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Comparative assessment of two different designs of box solar cookers under algerian sahara conditions

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Abstract - *This paper deals with the experimental study of two box-type solar cookers equipped with booster mirrors and suitable for cooking a single family's food. The first one has a conventional, ordinary horizontal aperture area and the second one has an inclined aperture area. The latter is a new configuration which allows for much higher solar radiation interception, resulting in better cooking performance, especially in the winter when the sun's elevation is low. Optimum inclination angles of the booster mirrors were calculated in order to maximize the reflection of the solar rays on the absorber plates. The cooking performance of the proposed new cooker was compared with the conventional box solar cooker of the same material and surface during Winter 2013 in the Ghardaîa Sahara climate (32.39°N, 3.78°E), Algeria. According to the values of some essential thermal performance parameters suggested by International Standards and evaluated by experimental studies, the inclined aperture area improves the thermal performance of the box-type solar cooker remarkably, reducing cooking time considerably. The first and second figures of merit for the improved cooker, respectively, were 0.15 and 0.47 compared to 0.13 and 0.38 for the conventional cooker*.

Résumé – *Cet article s'intéresse à l'étude expérimentale de deux fours solaires équipés de miroirs amplificateurs, et qui sont adaptés pour une seule famille. Le premier a une ouverture horizontale conventionnelle et ordinaire et le second a une ouverture inclinée. Ce dernier a une nouvelle configuration qui permet des performances de cuisson bien plus importantes grâce à une interception des rayons solaires plus élevés, particulièrement en période hivernale ou la durée d'ensoleillement est basse. Des angles d'inclinaisons optimales ont été calculés afin de maximiser la réflexion des rayons du soleil sur les plaques absorbantes. Les performances du nouveau four solaire ont été comparées en hiver avec celle du four conventionnel fait avec les mêmes matériaux et de même taille et ce dans les conditions climatiques du désert de Ghardaïa (32.39°N, 3.78°E), Algérie. Selon les valeurs de quelques paramètres de performances thermiques essentiels suggérés par des Normes Internationales et évaluées par des études expérimentales, la zone d'ouverture inclinée améliore remarquablement la performance thermique du four solaire, réduisant le temps de cuisson de manière significative. Les premières et deuxièmes figures de mérite pour le four amélioré, respectivement, étaient de 0.15 et 0.47 comparées à 0.13 et 0.38 pour le four conventionnel.*

Keywords: Solar cooker - Solar radiation - Thermal performance - Inclined aperture area.

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1 INTRODUCTION

In developing countries, direct solar radiation is considered to be one of the most prospective sources of energy with mean daily illumination intensity in the range of 5-7 kWh/m^2 and more than 275 sunny days in a year [1, 2]. Algeria lies in the sunny belt of the world. The insolation time over the quasi-totality of the national territory exceeds 2000 h annually and can reach 3900 h in the high plains and Sahara [3]. From this point of view, it can be easily said that these are very favorable climatic conditions for all solar energy applications especially for the domestic sector which account for the major energy consummation (higher than 25 % of primary energy use in developing nations [4]. Among the different energy domestic end uses, energy for cooking is one of the basic and dominant end uses. The use of solar cookers provides many advantages like fuel economy, greenhouse gases emission reduction, firewood utilization saving, lower cost, and high durability [5].

Different types of solar cookers such as; box type, concentrator type and indirect type have been realized and tested around the world during the last years. However, only box types have gained maximum popularity, in developing countries, among all other existing models because of its simple design operation and lowest cost, but the cooking time remains higher than other cooker types. Many important studies have been reported in literature to study the most important parameters of the box solar cooker such as the booster mirror, absorber tray, insulation, glazing system, cooking vessel, and thermal energy storage materials in order to improve their performances. In the year 2011, Saxena *et al.* [6] analyzed in their thermodynamic review the major parameters optimization related to box type solar cookers. Another study reported by Cuce *et al.* [7] to describe the state of the art of major parameters and energetic/exergetic evaluation of solar cookers. Recently, Yettou *et al.* [8] presented the recent advances in research and development of solar cooking technologies, their thermal performance and thermodynamic analysis. Several contributions reveal that various researchers around the world have developed many improved designs of box-type solar cookers. However, their performances are still significantly lower during the winter months due to lower solar radiation availability on the horizontal surface which results to lower temperatures.

