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Developing a Model for Predicting the Thermal Properties of a Solar Concentrator

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Abstract- It is the purpose of this document to describe the behavior of a solar concentration cooker using the thermal model that has been developed. The solar concentration cooker's ability to concentrate sunlight and generate high temperatures, as well as its durability, can be explained by this model. A coupled system of ordinary, differential nonlinear equations is used to calculate the average temperature of reflector surfaces, container surfaces, and liquid within containers. Experimental measurements and numerical results are in good agreement. The standard cooking power and thermal efficiency of a solar cooker were estimated based on some design parameters. The parameter 'emittance of selective absorbent film' on the surface of the cooking pot has the greatest effect on thermal properties.

Keywords: Thermal model, Solar cooker, Cooking Power, Data centres, Thermal Performance

1. Introduction

A solar cooker with a collector based on a CPC of revolution is studied for its thermal properties. The collector is designed in such a way that it captures the maximum amount of heat from the sun. It is then used to heat a cooking chamber, which in turn cooks the food. The CPC of revolution ensures that the collector remains stable and efficient. The study uses a thermal model based on a system of coupled, non-linear ordinary equations, which approximates very well the experimental behaviour of the water temperature in the solar cooker's container [1]. The study has found that the model can accurately simulate the temperature dynamics of the container, and the model can be used to accurately predict the temperature dynamics in different environmental conditions. The thermal performance of solar cookers can be estimated based on some of the thermal parameters obtained with the use of international experimental standards. These parameters include the temperature of the cooker's surface, the rate of heat gain, and the rate of heat loss. By measuring these parameters, the thermal performance of the solar cooker can be accurately estimated. A similar study was carried out, for example, in [2], which combined both a mathematical model of transient type with experimental results for a box-type solar cooker. An operational model based on controlled parameters and uncontrolled variables is presented in [3] to predict the firing power of a solar cooker. A mathematical model for a box-type solar cooker was developed in [4] that can be used to determine and influence the heating process of the cooker. In [5], the results of using a flat reflector in a box-type solar cooker are presented. The heating temperature increase and heating efficiency were demonstrated. A similar model has been produced for concentrating solar cookers as well as box-type cookers. The mathematical model accurately calculates the heat output of the solar cooker and can be used to optimize the design and performance of the cooker. It can also provide insight into how changes in the design or materials used in the cooker can affect its performance. An analysis of the solar cooker's thermal physics is used to develop the thermal model. The model simulates the average temperature of the water in the absorb vessel, the surface of the concentrator, and the surface of the absorb vessel. As a function of the average water temperature, some design parameters relevant to the study of this type of solar cooker can be used to estimate the standard cooking power and thermal performance of the solar cooker: the collector area, the fluid load, the reflectance of the concentrator material, and the absorption-emittance ratio of the absorbing coating (food container pot). These parameters are important because they determine how much solar radiation is absorbed by the solar cooker, how much energy is transferred to the food, and how long it takes to cook the food.

2. Thermal Model Description

In the solar cooker under study, the collector is based on a Compound Parabolic Concentrator (CPC) of revolution, which concentrates the sun's rays in the focal area where the absorption vessel is positioned. The CPC of revolution is made of two parabolic mirrors that focus the sun's rays on a single point. As the sun moves, the CPC tracks the sun's rays, so that the focal area is always in the optimal position to absorb the sun's heat. The geometry of the collector is composed of two parts, an involute and a parabola section, which are described below using equations corresponding to the polar coordinates of the CPC in the (x; y) plane. The design parameters used for the sensitivity analysis are considered the most important for solar cooker operation. According to the evaluation protocol for solar cookers [12], the mass of water is determined by the values. Reflectance values have been taken from the optimised sheet used for the experiment. Similar values are taken for the absorption-emission ratio of the absorb selective paint, the reflectance of the concentrator reflector, and the size of the collector.

$$x = \begin{cases} r(\sin\emptyset - \emptyset\cos\emptyset) & 0 \le \emptyset \le \dfrac{\pi}{2} + Q_{max} \\ r(\sin\emptyset - A\cos\emptyset) & \dfrac{\pi}{2} + Q_{max} \le \emptyset \end{cases}$$

$$y = \begin{cases} -r(\emptyset\sin\emptyset - \cos\emptyset) & 0 \le \emptyset \le \dfrac{\pi}{2} + Q_{max} \\ -r(A\sin\emptyset - \cos\emptyset) & \dfrac{\pi}{2} + Q_{max} \le \emptyset \end{cases}$$

