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# Optimization of a *Dish Stirling* system working with DIR-type receiver using multi-objective techniques

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## HIGHLIGHTS

- *Dish Stirling* model validation based on data of real technologies.
- Methodology to determine a receiver operating temperature is proposed.
- Optimization process determined optimal input parameter of *Dish Stirling* system.
- Correlation matrix shows influence of dominant parameters over system performance.

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## ABSTRACT

Stirling engine driven by solar energy for thermal to electricity conversion is one of the most promising solution of renewable technologies to reduce the dependency from fossil fuels. Unfortunately, the lack of data about the performance and some operational parameters of this technology limited its detailed characterization and sizing. This paper presents a modeling and simulation of a *Dish Stirling* system working with DIR receiver (Directly Illumined Receiver), to determine its energy production and efficiency, having Itajubá a city in MG/Brazil, as case of study. Mathematical model allows determine the influence of concentrator's parameters on overall system efficiency. Opto-geometric and transfer processes, in concentrator-receiver system are modeled in detail, and this analysis is used to develop a thermal balance of the *Dish Stirling* system, to determine operation parameters like: operating temperature of receiver, receiver thermal heat losses, receiver efficiency, global thermal efficiency and electrical power generated by the system. Also procedure described in this article allows to develop a sensitivity analysis for some parameters as: solar irradiation, collector diameter, wind speed and tilt angle of the cavity. Multi-objective optimization based on NSGA-II algorithm has been employed to optimize the power and the efficiency of the system, by means of integration of *Dish Stirling* mathematical model in *Modefrontier*.

Numerical results show that for low wind speed the radiation heat losses have more influence over system performance, representing 96.06% of total heat losses; when wind speed is greater than 8 m/s convection heat loss (45.27% of the total heat losses) becomes larger than emitted and reflected radiation. Pareto optimal front has been obtained for dual objective, and a final optimal solution has been selected using a decision-making approach by Simple Additive Weighting of decision variables (output electrical power and heat losses). Multi-objective optimization shows a way to obtain an output power of 11.1 kW, with an overall efficiency of 21%, with a significant decrease in heat loss, for the weather conditions of Itajubá-MG. Model gives consistent results confirmed by experimental data used in the validation, showing also that for regions with similar environmental condition like Itajubá, it is more interesting to improve the system material, reducing radiation heat losses.



## 1. Introduction

Among renewable energy source technologies, Stirling engine powered by solar energy, is one of the most promising solution, because combines solar energy, a readily available resource, with an efficient thermal cycle. This technology had received in recent

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**Nomenclature**

| | |
|---|---|
| $A_{con}^{aper}$ | concentrator aperture area, $m^2$ |
| $A_{cav}^{aper}$ | area of the radiation emitting surface |
| $A_{ic}$ | internal cavity area, $m^2$ |
| $A_{ec}$ | external cavity area, $m^2$ |
| $A_a$ | insulation section, $m^2$ |
| Ca | cavity tilt angle, ° |
| $CW_n$, $CW_{n1}$ | power constraints |
| $Cn_s$, $Cn_{s1}$ | system thermal efficiency constraints |
| $D_a$ | aperture diameter in the cavity, m |
| $f_{int}$ | interception factor |
| g | acceleration of gravity, $m/s^2$ |
| *Gr* | Grashof number |
| $h_{ec}$ | convection heat transfer coefficient outside of the cavity, $W/m^2$ |
| $h_{in}$ | coefficient of heat transfer by natural convection inside the receiver cavity, $W/m^2$ K |
| $h_{if}$ | coefficient of heat transfer by forced convection inside the receiver cavity |
| I | beam irradiance, $W/m^2$ |
| K | thermal conductivity of air, W/m K |
| $K_a$ | thermal conductivity of the insulation, W/m K |
| $K_{ac}$ | thermal conductivity of the cavity material, W/m K |
| $K_s$ | *Stirling* coefficient |
| $L_a$ | thickness of the thermal insulation, m |
| $L_c$ | length of each side of the cavity, m |
| $L_{cs}$ | receiver internal diameter at cylindrical region, m |
| $L_{pc}$ | wall thickness of the cavity, m |
| $Nu_{ec}$ | Nusselt number on the outside of the cavity |
| $Nu_{en}$ | outside cavity Nusselt number by natural convection |
| $Nu_{ef}$ | outside cavity Nusselt number by forced convection |
| *Pr* | Prandtl number |
| $Q_m$ | thermal energy received by the working gas, W |
| $Q_{re}$ | concentrated solar energy on the receiver cavity, W |
| $Q_{cc}$ | heat loss by conduction and subsequently by convection to ambient, W |
| $Q_{cn}$ | heat loss by natural convection through the opening, W |
| $Q_{cf}$ | heat loss by forced convection through the opening, W |
| $Q_{rad,em}$ | heat loss by emitted radiation, W |
| $Q_{rad,ref}$ | heat loss by reflected radiation, W |
| *Ra* | Rayleigh number |
| $R_{ef}$ | reflectance of the Concentrator material |
| *Re* | Reynolds number |
| $T_{amb}$ | ambient temperature, K |
| $T_{cav}$ | mean temperature of the cavity, K |
| $T_m$ | mean temperature between the inner wall and the air, K |
| $T_{co}$ | temperature of the working fluid of the *Stirling* engine in the compression space, K |
| v | wind speed, m/s |
| $W_{sistemaDS}$ | electrical power generated by the system |