This paper presents the design realization of two box type solar cookers equipped with reflectors as the booster mirrors. The first solar cooker was with ordinary horizontal aperture area, and second cooker was with inclined aperture area. A comparative experimental study of the two solar cooker designs was performed in terms of two important thermal performance parameters; first figure of merit and second figure of merit as per Bureau of Indian Standards (BIS) [9, 10]. The effect of booster mirrors on cookers performance was also analyzed in the present study.

2 DESIGN DESCRIPTION OF REALIZED SOLAR COOKERS

Two box-type solar cookers were designed and developed by the authors in the Applied Research Unit on Renewable Energies of Ghardaïa, Algeria. Each box solar cooker consists of an outer box, an inner cooking box, a simple glass lid, a thermal insulator, mirrors and cooking containers. The insulation, glazing number and absorber materials are the same for both. The main difference is in the design with respect to the same area for both.

The first solar cooker is designed with an ordinary horizontal aperture area and the second one with an inclined aperture area. This latter configuration was introduced to increase the exposed absorber area to solar rays and improve the interception of solar radiation especially during winters when sun elevation is low without a complex design

(Fig. 1). The overall dimensions of the conventional cooker are 500 × 400 × 280 mm. The modified box cooker dimensions are 500 × 400 × 445 × 125 mm. The area and volume of the cookers are same: 0.2 m^2 and 0.057 m^3, respectively.

The space between the outer box and inner tray, including the bottom of the tray, is packed with insulating material to reduce heat losses from the cooker. The absorber made of an aluminum sheet painted matt black absorbs the solar radiation and transfers the heat to the cooking pots. The glass covers prevent heat from flowing out of the cookers. The aluminum cooking pots (180 mm in diameter and 100 mm in height) were filled with water and equipped with black covers, then placed inside the solar box cookers. Two reflectors (booster mirrors) of 500 × 400 mm were hinged on the top and side edges of the cookers with adjustable bends. The booster mirrors were used to raise the temperature of the hot box.

Fig. 1: View of realized box type solar cookers

3 EXPERIMENTAL SET-UP

To assess the thermal performance of solar cooker, the experiment was conducted during the winter season of year 2013 at the Applied Research Unit on Renewable Energies affiliated with the Center of Renewables Energies Development, located Ghardaïa, South Algeria (32.39°N, 3.78°E, 463 m above sea level). The following parameters were recorded: ambient temperature (T_a), water temperatures in the pot (T_w), air temperature inside the box (T_i), glass cover temperature (T_g), absorber plate temperature (T_p), global solar radiation on a horizontal surface (Is), and wind speed (V_s). Temperature profiles, solar radiation, and wind speed were measured at regular interval of 5 min throughout during the experiment.

The solar radiation on a horizontal surface was measured using a Kipp & Zonen CMP21 pyranometer and the direct normal irradiance in W/m^2 was measured with a K&Z CHP1 pyrheliometer. Three thermocouples located at different places inside the cooker were used to measure the glass, absorber, and inside air temperatures. The ambient temperature and water temperature inside the cooking pot were measured using a Campbell CS215 temperature recorder and thermocouple respectively. The thermocouple was inserted through a hole in the lid of the cooker and was immersed in the water inside the pot at 20 mm above the bottom of the pot. The wind speed in m/s was measured using an NRG 40H anemometer. The accuracy of the anemometer was 1% ± 0.1 m/s. The wind speed was always below 1.3 m/s and was recognised as small; thus, the effect of wind and its direction was negligible. All the sensors (thermocouples) were connected to a data acquisition system (data-logger Agilent 34972A), which enabled to measure the temperatures at intervals of 5 min.

4 PARAMETERS OF COOKER PERFORMANCE

This section includes the formulae of the different TPPs through which these have been calculated with the help of relevant thermal profiles.

