, 2016). The solar dish tracks the sun direction to focus the heat on the receiver, which drives a Stirling engine-generator unit. This technology has many applications in relatively small capacity applications due to the size and the weight of available Stirling engines and wind loads effects on the dish reflector. The applications include generating electricity, cooking, irrigation and water heating.

Since the source of this technology is the solar energy, its availability should be assessed. Among the Brazilian regions, it is the Northeast that stands out, presenting the greatest potential of solar radiation in the country, result from the semi-arid climate added to the low precipitation and cloud cover, with average annual values of 4.8 to 6.0 kWh/m² (SUDENE, 2016), which can be used to bring sustainable development, health and social well-being for its habitants, as well as making it possible to gradually replace the use of wood as an energy source that still represents 35% of the

semi-arid region's energy matrix (INSA, 2016). Figure 1 shows the solar radiation distribution in the Brazilian Northeast.
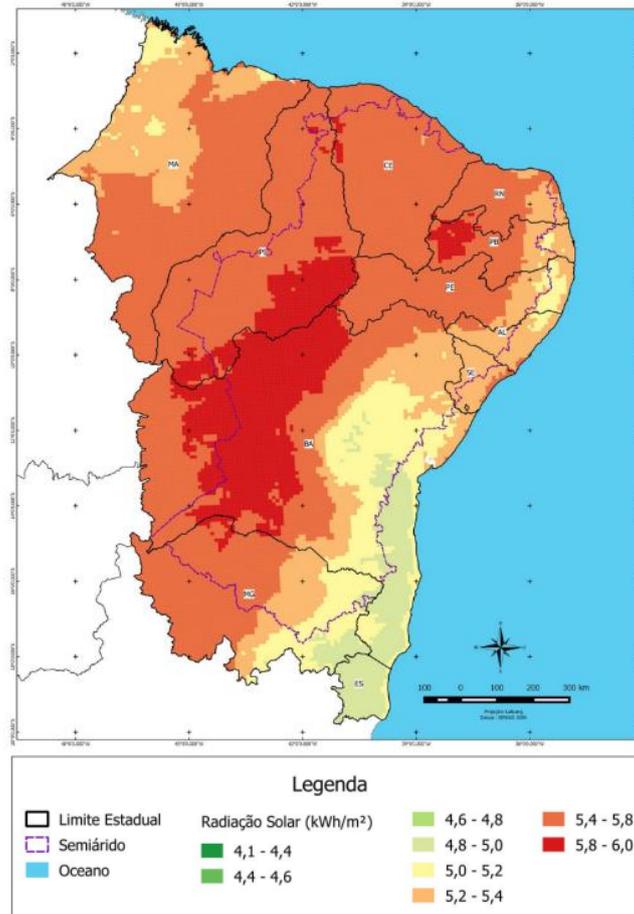

Figure 1. Solar radiation (annual average) in the area of operation of the Superintendence of Development of the Northeast. Source: SUDENE, 2016.

The advantages of solar energy are varied, among them are the possibility of distributed generation (GD) of energy, which is more ideal for large territories due to the reduction of distribution and transmission costs (Corria, 2006), high exergoeconomic and environmental efficiency, that is, less aggressiveness to the environment and economic viability, also has low outstanding limitations.

In fact, the new development of the Stirling technology was mainly motivated by the recent interest in DG, being one of its most researched applications, with another substantial motivator being its possibility to be used in cogeneration systems, proportioning better energy usage and power saving. Thus, the objective of this work is to simulate the performance of a solar parabolic dish Stirling engine, Alpha type – same used by Urieli (1997) –, using solarimetric data from Natal-RN (Brazilian northeast city), in order to evaluate the feasibility of its implementation in this Brazilian state as a form of distributed generation.

