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Study and simulation of concentrating irradiance in box solar cooker with tracking reflectors

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Abstract - *In this work a design of solar cooker with mirror reflectors has been studied for two tracking modes and his performances are analyzed by the simulation of collected energy on the absorber of the cooker. The box of the cooker receives the solar radiation both directly and by reflection from the mirror reflectors. The plane mirrors with high optical reflectivity allows sun tracking in the north south direction (for seasonal tracking) as well as in the east west direction (for tracking during the day) by moving theses reflectors with the correct angles. Adding reflectors improves the performances of the cooker, which is interesting in particular in winter, where the elevation of the sun is relatively low. The combination of north-south and east-west facing mirror reflectors are favorable for more energy collection, the cooker is enabling to cook during the day and around the year.*

Résumé – *Dans ce travail, une conception d'un cuiseur solaire avec réflecteurs à miroir a été étudiée pour deux modes de suivi. Les performances de ce cuiseur sont analysées par simulation de l'énergie recueillie sur l'absorbeur. La boîte de l'appareil de cuisson reçoit le rayonnement solaire à la fois directement et par réflexion à partir des réflecteurs miroirs. Les miroirs plans de réflectivité optique élevée permettent au suivi du soleil dans la direction Nord-Sud (pour le suivi en latitude), ainsi que dans la direction Est-Ouest (pour le suivi au cours de la journée) en déplaçant ces réflecteurs à des angles précis. L'ajout des réflecteurs améliore les performances du cuiseur, ce qui est intéressant, en particulier en hiver, où l'élévation du soleil est relativement faible. La combinaison des réflecteurs à miroir, Nord-Sud et Est-Ouest, est favorable pour collecter le plus d'énergie. Le cuiseur est fonctionnel au cours de la journée et pour toute l'année.*

Keywords: Solar cooker reflectors - Sun tracking - Concentrating irradiance.

1. INTRODUCTION

Cooking with the sun is a potentially viable substitute for fuel wood in food preparation in much of the developing world [1]. Different types of solar cookers have been developed and tested all over the world. There has been a considerable interest recently in the design, development and testing of various types of solar cookers. A conventionally used solar cooker is a device with horizontal glazed top surface and a

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reflector mirror, which can be tracked accordingly to the seasonal variations in the position of sun. The tracking is two ways; firstly, the angular position of the lid mirror is changed as sun changes its latitudinal position and secondly, for an effective use of the device, it has to be rotated in the east–west direction, so that the mirror faces the sun [2].

In this paper, the concentrating irradiance on the collecting surface of a box type solar cooker with titled glazed surface was studied and simulated. The sun tracking in the north south direction as well as in the east west direction is also analyzed by adding reflectors to the design.

2. A BRIEF REVIEW OF SOLAR COOKERS DESIGNS

As reported by Thirugnanasambandam *et al.* [3], researchers performed intensive efforts; in recent years, on study, design and development of solar cookers. Kumar presented simple thermal analysis to evaluate the natural convective heat transfer coefficient for an absorber plate-inner glass trapezoidal enclosure of a double-glazed box-type solar cooker [4].

In year 2001, Kumar *et al.* presented the performance results of experimental study conducted on solar pressure cooker and developed a simulation model for predicting the cooker performance under a variety of operating and climatic conditions [5].

In 2005, Kumar discussed a thermal test procedure to determine the design parameters, which in turn, can be used to predict the heating characteristic curves (or thermal performance) of a box-type solar cooker [6].

Reddy *et al.* compared the performance of the cooking vessel with depressed lid on lugs with that of the conventional vessel on lugs and found that the average improvement of performance of the vessel with depressed lid is 8.4% better than the conventional cylindrical vessel [7].

Amer introduced and extensively investigated the performance of a novel design of solar cooker in which the absorber was exposed to solar radiation from the top and the bottom sides and a set of plane diffuse reflectors was used to direct the radiation onto the lower side of the absorber plate [8].

In year 2002, Sharaf revealed the concept of the conical focus and explained and tested the design of an economical, highly efficient, conical solar cooker [9]. Sonune *et al.* designed and developed a Fresnel type domestic SPRERI concentrating cooker which provides adequate temperatures needed for cooking, frying and preparation of chapattis [10].

In 2004, Ozturk applied the international standards for testing and reporting the solar cooker performance to the experimental determination of the energy and exergy efficiencies of the solar parabolic cooker and calculated the time-variations of these efficiencies based on the applied formulae and measurement data [11].

Petela presented the theoretical exergy analysis of a solar cooker, the distribution of the exergy losses in the cooker and the exergy analysis of the radiating surface absorbing radiation fluxes of different temperatures [12].

Pohekara *et al.* computed the utility of parabolic solar cooker (PSC) in India with respect to eight prevalent cooking devices by knowing users' preferences and expert opinion on thirty different criteria using the additive multi-attribute utility theory (MAUT) model for evaluation [13].

In year 2008, Kumar *et al.* designed and fabricated a truncated pyramid type solar cooker cum dryer which meets the standards prescribed by the Bureau of Indian Standards for solar box-type cookers and also recommended minor modifications to achieve higher temperatures and reduced cooking times [14].