4.1 First figure of merit (F_1)

It has been determined by the stagnation test as per BIS [10] and Mullick *et al.* [9] using following relation:

$$F_1 = \frac{\eta_0}{U_L} = \frac{T_{ps} - T_{as}}{I_s} \tag{1}$$

Where η_0, U_L, T_{ps}, T_{as} and I_s are the optical efficiency, overall heat loss coefficient, absorber plate temperature, ambient temperature and the insolation on the horizontal surface at the time when plate temperature stagnated respectively.

4.2 Second figure of merit (F_2)

It has been obtained from the sensible heat test by using the following relation (Mullick *et al.* [9], BIS [10]):

$$F_2 = \frac{F_1 (m C_p)_w}{A_{sc}\,\tau} \ln \left[\frac{1 - \frac{1}{F_1}\left(\frac{T_{wi} - \overline{T_a}}{\overline{I_s}}\right)}{1 - \frac{1}{F_1}\left(\frac{T_{wf} - \overline{T_a}}{\overline{I_s}}\right)} \right] \tag{2}$$

Where A_{sc} is the aperture area, $(mC_p)_w$ is the thermal capacity of water, τ is the time during which water temperature rises from T_{wi} to T_{wf} , $\overline{I_s}$, $\overline{T_a}$ are the average solar radiation and the average ambient temperature, respectively, for the time period τ .

5 TEMPERATURE PROFILES OF VARIOUS COMPONENTS

The temperatures profiles of two box solar cookers that have been collected outdoors and experimentally measured to evaluate the performance of solar cooking systems can be classified into three categories according to the necessary test conditions. The conditions are tests without water load and without reflectors, tests with water load and without reflectors, and finally tests with water load and with reflectors.

The performance of solar cookers can be optimized when the cookers are oriented in such a way that the sunlight falls on solar cookers with an incident angle equal to zero. During all tests, solar cookers were not opened and were tracked at an interval of 30 min by rotating the cookers azimuthally to illuminate the entire cookers apertures [11].

The booster mirrors positions also have to be adjusted regularly in order to track the sun and assure the maximum reflection of sun rays on plate absorbers.

5.1 Tests without water load, without reflector (stagnation test)

This test was conducted to find the first figure of merit (F_1). Both the solar cookers without reflectors and pots were exposed to solar radiation from 10:00 to 16:00 h. Temperatures of absorber plate of solar cookers (T_p) were recorded at an interval of 5 min until achieving the stagnation condition achieved. The values of radiation intensity on horizontal surface (I_s) and ambient temperature (T_a) were also measured. A typical thermal performance curve is shown in figure (2), obtained under stagnation test conditions on typical winter days (02/2013).

5.2 Tests with water load, without reflector (sensible heat test)

This test was conducted to find the second figure of merit (F_2). The solar cookers without reflectors were loaded with a known amount of water. As per BIS test protocol such experiment should be conducted within 2 h before the solar noon with the intensity of radiation above or equal to 600 W/m^2. It has been also recommended that the amount of water load should be calculated according to 8 kg water/m^2 and should be equally distributed in containers.

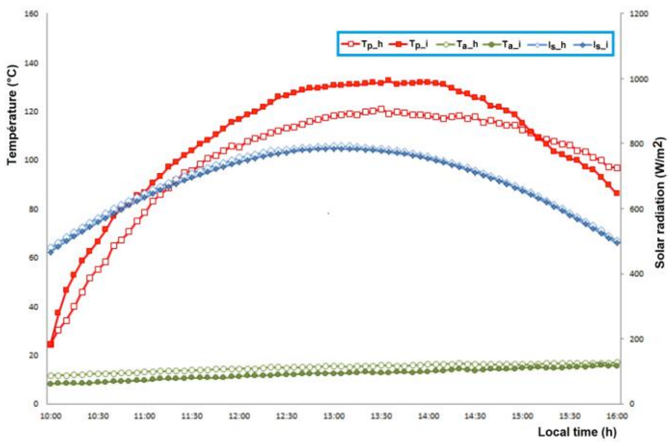

Fig. 2: Variation of measured temperatures at different positions corresponding to global solar radiation for the conventional cooker (14/02/2013) and improved cooker (10/02/2013) used to determine the first figure of merit

In this study, the amount of water load was found to be equal to 1.6 kg, which is distributed in two cooking pots. The values of instantaneous water temperatures were averaged for 10 min interval. Global solar radiation (I_s), ambient air temperature (T_a), and water temperatures (T_{wi}), (T_{wf}) were recorded for each cooker till water temperature exceeded 95 °C. Figure (3) presents the variation of water temperature with time in both cooking utensils under the same test conditions during sensible heating test on the sunny day of 17/02/2013.