2. COMPUTACIONAL PROCEDURE

2.1 Proposed system

The proposed system by this work is composed by a parabolic solar concentrator, which directs the solar radiation to an absorber, and by a Stirling type Alpha engine, which uses this absorber as a heat source, generating work and dissipating heat to the ambient. Figure 2 presents an illustrative scheme of this system.
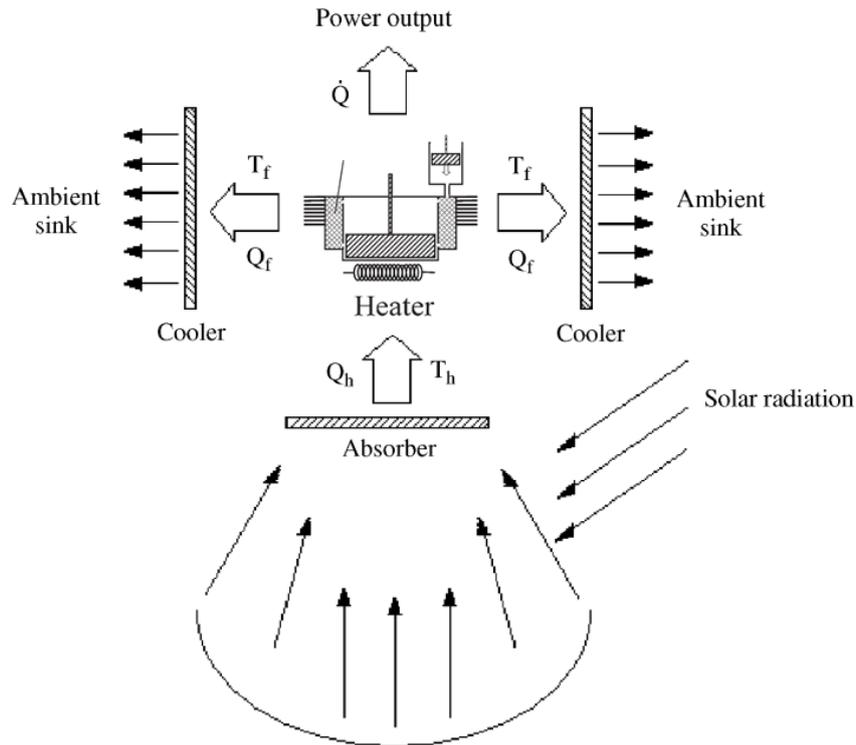
Figure 2. Illustrative scheme of solar parabolic dish Stirling. Source: Tlili et al. (2008), Kongtragool and Wongwises (2003) (adapted).

2.1.1   Stirling configuration and parameters

Figure 3 shows the Stirling type Alpha engine model, suggested by Urieli (1977), which will be used for the analysis performed in this paper. The model consists of five sections: the compression space, the cooler, the regenerator, the heater and the expansion space. Also, the cooler, regenerator and heater are built in the form of pipes, without a matrix.
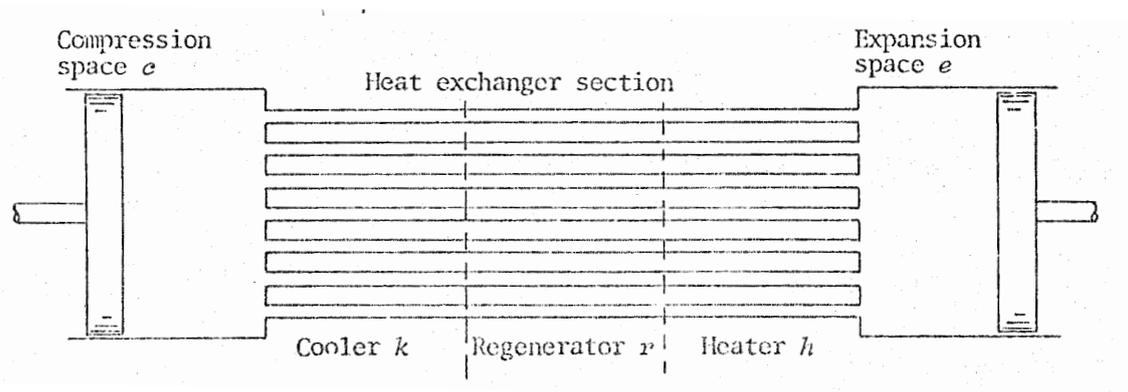

Figure 3. Stirling engine model. Source: Urieli (1977).

To evaluate the performance of the engine, when powered by solar energy, some geometrical and operational parameters must be defined, just as the material of the heat exchangers and working fluid must be specified. For this work, was used the values found by Tlili et al. (2008) to obtain optimum performance in mean temperature differential Stirling engines. Such data are presented in Table 1.