Where

$$A = \frac{\frac{\pi}{2} + Q_{max} - \cos(\emptyset - \theta_{max})}{1 + \sin(\varphi - \theta_{max})}$$

$$\frac{1}{\sin^2\theta_{max}} = C$$

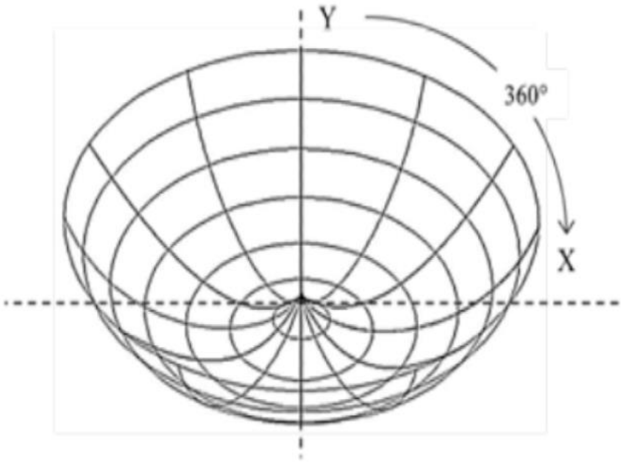

Fig 1. Design of the solar collector

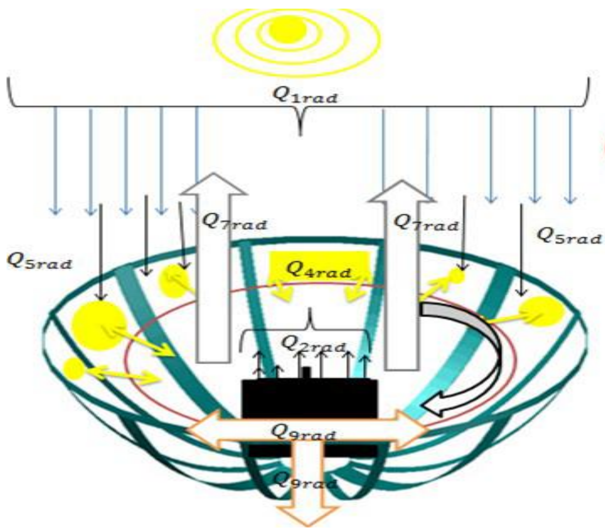

Fig 2. Solar cooker heat fluxes by radiation and convection

2.1 Solar cooker energy balance equations

The solar cooker is operating, radiation is incident on it, and a fluid load is contained in its pot. A coupled system of ordinary differential equations is proposed to model heat transfer, taking into account the energy balance for the absorbing vessel, the reflecting sheets, and the fluid [13].

2.1.1. Equation for heat transfer in an absorbent vessel

The energy balance for the absorber surface of the solar cooker can be expressed as follows

$$m_r C_r \frac{dT_r}{dt} = Q_{1rad} - Q_{2rad} - Q_{3rad} - Q_{4rad} - Q_{8rad} - Q_{9rad} - Q_{3conv2}$$

Where

Q_{1rad} is the heat flux of the radiation incident on the containing pot,

$$Q_{1rad} = A_r \alpha I_D + A_{rf} I_r$$

Q_{2rad} is the radiant heat flux between the pot and the sky,

$$Q_{2rad} = A_r \in_r (T_r^4 - T_{sky}^4)$$

Q_{3conv} is the convective heat flow between the pot and the environment,

$$Q_{3conv} = A_r h_{r,amb}(T_r - T_{amp})$$

Q_{3conv2} is the convection heat flow between the pot and the inside of the cooker

$$Q_{3conv2} = A_r h_{int2}(T_r - T_{int2})$$

Q_{4rad} is the radiant heat flux between the pot and the reflector sheets,

$$Q_{4rad} = A_r \in_r (T_r^4 - T_{rf}^4)$$

In addition,
T_{amb} is the ambient temperature.
T_{sky} is the temperature of the firmament. It is related to the ambient temperature as [13]:

$$T_{sky} = 0.0552 T_{amb}^{1.5}$$

T_{int2} is the average air temperature between the absorber and the reflecting surface.