5.3 Tests with water load, with reflector (booster's effect)

This test was conducted to find the effect of booster mirrors (reflectors) on cookers performance. Thus, during the water heating test, both the solar cookers without, with one and with two reflectors were loaded with 1.0 kg of water and exposed to solar radiation in several clear sky days from 9:00 to 16:00 h. Two booster mirrors were provided on horizontal area cooker as well as on inclined area cooker; these reflectors were hinged on the top and side edge of each cooker with adjustable bends allowing the change of inclination angle.

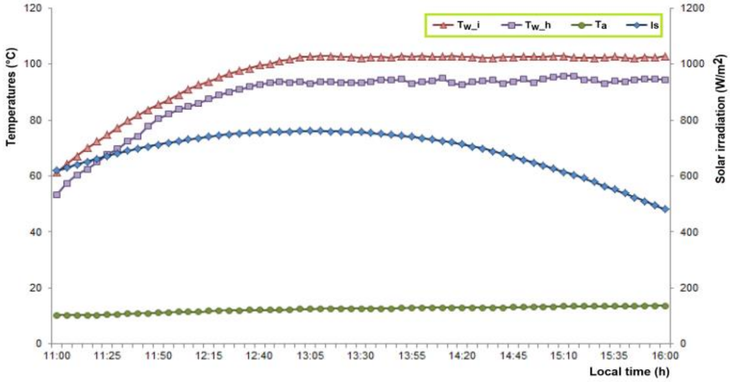

Fig. 3: Variation of measured water temperatures with global solar radiation for both solar cookers (17/02/2013) used to determine the second figure of merit

The following data were taken at a regular interval of 5 min: absorber plate temperature (T_p), water temperature in pots (T_{wf}), ambient temperature (T_a) and solar radiation (I_s) for each test and each cooker. The thermal profiles of different recorded temperatures are plotted in figure 4, obtained in three typical winter days in 02/2013.

6. DISCUSSION OF RESULTS

6.1 Stagnation temperature test

Figure 2 present typical diurnal variations in global solar radiation on a horizontal surface, ambient temperature and absorber plate temperatures of both the solar cookers without reflector under no-load condition. It is clear that; in two selected days of tests, the solar radiation intensity increases with time until it reaches a maximum value at about 13 h (after solar noon).

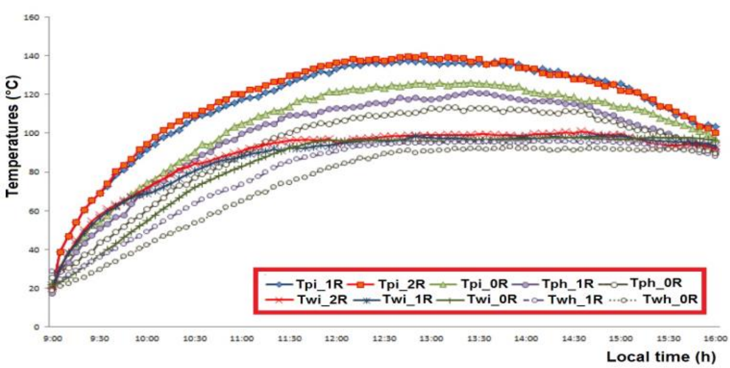

Fig. 4: Variation of measured absorber plate temperatures and water temperatures with local time, for the conventional cooker and improved cooker used without, with one and two booster mirrors.

