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Research Article

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Comparative Exergy Experimental Evaluation of Parabolic and Elliptical Solar Cookers

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Abstract

This article focuses on the comparative exergy experimental evaluation of parabolic and elliptical solar cookers designed at the solar energy laboratory of Felix Houphouöt Boigny University in Abidjan. Two specificities characterize the two prototypes: the focal point which is wrapping up by a glass cubic box and the bottom of the receiver (pan) which is placed at an optimized axial distance from the focal point. Exergy analysis is a useful tool to assess the relative performance of different geometry solar cookers. In fact, exergy measures the "useful" energy that can be extracted from an energy flow. The purpose of this study is to compare experimentally the output exergy of the designed cookers. Other performance indicators are also calculated such as the peak power exergetic (Ξ_{x0_max}), the exergetic temperature difference gap product ($\Delta T\Xi_{x0}$), the heat loss coefficient (U_{Lx0})) and the quality factor (ρ_{x0}). The results of the cooking tests showed that the parabolic cooker is performed better than the elliptical cooker. A comparative study of parameters indicators of exergy performance for concentrator cookers met in the literature with the cookers studied show that they can belong to the range of SK-14 type cookers which is considered as the best devices for fast cooking small residential operations.

Keywords: Exergy output; Parabolic and elliptical cookers; Exergy peak power; Heat loss coefficient; Quality factor

Introduction

In recent years, most sub-Saharan countries experience considerable urbanization resulting in increased request for energy. On the culinary level, gas (LPG) is used in large cities, and especially in residential neighbourhoods of a certain standing. But it is increasingly expensive and often out of stock. In rural areas where isolated remote villages, cooking is always done with firewood for both family and collective needs. In Côte d'Ivoire, this source of wood energy is widely used. Its share in the overall energy needs is estimated about 76% (in 2008) [1]. It is mainly exploited in the form of firewood and charcoal, agricultural, agro-industrial and forestry residues [1]. The domestic use of vegetation cover (firewood, coal, etc...) and especially the extraction of fuel wood increases with population growth. The supply of wood and charcoal is also becoming increasingly difficult and expensive linked to rapid desertification result of strong droughts. To overcome these problems, one of the natural and easy alternatives is of course the use of the energy carried by the solar radiation. Côte d'Ivoire has an enormous solar field. The average daily sunshine varies between 3 and 5 kWh/m^2 depending on the region and insolation duration of 6H [1]. This non-polluting and free energy can be converted into useful energy for cooking by the collectors called solar cookers. These are devices which concentrate the energy of the solar radiation and convert it into thermal energy. This study focuses on the comparative exergy evaluation of two cookers parabolic and elliptical. The exergy analysis is another means of evaluation and comparison of solar cookers [2]. Panwar et al. [3] noted that the study and the testing of systems used solar energy according to the laws of thermodynamics further draws the attention of many researchers. This concept has been widely discussed by several authors whose Bejan and Petela [4-6]. In addition, the first to introduce this notion is Gouy, who, at the end of the 19th century, defined the notion of usable energy, now renamed exergy by many authors [7]. The basic idea is to consider that a thermodynamic system interacts with its environment, which behaves as an infinite reservoir at constant temperature and pressure, and of fixed composition, which means that the studied system is small enough in front of this environment to do not disturb it. However, the first study on the energy and exergy analysis of solar cookers was conducted by Oztürk [8]. He noted that the exergy analysis is best and is more convenient than the energy analysis for predicting the performance of the solar cooker. Currently, in the world, thermodynamic analysis of solar cooker performance is considered the most efficient way of obtaining accurate information on energy yields and losses due to irreversibility in real-life situations [9]. In addition, Larson et al. [10] and Szargut et al. [11] also performed work on exergy. The experimental data, to perform the calculation and obtain the thermal parameters, are extracted from Kaushik et al. [12].

Presenting and Sizing of the Cookers

Experimental device

Figure 1 the reflector of the cookers is wrought of galvanized sheet, divided into 12 facets covered with square mirrors of 3 cm side. A glass cubic box, dimensions 27.00 cm x 27.00 cm x 27.00 cm is suspended to a metal beam. The glass used for making the box has a thickness of 0.30 cm and a transmission coefficient of 0.90. He wraps the focus. Its docket is to reduce the impact of the wind on the receiver placed on the focus but also create a greenhouse effect. In its operation, the opening of the reflector must be oriented in the direction of the sun. This orientation is carried out manually every 20 minutes.