Table 1. Stirling engine parameters. Tlili et al. (2008) and Urieli (1977).

Engine geometry	Compression e expansion clearence volume (cm³)	370
	Compression e expansion swept volume (cm³)	75
	Compression and expansion spaces diameter (cm)	60
	Heat exchangers pipes diameter (cm)	1.1
	Heat exchangers length (cm)	45
	Number of pipes	10
Operational parameters	Mean effective pressure (bar)	8.7
	Cold sink temperature (°C)	from solarimetric data
	Hot source temperature (°C)	from solarimetric data
	Frequency (hz)	75
	Angular phase	90°
Gas properties	Chosen gas	hydrogen
	Ratio of specific heat	1.4
	Gas constant (J/kg.K)	4157.2
	Dynamic viscosity (kg/m.s)	8.35×10^{-6}
	Sutherland constant	84.4
Pipe wall material properties	Chosen material	Stainless Steel
	Thermal condutivity (W/m.K)	25
	Specific heat capacity (J/kg.K)	461
	Density (kg/m³)	7690

2.2 Natal's solarimetric data

Data from 2016 of the city of Natal (Rio Grande do Norte, Brazil), made available by the National Institute for Space Research (INPE), were used (Figure 4). It was considered only the time range in which there is solar radiation. For the data, the defined range was from 420 to 1200 min (07:00 to 20:00), with no noise coming from cloud cover or random measurement errors.
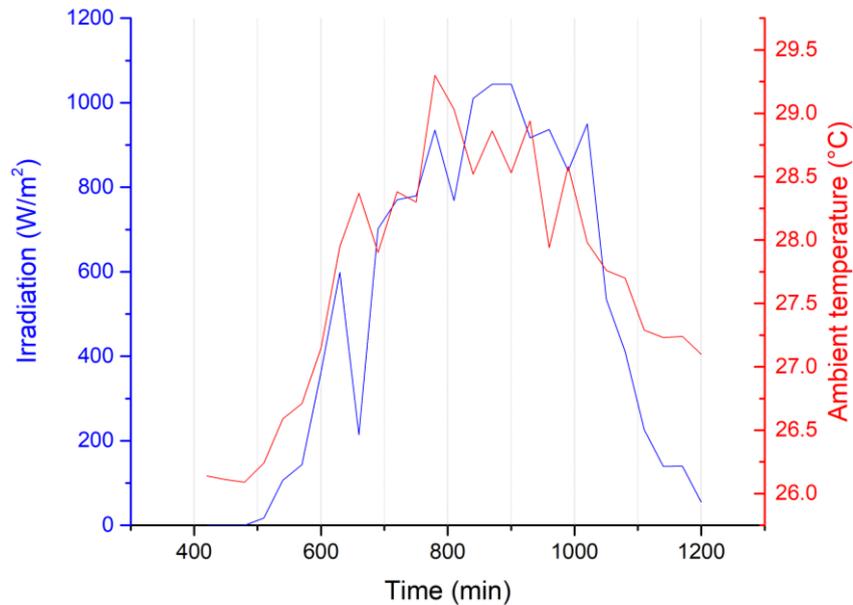

Figure 4. Temperature and radiation values for Natal/RN at the day 01/01/2016.

It is possible to observe that at the top of the Sunshine, the radiation values exceed 1,000 W/m², potential characteristics of the region. It is important to state that the solar radiation data is the Direct Normal Irradiance (DNI).