$$T_{int2} = \frac{T_r + T_{rf}}{2}$$

T_{int} is the average temperature of the air inside the container
$T_{int} = \frac{T_r + T_f}{2} T_f$, It is the average temperature of the water.
T_{rf} is the average surface temperature of the reflectors
T_r is the average temperature of the surface of the containing pot
ϵ_r is the emittance of the selective film of the absorber
σ is the Stefan Boltzmann constant.
h_r ,amb is the convective heat coefficient between the pot and the environment.
h_r ,int 2 is the convective heat coefficient between the absorber and the air inside the solar cooker.
h_r ,inte is the convective heat coefficient between the pot and the fluid.
c_r is the specific heat of the aluminium.
m_r is the mass of the pot container.
m_f is the mass of water.
m_{rf} is the mass of the reflecting lamellae of the concentrator.
α_{rf} is the absorptance of the reflectors.
α is the absorbance of the absorber.
A_r is the surface area of the containing vessel.
t is the time.
c_{rf} is the specific heat of the aluminium reflector foils.
c_f is the specific heat of water.
η_0 is the optical efficiency.
ρ_m is the reflectance of the reflecting surface.
n is the average number of reflections in the CPC.
P_c is the firing power.
P_{test} is the standard firing power.
h_r, amb is the convective heat coefficient between the reflecting surface and the environment.
ID is the direct irradiance.
IR is the reflected irradiance.
Q_{5rad} is the incident radiant heat flux.
Q_{6conv} is the convective heat flux between the reflective sheeting and the environment.

2.1.2. Equation for Heat Transfer at a Reflecting Surface

Applying the energy balance on the surface of the reflecting surface of the cooker, the following equation is obtained:

$$m_{rf} c_{rf} \frac{dT_{rf}}{dt} = Q_{5rad} + Q_{4rad} - Q_{6conv} - Q_{7rad} - Q_{3conv2} \quad \text{----------} \ (2)$$

Where,
Q_{7rad} is the radiative heat flux between the reflecting surface and the firmament.

$$Q_{7rad} = A_{rf} \in_{rf} \sigma(T_{rf}^4 - T_{sky}^4)$$

Where,
A_{rf} is the area of the solar collector.
ϵ_{rf} is the emittance of the reflective sheeting.

2.1.3. Equation for Fluid Heat Transfer

Finally, the equation for the energy balance in the fluid contained in the pot is presented:

$$m_r C_r \frac{dT_r}{dt} = Q_{8conv} + Q_{9rad} \quad \text{----------} \ (3)$$

Where,
Q_{8conv} is the convective heat flux between the pot and the inside of the cooker

$$Q_{8conv} = A_r h_{r,int}(T_{int} - T_r)$$

Q_{9rad} is the radiant heat flux between the fluid and the containing vessel.

$$Q_{9rad} = A_r \epsilon_r \sigma(T_r^4 - T^4)$$

Equations (1), (2) and (3) represent a system of coupled, non-linear differential equations for the variables (1), (2) and (3). Variables T_r , T_{rf} and T_f .The values for the convective heat transfer coefficients are taken from [13,14].

3. Parameter Calculation and System of Equations Solution

To solve the set of coupled nonlinear differential equations, (1), (2) and (3), the fourth order Runge-Kutta method has been used, through a code programmed in Fortran [15]. The initial conditions have been taken as the ambient temperature. That is to say;

$$T_r(t=0) = T_{amb,} T_{rf} = T_{amb} Y T_f = T_{amb}$$

According to the results obtained by comparing the numerical solution of the average water temperature with the experimental data, an error of less than 5% is found in the test cases considered [16].

3.1 Thermal Efficiency and Firing Power Calculation

By solving the system of equations, numerical values were obtained for the average temperatures of the vessel surface, the reflecting surface and the water as a function of time. With the latter, the firing power can be estimated by using the right-hand side term of equation (3), the standard firing power is defined when the temperature difference between the temperature of the fluid and the ambient temperature, i.e,

$$\Delta T = T_f - T_{amb} = 50°C\, P_c = mc_p \frac{dT}{dt}$$

where ΔT, is the difference between the fluid and ambient temperature (K).