Hussein *et al.* designed, constructed and tested a novel indirect solar cooker with outdoor elliptical cross section, wickless heat-pipes, flat-plate solar collector and integrated indoor PCM thermal storage and cooking unit under actual meteorological conditions of Giza, Egypt [15].

Chen *et al.* investigated the feasibility of selected PCMs as the storage medium in a box type solar cooker to cook and/or to keep food warm in the late evening hours and also presented a two dimensional theoretical model based on enthalpy formulation to predict the thermal performance of the storage system [16].

In Algeria, Harmim *et al.* have fabricated and tested a double exposure SBC carrying a specially designed cooking pot with fins on the outer joint of lid. A parabolic reflector was a section of a linear parabolic concentrator, which was made of a wooden frame and rectangular glass mirrors were fixed on it for boosting. The vessel was made of aluminium and painted black [17].

In the year 2010, Harmim *et al.* carried out some experiments to compare experimental performance of a SBC equipped with a finned absorber plate to a SBC carrying absorber plate without fins. Tests have been carried out in the desert of Algeria at Adrar (latitude 27°53’ North and longitude 0°17’ West). Fins that have been used in solar air collectors enhanced heat transfer from absorber tray to air. The results of the experimental investigation have been carefully analyzed and shown that the T_{stag} for a SBC equipped with a finned absorber plate was about 7 % more than a SBC with an ordinary absorber tray. The cooking time was found to be reduced about 12 % with a finned absorber tray [18].

3. THEORICAL STUDY

3.1 Sun position and solar irradiance

The position of the sun in respect to a horizontal surface is given by the two coordinates: solar altitude γ_S (an angle between the sun path and a horizontal surface), and solar azimuth χ (a horizontal angle between the sun and meridian), and is calculated as follows [19]:

$$\sin(\gamma_S) = \cos(\varphi)\times\cos(\delta)\times\cos(\omega) + \sin(\varphi)\times\sin(\delta) \tag{1}$$

$$\cos(\chi) = \frac{\cos(\delta)\times\cos(\omega)\times\sin(\varphi) - \cos(\varphi)\times\sin(\delta)}{\cos(\gamma_S)} \tag{2}$$

where: δ is the sun declination, ω is the hour angle and φ is the geographical latitude of the location.

The beam irradiance received by the plate absorber of the solar cooker is expressed in terms of Linke turbidity factor TL [20]:

$$I_B = G_0 \times \sin(\gamma_S)\times \exp(-TL \times m_A \times \delta_R) \tag{3}$$

In which G_0 is the extraterrestrial solar radiation, δ_R is the spectrally integrated optical thickness of the clean dry atmosphere and m_A is the relative optical air mass.

3.2 Reflectors tilted angles

A solar cooker with tilted collecting glazed surface is shown in (Fig. 1), the angle θ which the incident radiation makes with the vertical is given by [2, 21]:

$$\theta = \varphi \pm \delta \tag{4}$$

when the collecting glazed surface makes an angle β with the horizontal, the α angle of the south facing reflector mirror is given by:

$$\alpha = \frac{1}{3} \times \left(2\theta + \beta - \frac{\pi}{2} \right) \tag{5}$$

when the latitudinal position of the sun is changing, the angle α of the north facing mirror is calculated from:

$$\alpha = \frac{1}{3} \times \left(\pi - 2\theta - \beta \right) \tag{6}$$

with the respect to east-west direction of the sun, several parameters have to be taken in to account for calculation of γ angle; in literatures we found the following suggestions [2]:

$$\gamma = \begin{cases} 0° & \text{for} \quad 6:00\,\text{am to } 9:00\,\text{am} \\ 45° & \text{for} \quad 9:00\,\text{am to } 12:00\,\text{am} \end{cases} \tag{7}$$

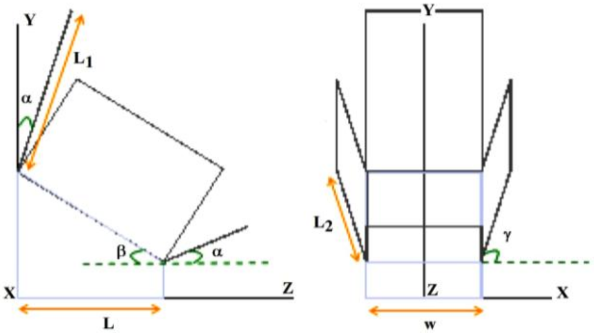

Fig. 1: Tilted reflectors angles of box type solar cooker

4. DESCRIPTION OF SOLAR COOKER

A box-type solar cooker (Fig. 2) consists of an outer box, inner cooking box, the simple or double glass lid, thermal insulator, mirror and cooking containers. The inner cooking box is made of Aluminum sheet that absorbs solar radiation, it is coated with black paint so as to easily absorb solar radiation and transfer the heat to the cooking pots. A glass lid covers the inner box.