For experimental solar cookers, we have calculated a first figure of merit, F_1 = 0.13 m^2°C/W, with values of T_{ps} = 118 °C, T_{as} = 15.4 °C, and I_s = 764.5 W/m² and F_1 = 0.15 m^2°C/W with values of T_{ps} = 130.6 °C, T_{as} = 12.4 °C, and I_s = 758.9 W/m² stagnation, from equation (1) for cooker with horizontal aperture area and cooker with inclined aperture area, respectively. These are the recommended values of BIS for solar cookers. From this result it is clear that the improved cooker has a higher (F_1) value and consequently a better performance than the conventional cooker.

6.2 Heat-up condition test

From the sensible heating curves shown in figure 3 and {Eq. (2)}, the second figure of merit F_2 = 0.38 using F_1 = 0.13 m^2°C/W, M_w = 1 kg, C_{pw} = 4200 J/kg°K, A_{sc} = 0.2 m^2, τ = 105 min (6300 s), T_{wi} = 62.3 °C, T_{wf} = 93.2 °C, $\overline{T_a}$ = 14.3 °C, and $\overline{I_s}$ = 775.1 W/m², the corresponding F_2 value was obtained as 0.47 with values of using F_1 = 0.15 m^2°C/W, M_w = 1 kg, C_{pw} = 4200 J/kg°K, A_{sc} = 0.2 m^2, τ = 80 min (4800 s), T_{wi} = 61.3 °C, T_{wf} = 95.1 °C, $\overline{T_a}$ = 12.1 °C, and $\overline{I_s}$ = 750.3 W/m², for conventional and improved solar cooker without reflectors, respectively.

The above calculations are in respect of values of $T_{wi} > T_a$ recommended (Mullick *et al.* [9, 12]) and values of T_{wf} lower than the boiling point suggested also by (Mullick *et al.* [12]). It can be seen clearly, that the time interval τ of the sensible heating process was reduced markedly (by 23.8 %) for the case of cooker with inclined aperture area, which was sufficient time duration for two meals cooking for a family during the day. The (F_2) value is higher for the improved cooker which also established the fact about its better cooking performance.

6.3 Water heating test

From water heating tests curves shown in figure 4, it is clear, as anticipated, that by adding booster mirrors to the cookers designs, the absorber plate temperatures have higher values than the cookers without reflectors. The maximum absorber plate temperatures achieved without a reflector, with one, and with two reflectors were found to be 113.3, 121.1, and 122.6 °C for the horizontal cooker area, respectively; whereas, these values are greater for the inclined cooker area 126, 137.3, and 139.8 °C, respectively. However, the addition of the second reflector (placed on the side edge of the cookers) did not significantly affect the maximum absorber plate temperatures for both cookers (temperatures' difference is only 2.5 °C). This suggests that; in Sahara regions like Ghardaïa City, using one more reflector (the second booster mirror) does not significantly improve the performance of the cookers. This is explained by the height incidence angle of solar rays on the second reflector (side edge booster); the sunlight falls at normal incidence on the first reflector surface which enables a better contribution to the energy collection inside the cookers. In other case, the use of multiple reflectors increases the overall cost of the cookers. From the results of figure 4, it can also be observed that the time difference for heating 1 kg of water from 20 °C using the inclined area cooker is improved by 18.7 % in the case of adding one booster (130 min compared to 160 min). So, we can conclude that the performance of the cooker with the plane reflectors in place (top edge booster) was improved tremendously when compared with the cooker without the reflector.

7. CONCLUSION

The design realization of two box type solar cookers equipped with reflectors as the booster mirrors was presented and their thermal performances were tested. The first cooker was with ordinary horizontal aperture area and the second cooker (modified) with inclined aperture area. The results from this experimental study show successful cooking performance of the improved solar cooker which can be used around year.

The cooker performance parameters such as the first and second figures of merit (F_1 and F_2) for inclined area were 0.15 and 0.47 compared to 0.13 and 0.38 for horizontal area respectively, and were found in permissible limit of BIS. It was also experimentally demonstrated that cooking time can be reduced by using a single booster mirror on the top edge of the cooker (by 18.7 %). This reduction is the advantage of using the cooker with inclined aperture area design, which increases the interception of solar radiation

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