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Determination of the Performance of a Box Solar Cooker with an Inclined Opening: Application of the Performance Indicators of the Standards IS13429 and ASAE S580 JAN03

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Abstract - *The standards performance indicators are some measures who value solar cookers. In this present, it's about estimating the performance an inclined opening box solar cooker by using the indicators of standards IS13429 and ASAE S580 JAN03. This cooker was designed and tested in the LASMES laboratory of University Felix Houphouët Boigny of Cocody, Abidjan. Thus, stagnation and boiling tests of water were carried out. From the experimental results obtained, the factors of merit F_1 and F_2 have been quantified and the values are 0.127 (m^2.°C/W) and 0.344 respectively. Moreover, the cooking power of the cooker has been estimated at 30 W for a temperature difference of 50 °C between the water and the ambient air. Finally, these results are compared to those of other cookers deemed effective encountered in the literature.*

Key Words: *Box solar cooker, indicators performance, stagnation test, figure of merit, cooking power.*

1. INTRODUCTION

In Côte d'Ivoire, 70% of energy consumption comes from biomass. Households have recourse to cooking with inefficient traditional stoves. Access to energy for productive uses remains limited. Many industrialists still use wood fuels for heating purpose [1]. As for the cooking, it is done mainly with wood fire or gas. But for most families, gas often seems very expensive and is not affordable for all budgets. In addition, the use of fuelwood continues to have serious repercussions on health. According to the World Health Organization, every year, indoor air pollution is responsible for the death of four million people worldwide, or one death every eight seconds [2]. Also, the United Nations indicate that two thirds of the world population, e.g two billion people suffer from a lack of wood [3].

In order to limit the pressures on forests and ensure access to a clean and sustainable resource, solar cookers can be a solution. According to [2], the practice of solar cooking can bring two major benefits to populations. These are mainly the environmental benefits and the economic and social benefits.. Regarding the environmental benefits, the populations will benefit from the soils protection and the erosion prevention, the fight against climate changewith a reduced use of fossil fuels and the biodiversity protection, thanks to a deforestation reduction. For the economic and social benefits they will gain, among other numerous jobs with poverty reduction through the provision of expertise, reduced health risks for women (less indoor air pollution) and an improvement in the education and schooling of children. Understand that these benefits will vest for solar cookers effective, available and meet international standards or procedures. These standards characterize solar cookers because they give an evaluation of the performance and ensure a better comparison of one compared to the other [4]. Thus, three major standards exist: the Indian standards of Mullick IS13429, the European standards of Funk and the American standards ASAE S580 JAN03 (American Society of Agricultural Engineers). Regarding box solar cookers with inclined opening, many studies have been carried out using these standards. We quote among others Yettou et al [3], Joshua Folaranmi [4], Zeleke et al [5], Amor Gama et al [6], Ashok Kundapur et al [7] and Harmim A. et al. [8].

The objective of this present work is the evaluation according to Indian and American standards of the thermal performance of a box solar cooker with an inclined opening designed at the LASMES laboratory of the University Felix Houphouët Boigny. from Cocody, Abidjan.

2- Presentation of performance indicators of the standards used

2.1- Indian standards Mullick, IS13429

Mullick et al. [9] have developed a thermal test procedure for box solar cookers . According to this procedure, a complete test method with IS13429: 2000 standard is available to test these systems. Thus, two main tests are to be carried out:

- **stagnation test** without taking into account the effect of the reflecting mirror. During this test, the performance indicator called "figure of merit" F_1 is determined. It is governed by the relationship:

$$F_1 = \frac{\eta_0}{U_L} = \frac{T_P - T_a}{I_G} \qquad (1)$$

Where :

η_0 : Optical efficiency

U_L : The overall coefficient of heat loss of the cooker (W / m².K)

T_P: The temperature of the absorber (K)

T_a : Ambient temperature (K)

I_G: Solar radiance incident on a horizontal surface respectively at stagnation (W / m²).

Experimentally, F_1 is a measure of the temperature difference gained by the absorbent plate at a particular stage of solar irradiance.

- sensible heat test: under full load conditions, a second performance indicator is deduced, the "second figure of merit" F_2. To achieve this, the reflectorless cooker must be loaded with a well-known quantity of water, e.g. 8 kg/ m² of opening area. The water temperature should then be allowed to gradually increase until it reaches the boiling point. F_2 is governed by the relation (2), [5, 9] :

$$F_2 = \frac{F_1 (mC_p)_w}{A_{op}\tau} \ln \left[\frac{1-\frac{1}{F_1}\left(\frac{T_{Wi}-T_a}{I_G}\right)}{1-\frac{1}{F_1}\left(\frac{T_{Wf}-T_a}{I_G}\right)} \right] \qquad (2)$$

Were:

A_{op}: The area opening of the solar cooker;

$(mC_p)_w$: The water heat capacity in the cooking vessel,

m_w: water mass or the quantity ;

τ: The time interval during which the water temperature increases from T_{wi} to T_{wf};

T_{wi}: The initial water temperature (60 °C);

T_{wf}: The final water temperature (90 °C);

T_a : The average ambient temperature;

I_G: The average solar irradiance received by a horizontal surface.