The standard firing power [12]:

$$P_{test} = P_C(\Delta T = 50°C)\frac{700W}{I_R} \text{ ----------- (4)}$$

The thermal efficiency is calculated using the expression (8) (see for example [15]).

$$\eta = \frac{mc_p(T_{f2} - T_{f1})}{A_r \int_{t_i}^{t_f} I_R\, dt} \text{ -------------- (5)}$$

Where,

η is the thermal efficiency of the solar cooker

T_{f1} is the water temperature at time t_i

4. Variations of Design Parameters in Numerical Simulations

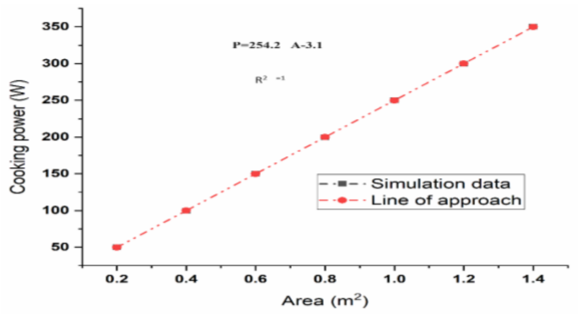

Fig 3. Standard firing output.

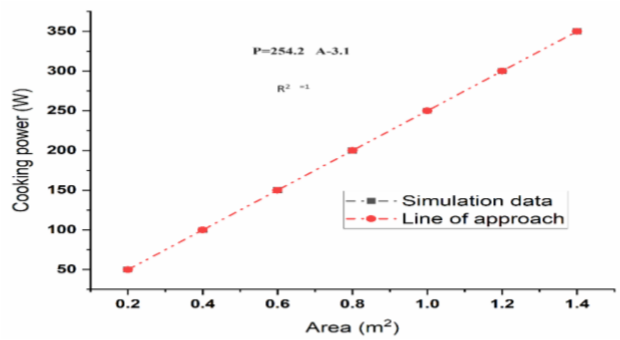

Fig 4. Solar cooker collector area thermal performance

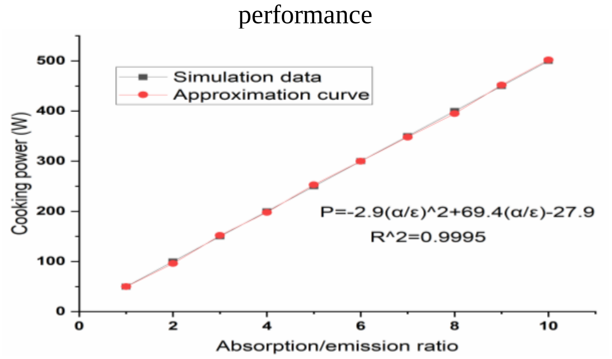

Fig 5. Standard firing output

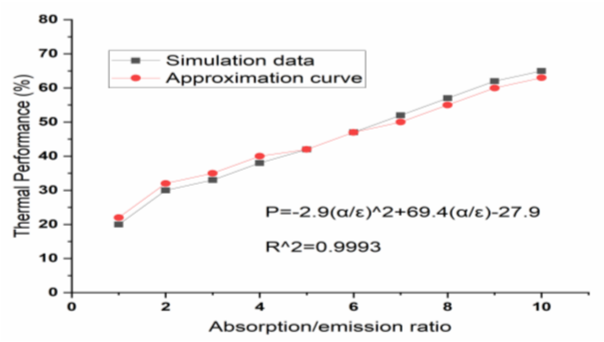

Fig 6. Emittance-to-absorbance ratio of thermal performance

In the following, the variation of some of the design parameters of the solar cooker is presented, obtaining the corresponding numerical simulations for the standard firing power and thermal efficiency [17]. The set of parameters considered are the following: the absorptance-emittance ratio of the selective absorber film, the reflectance of the concentrator reflector, the size of the collector, and the amount of fluid in the pot. The fixed values take these values because these are the values of the materials used for the construction of the solar cooker [18]. The absorbance-emittance ratio is that of the paint used, likewise, the reflectance value corresponds to that of the solar cooker foil used in the production of the solar cooker. The corresponding graphs are shown below, considering the variation of the parameters. The other parameters are considered fixed, the numerical values taken for the simulation are shown in Table 1.

Table 1. For the case of the variation of the solar collector area

Parameter	Value
Absorbance-Emittance ratio	2.5
Reflectance	0.94
Mass of water (kg)	5.00

Figure 3-4. shows the standard firing output and thermal efficiency as a function of the collector collector area of the solar cooker, which has been taken in the range (0.1, 1.5) m2, because these are the values corresponding to the case of small solar cookers. In both cases, an approximation curve to the numerical simulation data is considered, relating the standard firing power and the thermal efficiency, as a function of the solar cooker's collection area [19]. Figure 4-5. shows on the vertical axis the standard firing power and thermal efficiency and on the horizontal axis the absorptance-emittance ratio, which has been taken in the range (1, 10). The lower limit corresponds to surfaces that emit as much as they absorb and the upper limit to those that absorb 10 times as much as they emit. This limit corresponds to that of optimised solar selective paints [20]. The numerical values of the fixed parameters are shown in Table 2.