2.3 Numerical Analysis

2.3.1 Modeling of the Solar dish

The main contributions of heating the Stirling Engine (with mass M and superficial area A), when its geometric center is inserted in the Focal Point (F), are represented in Figure 5.
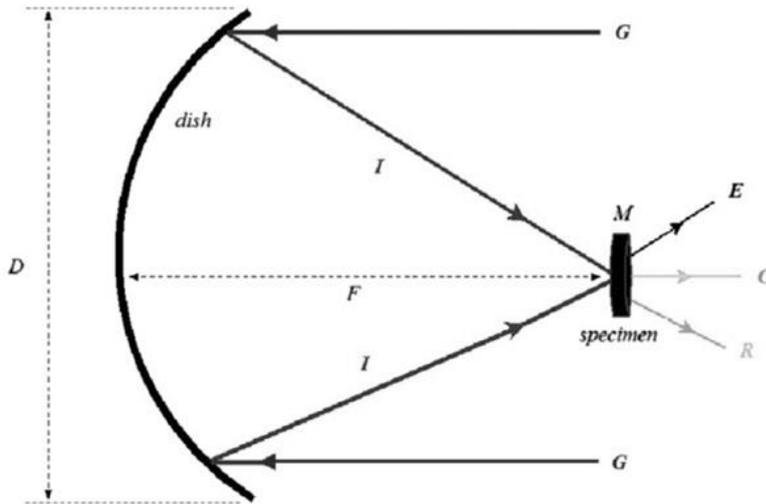
Where:
G is the radiation flux incident on te top of the dish;
I is the rate of radiation reflected of the dish towards the focal point;
R is the rate of radiation reflected off the specimen;
E is the rate of heat losses by emission;
C is the rate of convection heat losses.

Figure 5. Main contributions responsible for heating the specimen (solid) inserted in the Focal Point.
Adapted from Andrade et al (2016).

Concerning physical-mathematical terms, the contributions mentioned in Figure 5 can be systematically organized in the energy balance (performed in the Stirling Engine) represented in Equation 1.

$$Mc_{ps} \frac{dT}{dt} = I - R - E - C \tag{1}$$

By expanding each term, Equation 1 can be rewritten as follows:

$$Mc_{ps} \frac{dT}{dt} = \rho_P \left(\gamma \frac{\pi D^2}{4} G \right) - \rho_C \left[\rho_P \left(\gamma \frac{\pi D^2}{4} G \right) \right] - \varepsilon F_{C \to V} A \sigma (T^4 - T_\infty^4) - hA(T - T_\infty) \tag{2}$$

One of the key challenges in this study was the analysis of some physical properties, such as the reflectivity of the dish surface (ρ_P), the reflectivity (ρ_C) and the emissivity (ε) of the specimen, the shape factor between the specimen and its immediate vicinity ($F_{C \to V}$) and the intercept factor (γ) (Li et al, 2013). However, depending on the operating conditions, it was possible to make some considerations to simplify Equation 2. The following assumptions, used in this work, was also taken by Andrade et al (2016) for numerical simulation:

- $F_{C \to V}$ tends to one: this is acceptable since the concentrating solar systems are exposed to the environment (large open spaces);
- ε is usually close to 0.9: the specimen has cylindrical disc shape and it was considered to be thermally black painted.
- T is same over the whole engine: solid has a high thermal conductivity and finite dimensions (Incropera and Dewitt, 2003);
- ρ_P and ρ_C is assumed to be 0.86: it is reasonable since the specular surfaces materials often exhibits a reflectivity in the range $0.80 - 0.95$ (Duffie and Beckman, 2013; Kumar and Reddy, 2008);
- γ assumed to be 1: the same value used in most of the tests performed by Andrade et al (2016);
- The model neglects the effect of the inclination angle of the dish/target in natural heat transfer correlations, due to the short time to reach the steady state (Andrade et al, 2016).
- h is assumed to be 150 $W/m^2.K$: mean value of that found in Antonietti *et al* (2011) under similar conditions to these analyzed in this work.
- $\frac{dT}{dt}$ assumed to be 0: steady state assumption is taken to performs the calculus at each pair radiation-ambient temperature.

Thus, Equation 2 can be simplified and rewritten as Equation 3. This structure was adopted to perform the numerical estimates of the first step of this work.

$$0 = (1 - \rho_C)\left[\rho_P\left(\frac{\pi D^2}{4}G\right)\right] - \varepsilon A\sigma(T^4 - T_\infty^4) - hA(T - T_\infty) \tag{3}$$