Thus, when F_1 is greater than 0.12 the cooker is classified "**Grade A**" and when F_1 is less than 0.12, it is classified "**Grade B**" [10]. Furthermore, according to [9], the first parameter Merit F_1 varies between 0.12 and 0.16 [9]. Then, a high value of F_1 (e.g. greater than 0.12) indicates a good optical efficiency η_0 and a low heat loss factor U_L.

2.2-American standards ASAE S580 JAN03 [11, 12]

This standard derives from that suggested by Funk.

In this procedure, the average water temperatures and vessels during the tests in the range should be recorded at time intervals not exceeding ten minutes and expressed in degrees Celsius. This will be the same for irradiance solar (W/ m²), ambient temperature (°C), and wind speed (m / s). The ASAE S580 jan03 standard, uses the following performance indicators:

- **the cooking power P_i.**

This is the average power delivered by the cooker during a particular time interval (Δt = 600 s) and is given by the following relation :

$$P_i = \frac{(MC_p)_W (T_2 - T_1)}{600} \qquad (3)$$

Where:

P_i: Cooking power (W)

T_2: Final water temperature (° C)

T_1: Initial water temperature (°C)

M: Mass of water (kg)

Cp: Water heat capacity 4186 J / (kg · K)

- **the standardized cooking power P_{std}**

It is governed by the following relation (4):

$$P_{std} = P_i \frac{I_n}{I_G} \qquad (4)$$

Where :

P_{std}: Standardized cooking power (W)

P_i: Cooking power (W)

I_n: Solar irradiance standardized to 700 W / m²

I_G : Average solar irradiance (W / m²).

According to tests of this standard, the wind speed must be less than 1 m / s and the water temperature inside the cooking pots must be found between 60 and 90 °C. Ambient temperature and solar irradiance should be between 20 to 35 °C and 450 to 1100 W / m², respectively.

The values of the cooking power adjusted according to the temperature difference between the water and the ambient (T_d) give a linear regression curve P_{std} = f (T_d) governed by the regression relationship with a coefficient (r^2) greater than 0.75.

$$P_{std} = a + b\,T_d \qquad (5)$$

Where :

T_d: temperature difference (°C).

This temperature difference is:

$$T_d = T_w - T_a \qquad (6)$$

T_w: Water temperature (° C)

T_a: Ambient temperature (° C)

a: the initial cooking power P_{ini} (at T_d = 0 °C, intercept with the Y axis)

b: the heat loss coefficient (slope of the linear curve)

As for the normalized cooking power, P_{std} (W), it is obtained for a temperature difference T_d, of 50 °C using the regression relation (5).

3- Description of the studied prototype

Fig. 1 shows the studied prototype.

Fig. 1 : Studied prototype

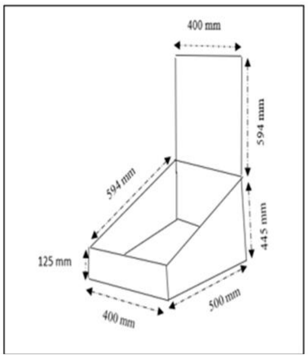

Fig. 2 : External dimensioning of the prototype

The studied solar cooker is a set of two plywood boxes, trapezoidal in shape. They each have an opening inclined 33° from the horizontal. The opening area is 0.24 m^2. These two boxes are recessed and separated by 20 mm thick polystyrene. Also, the inner face of the inner case is coated with 5mm thick reflecting mirror while the outer face of the outer case is covered with formica. A stainless steel absorber painted in black mast is placed on the bottom initially coated with a thin layer of plaster. In order to reduce losses before of the absorber, a transparent double-glazed cover surmounts the housings. The upper edge of the boxes is fixed to the cover via a hinge allowing the access of the cooking pot (also in black mast) to the absorbent plate. **Fig. 2** illustrates the external dimensioning of the cooker. The whole system is surmounted by an external reflector, whose the internal face is coated with a reflective mirror. Its role is to converge more radiation to the absorber.

4- Materials, results and discussion

4.1- Materials

During testing, three variables were measured. They are: solar irradiance using an Eppley-type pyranometer, temperatures (absorber, ambient air and cooking) through K-type thermocouples and wind speed with an anemometer. The recordings were made with a data logger at regular time intervals of 10 min.