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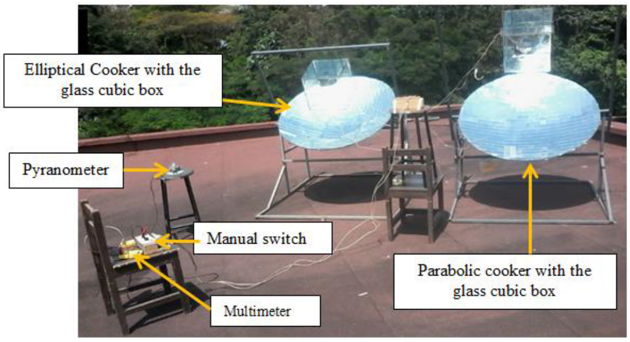

Figure 1: Gives a synoptic view of the experimental device with the glass cubic boxes.

	Concentration cockers	
Parameters	**Parabolic**	**Elliptical**
Opening diameter d (m)	1.20	1.20
Focal length f (m)	1.00	0.60
Depth h (m)	0.09	0.20
Receiver diameter d_2 (m)	0.15	0.15
Receiver height h_{abs} (m)	0.10	0.10
Opening angle (°)	33.40	30.00

Table 1: Geometric parameters of the cookers.

Geometric parameters of the cookers

In Table 1 are reported the values of some geometric parameters of parabolic and elliptical cookers designed. In addition, specificity also characterizes the studied prototypes. The bottom of the pan is always placed at a distance from the focal point called the back axial distance of the focal point. It has been optimized and can be calculated by the expression (1) [13]:

$$L = 2 \cdot h_{abs} \cdot \frac{|h - f|}{d} \quad (1)$$

With h_{abs}, the size of the pan

The values of L are 0.15 m and 0.07 m respectively for parabolic and elliptical cookers designed.

Figure 2 illustrates this back axial distance of the focal point [13]. The two prototypes have the same opening area of the reflector equal 1.13 m^2 and the same receptor area 0.14 m^2.

Methodology of the Thermodynamic Evaluation of Solar Cookers

Definition of exergy

According to Panwar et al, mentioned by Yettou [9], the exergy term is defined as the maximum amount of work that can be obtained from a system. As for Szargut et al. [11], they were interested rather in the interpretation of the quality of the process considered. Exergetic analysis involves examining exergy at different points in a sequence of energy conversion as well as the steps containing a lot of losses. This is based on the second law of thermodynamics and the notion of irreversible entropy production [9,12]. It is therefore a true measure of performance. It is a very useful tool to improve the performance of the systems. In an outflow steady process, during a finite time interval, the overall exergy balance of solar cooker can be written as [14-16].

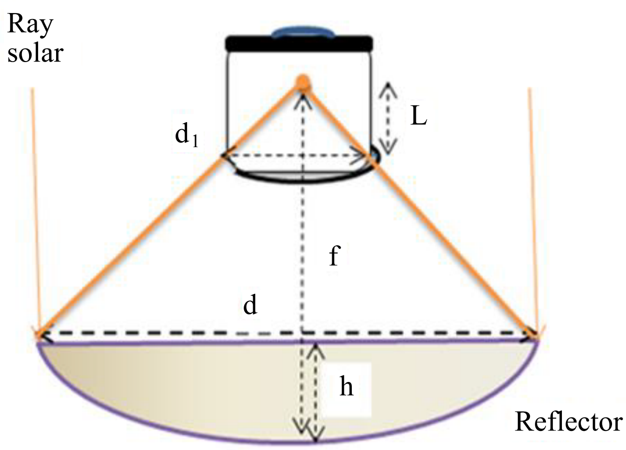

Figure 2: Back axial distance L of the focal point.

Exergy Input=Exergy Output +Exergy Loss (2)

The exergy of solar radiation, as exergy input Ξ_i in the solar cooker, can be calculated using the available solar energy flux ($I_s A_{SC} \Delta t$) and expressed via equation (3).

$$\Xi_i = I_s.\Delta t.\left[1 - \frac{4}{3}\left(\frac{T_a}{T_S}\right) + \frac{1}{3}\left(\frac{T_a}{T_S}\right)^4\right] A_{SC} \quad (3)$$

Where:

Δt=Recording time between two instants (s)

I_s=Intensity of solar irradiance (W/m^2)

T_s=The sun's surface temperature (~5800 K)

T_a=The ambient temperature (K)

A_{sc}=The cooker opening area (m^2)

Thus, the output exergy of the solar cooker is calculated using equation (4):

$$\Xi_o = (mC_P)_W \cdot \left[(T_{Wf} - T_{Wi}) - T_{ra} \ln\left(\frac{T_{Wf}}{T_{Wi}}\right)\right] \quad (4)$$

Where:

$(mC_p)_w$=Heat capacity of water in the cooking vessel (J/K)

$(m)_w$=Mass or quantity of water (Kg).