2.3.2   Stirling engine analysis method

To evaluate the type Alpha Stirling engine, the Adiabatic analysis will be used. This analysis considers constant temperatures for cooler (cold sink temperature) and for heater (hot source temperature), linear distribution of temperature for the regenerator, and adiabatic compression and expansion processes. As a consequence of this latter consideration, the temperature in the compression and expansion spaces varies cyclically. Also, the variation of the volumes in the spaces of compression and expansion is considered sinusoidal (Urieli, 1977). Figure 6 presents a schematic that illustrates the considerations of this type of analysis.
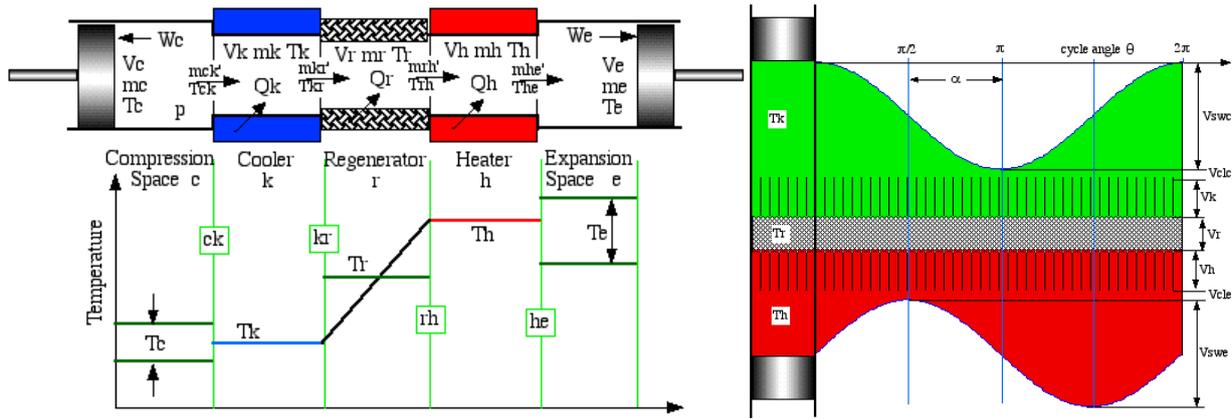

Figure 6. Illustrative model of Adiabatic analysis (Berchowitz and Urieli, 1984).

Following this illustration, some of the analysis equations for this method can be presented. Equations 4 and 5 are used to model the variation of volumes in the compression and expansion spaces, respectively. Equation 6 models the pressure variation, Equations 7 and 8 models the temperature variation, and, finally, Equations 9 to 14 model the heat transferred and work done.

$$V_c = V_{clc} + V_{swc}(1 + \cos\theta)/2 \tag{4}$$

$$V_c = V_{cle} + V_{swe}(1 + \cos\theta + \alpha)/2 \tag{5}$$

$$dp = \frac{-\gamma\,p\,(dV_c/T_{ck} + dV_e/T_{he})}{(V_c/T_{ck} + \gamma(V_k/T_k + V_r/T_r + V_h/T_h) + V_e/T_{he})} \tag{6}$$

$$dT_c = T_c\,(dp/p + dV_c/V_c - dmc/mc) \tag{7}$$

$$dT_e = T_e\,(dp/p + dV_e/V_e - dme/me) \tag{8}$$

$$dQ_k = V_k\,dp\,cv/R - cp\,(T_{ck}\,mck' - T_k\,mkr') \tag{9}$$

$$dQ_r = V_r\,dp\,cv/R - cp\,(T_k\,mkr' - T_h\,mrh') \tag{10}$$

$$dQ_h = V_h\,dp\,cv/R - cp\,(T_h\,mrh' - T_{he}\,mhe') \tag{11}$$
$$dW_c = p\,dV_c \tag{12}$$

$$dW_e = p\,dV_e \tag{13}$$

$$dW = dW_c + dW_e \tag{14}$$

These equations were solved numerically following the methodology presented by Urieli (1977). The results obtained are the useful power and efficiency for the different values of ambient temperature (cold source) and temperature in the focus of the solar concentrator (hot source), which were presented and calculated previously. Thus, the power curve generated by the engine over a day could be plotted and, then, fitting by a polynomial of order 6. The

function that adjusted the curve was integrated from 8,5 hours to 20 hours (range where the solarimetric data were obtained, excluding the period when the radiation is zero), resulting in the energy value, in kWh, generated by solar parabolic dish Stirling over a day. Multiplying this value by 30, was obtained the energy generated in a month.