4.2- Results and discussion

The testing took place in the climatic conditions of Abidjan. Thus, to quantify the standards performance indicators, several tests were carried out, whose two were retained because of their high solar activities. These are the days of 11/16/2019 and 11/19/2019.

During the experiments, the wind speed varied very weakly on the site around 2.1 m / s.

The stagnation test was carried out 11/16/2019. On this day, the incident global solar irradiance on the horizontal plane of the absorber (I_G), the ambient temperature (T_a) and the temperature of the absorber of the cooker (T_p), and the wind speed were measured on a cooker without load and without reflectors.

In **Fig. 3** are shown the evolution curves versus time of the overall incident irradiance, temperature of the absorber and that of the ambient air under the stagnation conditions.

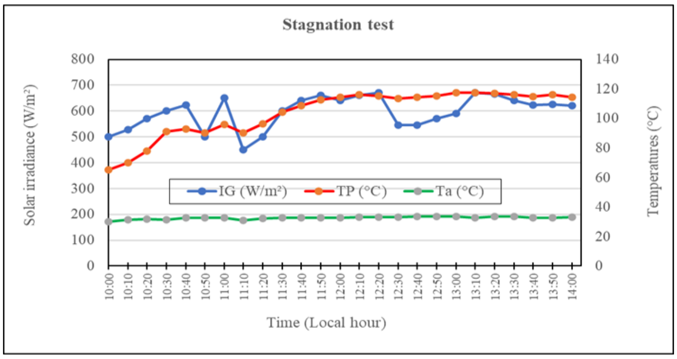

Fig. 3 : Evolution curves versus time of the solar irradiance and temperatures (absorber and ambient air) during the stagnation test of 16/11/2019

During this test, intermittent cloudy passages have been observed. The maximum values of incident global solar irradiance, absorber temperature and ambient air at 1:10 p.m. have been 670.6 W / m^2, 117.6 °C and 33.7 °C respectively.

In **Table 1** are logeed the results obtained and those from other cookers considered among the most effective [13].

Table 1 : Comparative stagnation temperature of the prototype with other solar cookers from the literature.

Stagnation time	References	Test date	Solar irradiance (W/m²)	Ambient temperature (°C)	Stagnation temperature (°C)
12 :00	Vishaya et al [14]	23/09/1982	1020	32	122
12 :00	Harmim et al [15]	23/07/2008	960	48	140
13 :00	Sethi et al [16]	January 2010	980	20	125
11 :55	Fayadh [17]	04/03/11	700	25	110
13 :05	Yettou et al [18]	05/0213	792	12.5	127.6
13 :10	**Prototype studied**	16/11/2019	**670.6**	**33.7**	**117.6**

The analysis of **Table 1** shows that the maximum solar irradiance received by the studied cooker is the lowest (670.6 W / m^2). As for the stagnation temperature reached by the absorber, it is 117.6 °C higher than that of Fayadh [17]. This result is cheering because it indicates that the studied cooker in the range of high stagnation temperature ranges. This shows that better control in the design and construction of the cooker has been carried out.

Fig. 4 illustrates the evolution curves versus time of the solar irradiance and the temperatures of the water and the ambient air for the day of 11/19/2019.

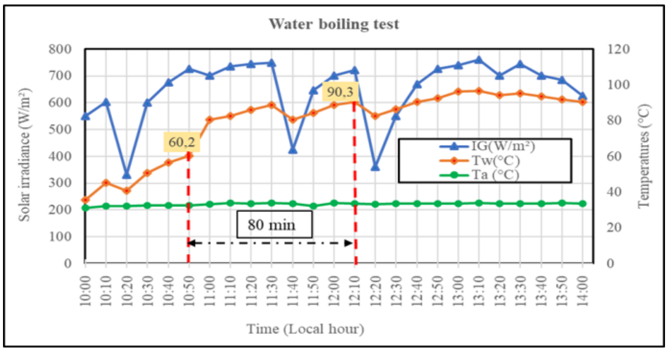

Fig. 4 : Evolution curves versus time of the solar irradiance and temperatures (water and ambient air) during the day of 19/11/2019

On that day, a water boil test was performed. It started at 10:00 am with an water initial temperature of 30 °C and an ambient air temperature of 30.2 °C. The maximum temperature reached by the absorber has been 117.8 ° C at 13:10 under solar irradiance of 760.80 W / m². Intermittent cloudy periods are also observable in Fig.4. Thus, to increase the water temperature from 60.2 °C to 90.3 °C, the time required have been 80 min.

In Table 2 are reported performance indicators F_1 and F_2 and the quantities of water used by our system and other recognized performance cookers [13].