T_{wi}=The initial water temperature (K).

T_{wf} =The final water temperature (K).

T_{ra} =Ambient temperature of reference during the given time interval (K).

Determination of cooker performance indicators parameters

The performance indicators of the solar cookers used are: the peak exergy power (Ξ_{xo}), the exergy temperature difference gap product (ΔT), the heat loss coefficient (U_{Lxo}) and the quality factor (ρ_{xo}). Each is defined as follows [9,16]:

The peak exergy power is the maximum output power obtained through curve fitting by plotting the graph between exergy output power and temperature difference (ΔT). This can be realistically considered as a measure of its fuel ratings. A cooker which reaches a high peak exergy power has a wide temperature difference.

The product gap of the exergy temperature difference corresponding to the half power points and the peak exergy power ($\Delta T\Xi_{xo}$), can also be considered as another reference indicator in this type of analysis. It represents the rate of increase in water temperature during the evaluation period. A high value of this product gap of exergy temperature difference means that heat losses are minimized.

The heat loss coefficient (U_{Lxo}) of the device can be calculated by dividing the value of the slope of the line, obtained through linear curve fitting of exergy lost variations with temperature difference, by the value of focal area. In this approach, we are not dependent much on extrapolation and all the parameters were realistically calculated from the graphs/data.

The quality factor (ρ_{xo}) is defined as the ratio of the peak exergy gained to the exergy lost at that instant of time can be considered the solar cooker. A higher quality factor is always desirable.

Results and Discussion

During the experiment, the measured quantities were global solar irradiance using Eppley-type pyranometers and the temperatures (cooking and ambient) with platinum resistance thermometers every 10 min. The experimental day selected was 26/10/2017 average daily global irradiance 806.86 W/m^2. Regarding the cooking test, it was to boil 10 eggs in 0.5 L of water. The maximum cooking time was set at 40 min. At the end of the test, all the eggs were cooked well with the two cookers.

Let's now examine the exergy results obtained with each of the cookers studied.

With the parabolic cooker

Figure 3 shows the variation curve of the exergy output power versus the water temperature difference for the parabolic cooker.

With this adjustment curve, the peak power and the product gap of the exergy temperature difference are determined. For a mass of water of 0.50 kg, they are respectively 12.80 W and 473.60 WK for a temperature difference of 37.00 K. As for the thermal loss coefficient, it is obtained from the evolution curve of the exergy power loss versus the temperature difference of water shown in Figure 4.

As the surface of the receiver is known 0.14 m^2, the heat loss

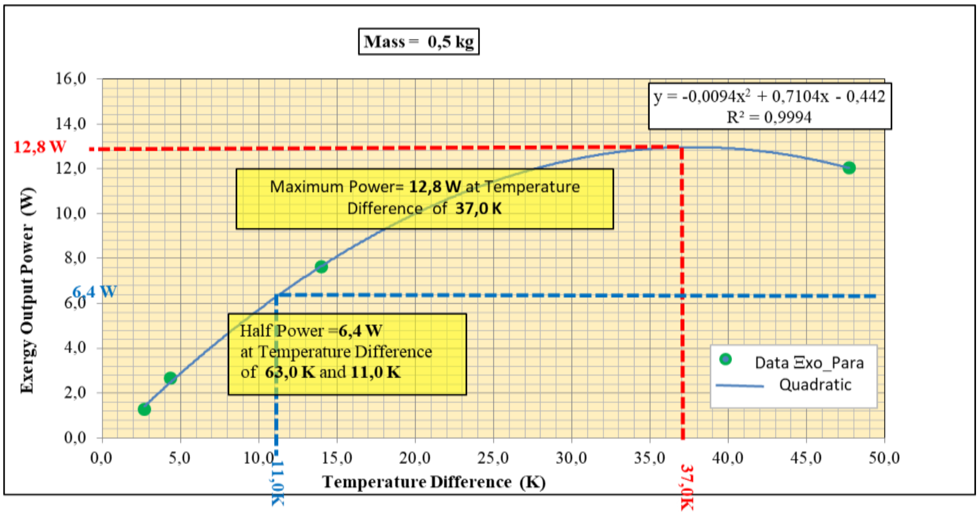

Figure 3: Curve of variation of the output exergy output power versus the temperature difference of the water (parabolic cooker).