Table 2. For the case of the variation of the emittance-absorbance ratio	
Parameter	Value
Reflectance	0.60
Reflectance	0.94
Mass of water (kg)	5.00

Similarly, in Figure 6-7, the standard firing power and thermal performance as a function of the reflectance of the reflecting surface is taken in the range of (0.5, 0.93). The lower limit corresponds to the reflectance in the solar spectrum of a mirror-finished steel surface and the upper limit to a surface optimised for solar applications [21]. The numerical values of the other parameters are shown in Table 3.

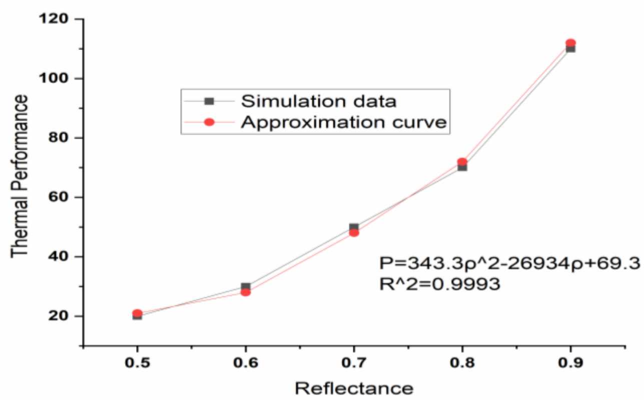

Fig 7. Standard firing rate

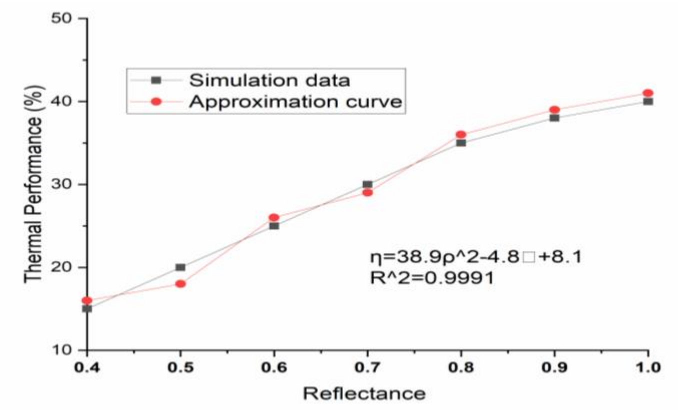

Fig 8. Thermal performance, as a function of reflectance

Table 3. For the case of the reflectance variation	
Parameter	Value
Emittance to absorbance ratio	2.22
Collector area (m2)	0.60
Mass of water (kg)	5.00

Finally, in Figure 7-8, the standard cooking power and the thermal efficiency are shown, as a function of the amount of water in the container [22]. The values are taken in the range (0.5, 5) kg, the lower limit corresponds to the amount of food for one person and the upper limit to the maximum capacity of the container [23]. The values for the other parameters are shown in Table 4.

Table 4. For the case of variation of the fluid load	
Parameter	Value
Emittance to absorbance ratio	2.22
Reflectance	0.94
Collector Area (m2)	0.60

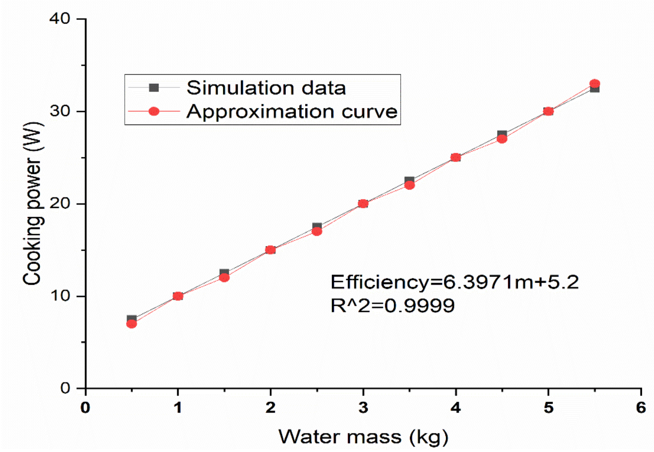

Fig 9. standard firing output as a function of the mass of water in the solar cooker container.