Table 2: F_1 and F_2 performance indicators of the studied prototype compared to other cookers with recognized performance

References	F_1 (m².°C/W)	F_2	Water quantity (Kg)
Kumar et al [19]	0.117	0.467	2
Purohit and Purohit [20]	0.1251	0.4805	1.844
Harmim et al [21]	0.152	0.47	3.5
Sethi et al [16]	0.16	0.54	-
Farooqui [22]	0.1258	0.369	1.37
Fayadh [17]	0.11	0.34	-
Yettou et al [18]	0.145	0.391	1.6
Joshua Folaranmi [4]	0.1135	0.3172	2
Studied prototype	**0.127**	**0.344**	**1.92**

The first merit parameter F_1 calculated for the cooker studied from equation (1) has been 0.127 m². ° C / W) with T_p = 117.6 °C, T_a = 32.5 °C and I_G = 670.6 W / m².

In **Table 2**, the value of F_1 obtained is greater than 0.12. This result is also satisfactory because the studied cooker is of "**Grade A**" [9,10]. This indicates that the studied cooker has a good optical efficiency η0 and a low heat loss factor U_L [13].

As for the second merit factor F_2, its calculated value has been 0.344 whose according to the standards must be less than 0.4. This result expresses the compatibility of our cooker with Indian standards. On the **Fig.5** is represented the evolution curve of the standardized cooking power (P_{std}) versus temperature difference (T_d).

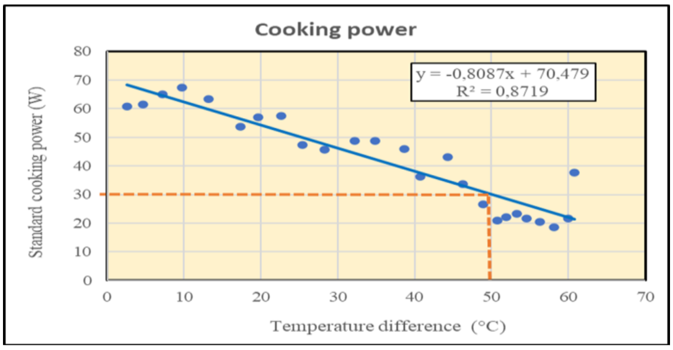

Fig. 5 : Evolution curve of the standardized cooking power (P_{std}) versus temperature difference (T_d).

Fig. 5 shows that the normalized cooking power curve is characterized by a low slope regression line and a regression coefficient of 0.8719 greater than the limit value 0.75. This result characterizes a good thermal insulation of the studied cooker.

Also in **Fig. 5**, the graphical normalized cooking power is 30 W for a temperature difference equal to 50 °C. This same value is obtained from the regression equation.

In the **Table 2** are consigned the standarized cooking power values for a temperature difference of 50 °C for the prototype and other cookers known for their performance.

Table3 : Standarized cooking power values for a temperature difference of 50 °C for the prototype and other cookers known for their performance [13].

References	Test date	Regression equation	Cooking power at 50°C (W)
Funk [12]	17/11/1998	$P_{std} = 115 - 1.56 * \Delta T$	37
El-Sebaii and Ibrahim [23]	28/07/2002	$P_{std} = 103.92 - 1.598 * \Delta T$	24
Mahavar et al. [24] SFSC-1	24/06/2009	$P_{std} = 103.5 - 1.474 * \Delta T$	30
Sethi et al. [16]	23/01/2013	$P_{std} = -14.923 + 2.4418 * \Delta T$	107
Yettou et al [18]	26/06/2014	$P_{std} = 110 - 1.6715 * \Delta T$	26
Studied Prototype	19/11/2019	$P_{std} = 70.479 - 0.8087 * \Delta T$	30

Analysis of **Table 3** shows that the cooker studied is in the range of high-performance cookers.

5- CONCLUSION

In this article, the objective was to evaluate the performance of a box solar cooker with tilted opening which was designed and tested by applying him the performance indicators of Indian and American standards. The values of F_1 and F_2

(performance indicators) which are respectively 0.127 m^2. °C. W and 0.34 show that the studied solar cooker is compatible with Indian standards IS13429. It is "Grade A" and has a low loss coefficient.

In addition, the application of ASAE S580 JAN03 standards shows that the adjustment curve of the standardized cooking power as a function of the temperature difference of the absorber and the ambient air for the studied cooker has a slight slope and a regression coefficient greater than 0.75. The standard cooking power calculated for a temperature difference of the absorber and the ambient air of 50 °C has been 30 W.

These very encouraging results give a good visibility on the performances of the studied cooker. However, improvements can be made including increase the tilt angle of the aperture to 45° and the number of outside reflectors to four.

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