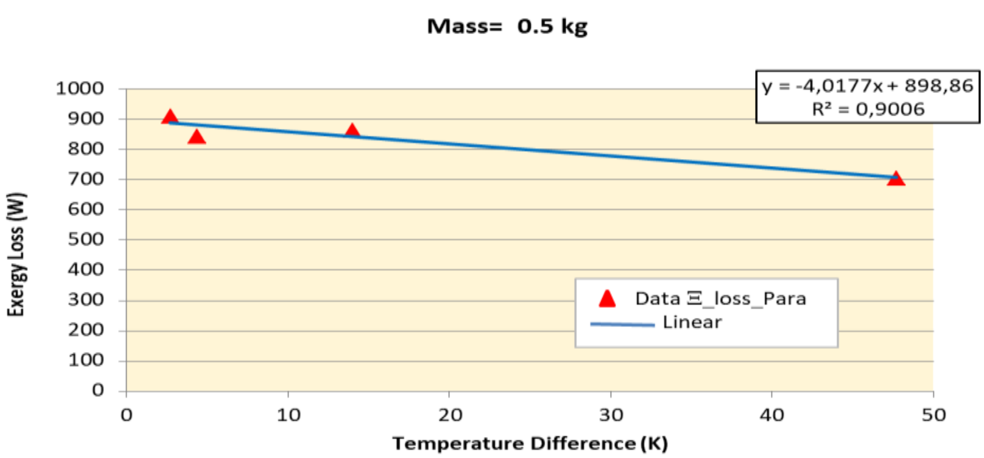

Figure 4: Curve of variation of the exergy power loss versus the temperature difference of the water (Parabolic cooker).

coefficient obtained by dividing the slope of the curve by this surface is 22.60 W/m^2 K for the parabolic cooker.

With the elliptical cooker

Figure 5 illustrates the variation curve of the exergy output power versus the temperature difference of the water.

For the same mass of water of 0.50 kg, the peak power exergy is 11.80 W for a temperature difference of 36.80 K. The corresponding product exergy temperature difference is 429.52 WK.

Figure 6 shows the evolution curve of the exergy power lost versus the temperature difference of the water.

Comparative evaluation

Of the two cookers studied in Table 2 are recorded the values of the various performance indicators of the two cookers.

Mw and Ar respectively denote the mass of water and the area of the receiver.

The analysis in Table 2 shows that the parabolic cooker has a low heat loss coefficient compared to that of the elliptical cooker. As for the quality factor, it is higher for the parabolic, 0.11 than for the elliptical, 0.09. In addition, the peak power and the product gap of the exergy temperature difference are relatively high for the parabolic cooker than for the elliptical cooker. This shows that the parabolic cooker is more efficient than the elliptical cooker.

Two cookers with cookers from the literature

In Table 3 are recorded some indicators parameters exergy performance of the cookers parabolic and elliptical concentrator collected in the literature [9,16,17].

The comparative analysis of Tables 2 and 3 used to assess the performance of the studied prototypes.

Thus, when considering the product of the exergy temperature difference which represents the rate of increase in water temperature during the evaluation period in Table 3, the SK-14 type and the Scheffler type give a high value. According to a study [9], they are more suitable for quick cooking. In Table 2, the prototypes studied have lower values of the rate of temperature increase than SK-14 and

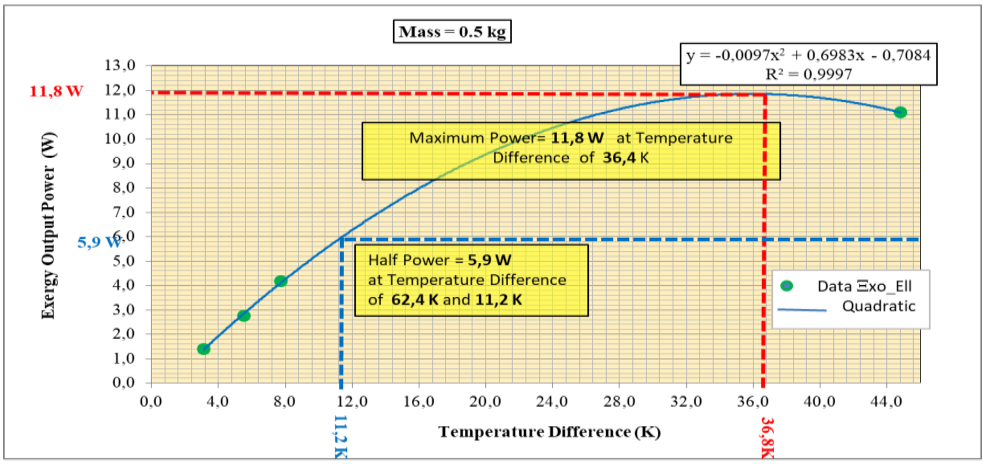

Figure 5: Curve of variation of the output exergy output power versus the temperature difference of the water (Elliptical cooker).