3. RESULTS AND DISCUSSIONS

3.1.1 Temperature in absorber

After the numerical solution of the Equation (3), the temperature in absorber was found. The temperature variation is intimately related to the radiation as can be observed in Figure 7. Its values exceed 200°C during 600 and 1080 min.
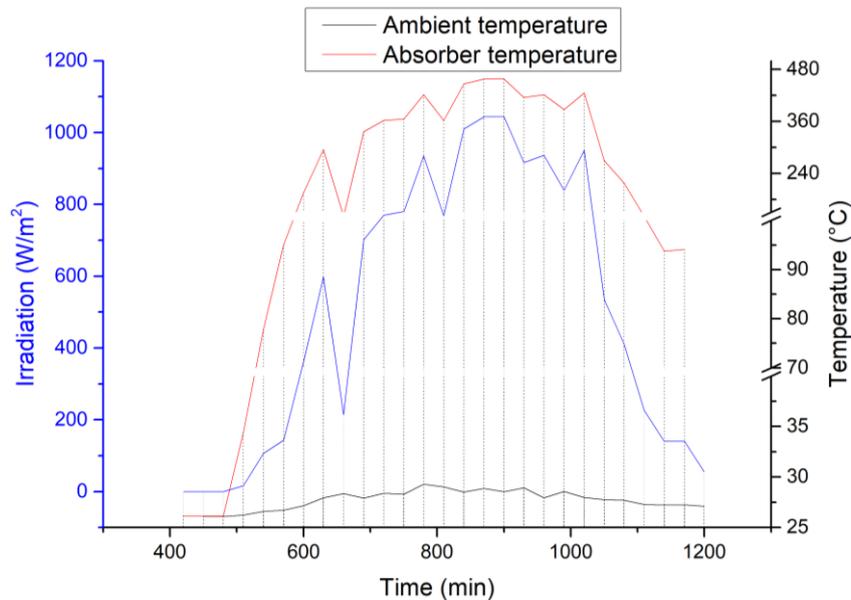

Figure 7. Radiation, absorber and ambient temperature values for Natal/RN at the day 01/01/2016.

3.1.2 Stirling engine performance

Following the methodology presented, graphs of useful power and efficiency were obtained over a day, which are presented in Figures 8 and 9, respectively.
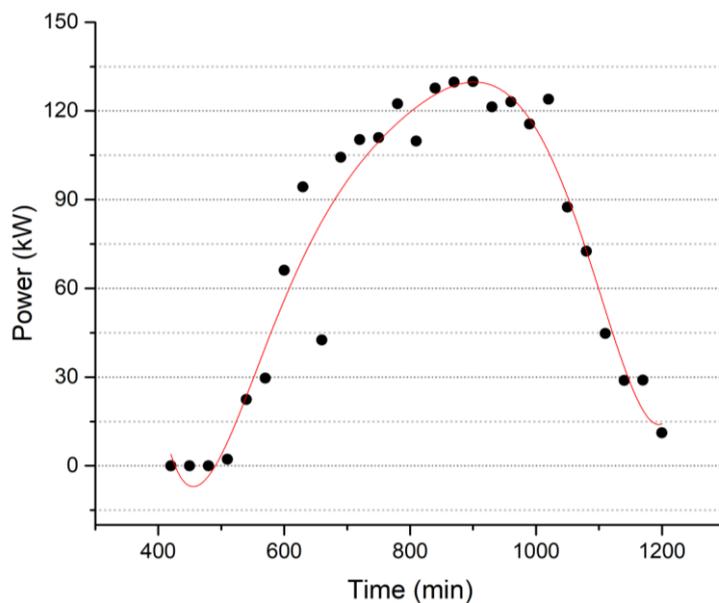