*Greek symbols*

| | |
|---|---|
| ρ | reflectivity |
| α | receiver absorbance |
| αcav | absorbance of the cavity surface |
| αter | thermal diffusivity, $m^2/s$ |
| $\alpha_{ef}$ | effective absorbance |
| β | coefficient of thermal expansion, $K^{-1}$ |
| ε | receiver emissivity |
| σ | Stefan Boltzmann constant ($5.67 \times 10^{-8}$ $W/m^2 K^4$) |
| θ | tilt angle of the cavity, ° |
| $\theta_i$ | angle of incidence |
| λ | factor of un-shading, 0.99 [8] |
| ν | kinematic viscosity of air, $m^2/s$ |
| $n_{rec}$ | receiver efficiency |
| $n_{sisDS}$ | overall system efficiency |
| $n_{motorS}$ | stirling engine efficiency |
| $\eta_{gen}$ | generator efficiency |
| τ | transmittance |

years privileged attention of researchers specifically its modeling, optimization and application in power generation systems [1], *Dish-Stirling* being now among most efficient ways to convert solar radiation into electricity. Currently, there are interesting works related to this kind of system, as one reported by Wu et al. [2], proposed a new system of electricity generation, based on the concentration of solar energy, which allows the direct conversion of thermal energy into electricity. Electricity converting unit (AMTEC) consist of a concentrator disc coupled to a heat exchanger, which uses a liquid metal as heat transfer medium. Reddy and Veershetty [3] carried a techno-economic feasibility study of a 5 MWe solar parabolic dish collector field, covering 58 locations in India; with dish collectors integrated in a power block of a standard steam turbine-generator to produce the electricity being fed to local grid. Ruelas et al. [4] developed a mathematical model for estimating intercept factor of a Scheffler-type solar concentrator, incorporating a thermal model of the receptor; coupled to a 3 kWe Stirling engine, in a fixed position. Shabanpour et al. [5] sized a solar *Dish-Stirling* micro CHP system for residential application, based on 3E analysis. García et al. [6] developed a characterization of power and efficiency of Stirling engine subsystems that are located between input and output power sections and authors reviewed experimental data from a V160 and V161 engines to evaluate the general validity. It must be pointed out that procedure described in this article is based on models, which have been previously developed through experimental data from very different prototypes. Ni et al. [7] presented an analytical thermodynamic model to predict output power and thermal efficiency of Stirling engines, considering heat and power losses; based on this model the authors built a 100 W b-type Stirling engine. Babaelahi and Sayyaadi [8] developed a thermal model to predict the performance of Stirling engine based on polytropic expansion/compression processes. Adiabatic model of Stirling engines were modified to consider polytropic heat transfers of the working fluid to surroundings by cylinders walls, to increase the accuracy of the model, some loss mechanisms including effect of mass leakage from working to buffer spaces and heat leakage from expansion to compression spaces were considered in basic differential equations of analysis. Kadri and Hadj [9] researched the feasibility and the performance of standalone *Dish-Stirling* micro generation plant for rural electrification, considering integration of different technologies, such as solar *Dish-Stirling* engine, synchronous generator and storage battery. Hafez et al. [10] modeled and simulated different parabolic *Dish-Stirling* engines, studying the effect of solar dish designed features and factors such as material, shape, diameter of parabolic dish. Mohammed et al. [11] proposed a *Dish Stirling* mathematical model to study potential of utilizing heat rejected from this system. Xiao et al. [12] proposed a model based on approach for optical performance assessment and optimization of a solar dish, testing a prototype and measuring flux density to validate such approach.

Other works are oriented to analyze thermal losses in cavity of receiver system, mainly because these can significantly reduce system efficiency, increasing system effective cost [13]. Wu et al. [13],