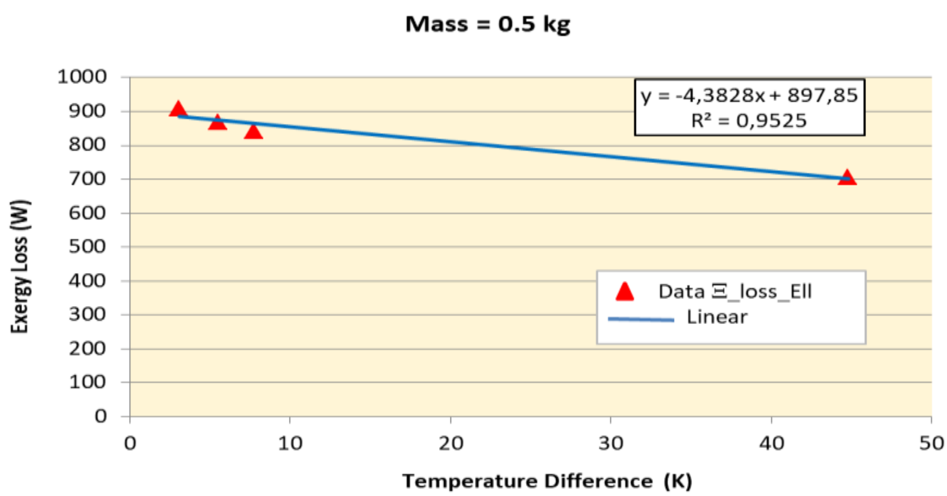

Figure 6: Curve of variation of the exergy power lost versus the temperature difference of the water (Elliptical cooker).

Concentration cookers	Peak power exergy (Ξ_{xo_max}) (W)	Product gap of the exergy temperature difference ($\Delta T\Xi_{xo\_max}$) (WK)	Heat loss coefficient (U_{Lxo}) (W/m²K)	Quality factor (ρ_{sc})
Parabolic Cooker Mw=0.50 kg Ar=0.14 m²	12.80	473.60	22.60	0.11
Elliptical Cooker Mw=0.50 kg Ar=0.14 m²	11.80	429.52	26.45	0.09

Table 2: Parameters practical performance indicators compared two cookers designed.

Concentration cookers	Peak power exergy (Ξ_{xo_max}) (W)	product gap of the exergy temperature difference ($\Delta T\Xi_{xo\_max}$) (WK)	Heat loss coefficient (U_{Lxo}) (W/m²K)	Quality factor (ρ_{sc})
SK-14 (type cooker) Mw=5 kg Ar=0.13 m²	18.21	735.30	40.35	0.11
Scheffler (Community type cooker) Mw=20 kg Ar=0.36 m²	55.75	2208.98	54.13	0.10
Parabolic Though Mw=6.3 Kg Ar=0.09 m²	6.91	160.80	47.74	0.09

Table 3: Exergy performance indicators for concentrator cookers collected in the literature [9,16,17].

Scheffler type. For heat loss coefficients, type SK-14 and Scheffler types have higher values than designed parabolic and elliptical cookers. They lose more exergy. Therefore, the glass cubic box around the focus of the studied prototypes minimizes the exergy losses. As for the quality factor, the SK-14 and the parabolic cooker have the same values while the elliptical cooker has a lower value. The exergy peak powers of the SK-14 and Scheffler cookers are also superior to those of the prototypes studied. In view of quality factors and heat loss coefficients, the studied parabolic cooker can be classified in the range of the SK-14 type cooker which is considered to be the best devices for rapid cooking with small residential operations [9].

Conclusion

This exergy study focused on two concentrators with different geometry, one of which is parabolic and the other elliptical. Thus, parameters of exergy performance indicators have been calculated. Comparative analysis of the two prototypes showed that the rates of increase in water temperature, the quality factor of the parabolic cooker are superior to those of the elliptical cooker. So, the parabolic cooker is more efficient than the elliptical cooker. Furthermore, comparison of the performance of the prototypes designed glass cube box with cookers from the literature shows that they can compete with the SK-14 which is a device for quick cooking in small residential operations.

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