Figure 8. Power generated by solar parabolic dish Stirling engine over a day.
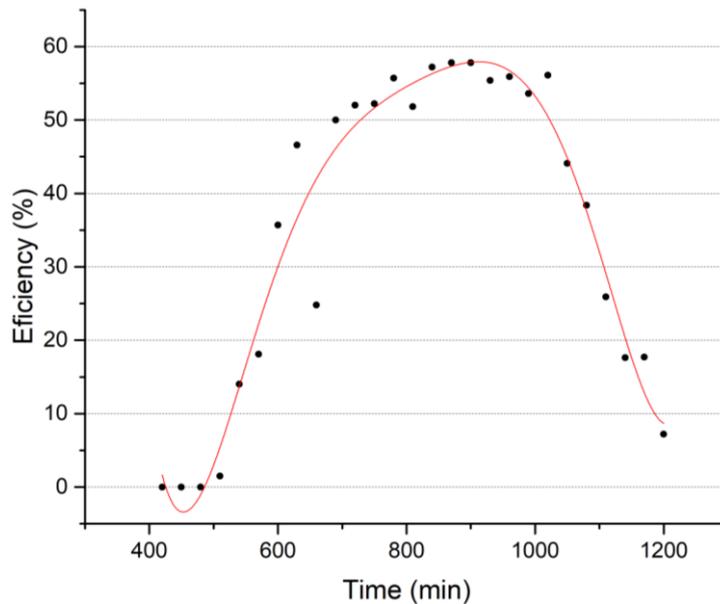
Figure 9. Efficiency of solar parabolic dish Stirling engine over a day.

The table containing the values used to generate these graphs is available in the appendix.
So, fitting the curve of Figure 8, the following function was obtained:

$$P(t) = 12739.825 - 105.023\ x^1 + 0.350\ x^2 - 6.06841 \times 10^{-4}\ x^3 + 5.811 \times 10^{-7}\ x^4 - 2.919 \times 10^{-10}\ x^5 + 6.003 \times 10^{-14}\ x^6$$

Integrating from 510 minutes (when the system effectively start the power generation) up to 1200 minutes, was obteined the value of energy that the system generates per day, which is equal to 968.13 Wh. Therefore, in a whole month it generates 29,04 kWh. According to the Statistical Yearbook for Electric Energy 2017 (EPE, 2017), the average monthly residential consumption for the Brazilian Northeast in the year 2016 was 121 kWh, which means that only one unit of the Stirling solar dish analyzed in this work manages to supply 24% of the monthly demand of residences located in the analyzed region. This is an expressive number, considering that, in general, there are several concentrators installed in a given region in which one wishes to exploit solar energy.

It is important to note, however, that the actual power generated will be lower than the calculated one, since several mechanisms of thermal losses that usually occur in parabolic concentrators were not considered.

4. CONCLUSION

Based on the results obtained, following the methodology established in this paper, it can be concluded that:

1. The useful power curve generated by the Stirling engine and its thermal efficiency at daytime presented the same behavior as the radiation curve;
2. At the time of best performance, the engine achieved power of 129.88 W and efficiency of 57.8%.
3. The energy generated over a month by the analyzed system is 29.04 kWh, which corresponds to 24% of the average monthly demand of the homes in Brazilian northeast.

5. ACKNOWLEDGEMENTS

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7. APPENDIX

Table 2. Values for DNI, temperatures and Stirling engine power and efficiency for Natal/RN at the day 01/01/2016.

Time (min)	Ambient temperature (°C)	DNI (W/m²)	Absorber Temperature (°C)	Power (W)	Efficiency (%)
420	26.14	0	26.14	0	0
450	26.11	0	26.11	0	0
480	26.09	0	26.11	0	0
510	26.24	16.9	34.41	2.21	1.5
540	26.59	107	77.85	22.37	14
570	26.71	143.2	95.05	29.66	18.1
600	27.15	363.3	195.73	66.09	35.7
630	27.95	598.3	295.36	94.27	46.6
660	28.37	214.4	129.77	42.56	24.8
690	27.9	702	336.02	104.33	50
720	28.38	770	362.08	110.31	52
750	28.3	780	365.73	110.98	52.2
780	29.3	935	421.84	122.44	55.7
810	29.03	768	361.84	109.77	51.8
840	28.52	1010	446.68	127.73	57.2
870	28.86	1044	458.14	129.74	57.8
900	28.53	1044	457.91	129.88	57.8
930	28.94	917	415.35	121.32	55.4
960	27.94	937	421.56	123.05	55.9
990	28.58	839	387.49	115.61	53.6
1020	27.98	950	426.05	123.91	56.1
1050	27.76	534.5	269.25	87.45	44.1
1080	27.7	411.2	217.12	72.52	38.4
1110	27.29	226.3	134.22	44.77	25.9
1140	27.23	139.3	93.72	28.82	17.6
1170	27.24	140.1	94.1	28.99	17.7
1200	27.1	55.3	53.72	11.12	7.2

8. RESPONSIBILITY NOTICE

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