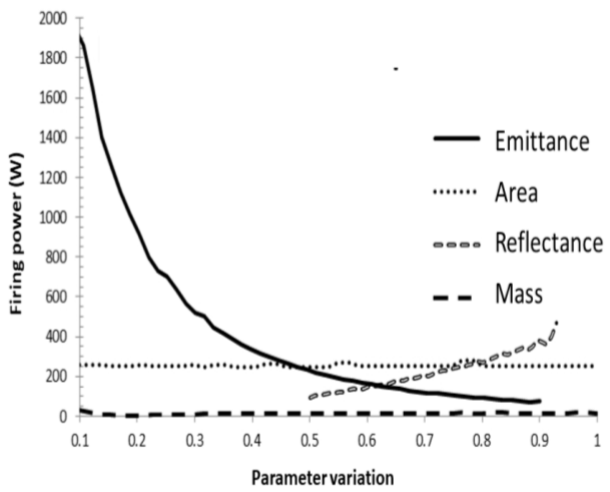

Fig 10. The ratio of the standard firing output to the design variables of the solar cooker

In the graphs (Figure 9.) showing the variation of the standard firing power and thermal efficiency, as a function of the different variables, a line of adjustment to the data obtained in the numerical simulation has been considered for the standard firing power and the thermal efficiency, obtaining some marked correlations. Finally, in order to study the variations of the standard firing power and thermal performance as a function of the design parameters, the rate of change has been considered [24]. Figure 10 below shows the rate of change of firing power with respect to each of the parameters that have been dimensioned and mapped to the interval (0,1). In the same way, Figure 11 shows the rate of change of the thermal performance of the solar cooker, as a function of each of the parameters considered. In both cases, it is noticeable that the ratio of change is greatest with respect to the emittance of the selective film. absorber, in small ranges of emittance [25]. Secondly, the rate of change with respect to reflectance implies significant changes, especially when the reflectance is greater than 90%. In the case of the collector area and the mass in the container, the rate of change remains approximately constant.

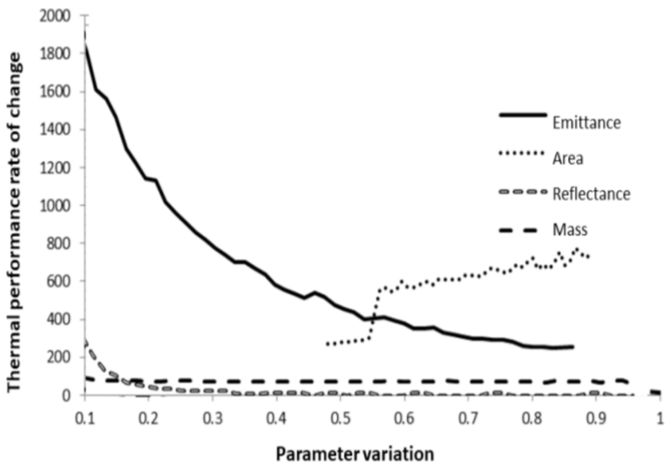

Fig 11. Thermal performance change as a result of design variables for solar cookstoves

5. Conclusion

This study proposes a thermal model to simulate the thermal behaviour of the solar concentrating cooker in terms of a coupled non-linear system of ordinary differential equations. The unknowns in these differential equations are: average temperatures of the water, of the absorber vessel surface and of the reflecting surface. An analysis of variation of design parameters based on numerical simulations of, specifically, the average fluid temperature, was used to calculate the standard firing power and thermal efficiency. The study considered variations in four design parameters: collector area, mass of fluid in the pot, absorbance-emittance ratio and reflectance. Fit curves were obtained for the data from the simulations for the standard firing power and thermal performance calculations, with a functional expression of these in terms of the design variables. Using the rate of change analysis technique, it was found that the largest variation for the design parameters corresponded to the case of the emittance of the absorber film on the surface of the vessel containing the food to be cooked with the solar cooker pot. It was also found that the rate of change related to the concentrator reflectance is significant in cases where it is greater than 0.9. Finally, the rates of change obtained for the size of the collector and the amount of water in the pot remained practically constant.

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