The space between the outer box and inner tray including bottom of the tray is packed with insulating material to reduce heat losses from the cooker. Mirrors are used in a solar cooker to increase the radiation input on the absorbing space. Sunlight falling on the mirror gets reflected from it and enters into the tray through the glass lid.

This radiation is in addition to the radiation entering the box directly and helps to quicken the cooking process by raising the inside temperature of the cooker [22]. The cooking containers are painted black on the outer surface so that they also absorb solar radiation directly. In this work, a conception design is made using SolidWorks [23] with le following sizes: 500 mm × 400 mm × 445 mm × 125 mm.

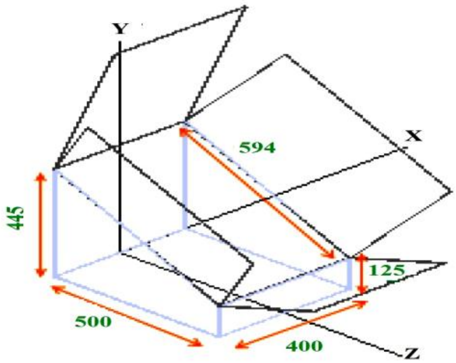

Fig. 2: Schematic diagram showing the size of box solar cooker

5. SIMULATION AND RESULTS

Using the values of sun position and the value of direct irradiance, we have done a simulation of the concentrating sunlight falling on the absorber of a box type solar cooker with titled glazed surface. The simulation is made for the Ghardaïa site's in winter season (December month). Ghardaïa is located in south Algeria (latitude 32.48°N, longitude 3.80°E and elevation 468 m above sea level). It is characterized by a Sahara climate: high mean values of temperature, low values of humidity and strong sand wind in spring seasons.

5.1 Solar cooker without reflectors

Firstly, we show the simulation results of the solar cooker facing south without reflectors. We can see that the overall absorber surface is covered by sunlight and its value is around 1000 W/m^2. Figure 3 will constitute the reference results.

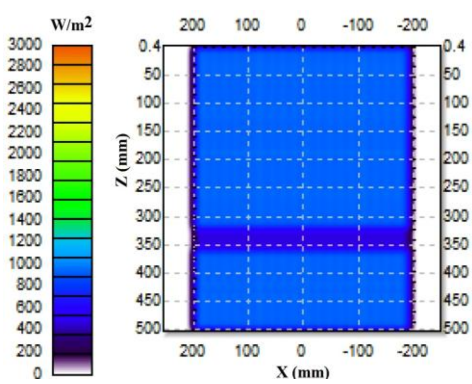

Fig. 3: Simulation results of box solar cooker without reflectors in December

5.2 Solar cooker with seasonal sun tracking

In this case we tray to tracking the seasonal variation of the sun position by titling the primary reflector with an angle α of 17° and the secondary reflector with an angle α of 23°, which are convenient angles for December month. The ray trace of the sunlight representing a solar cooker with two tracking seasonal reflectors is shown in figure 4. For clearness reasons, we choose to minimize the number of rays in the figures.

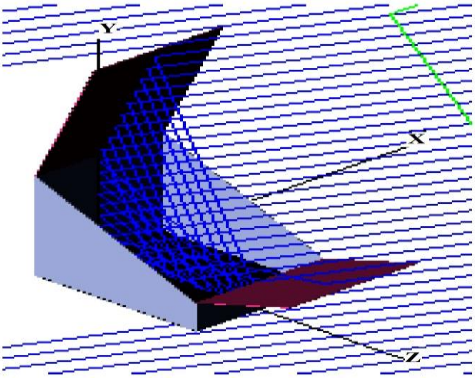

Fig. 4: Simulation ray trace of box solar cooker with two reflectors for tracking in north-south plane

Figure 5 shows the results of simulation of the solar cooker with two additional reflectors for south north tracking. We can see that the distribution of concentrated solar energy is uniform over all the plate absorber, which is good for stable cooking temperatures. The simulation step by step in this case show that the south facing reflector is adapted for winter season and the north facing reflector is used for summer season. The concentrated irradiance is important in this case (> 2000 W/m^2).

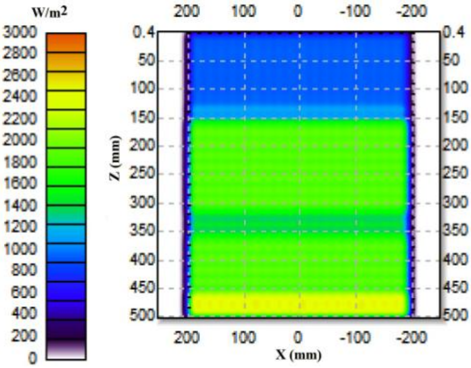

Fig. 5: Simulation results of two reflectors box solar cooker with respect to north-south sun direction

5.3 Solar cooker with diurnal sun tracking

In a purpose to track the sun during a day, we add two reflectors in the side of the cooker. For December month at noon in Ghardaïa site's, the γ angle is equal to 75°.

The ray trace of the sunlight representing a solar cooker with two reflectors tracking the sun during the day is shown in figure 6.

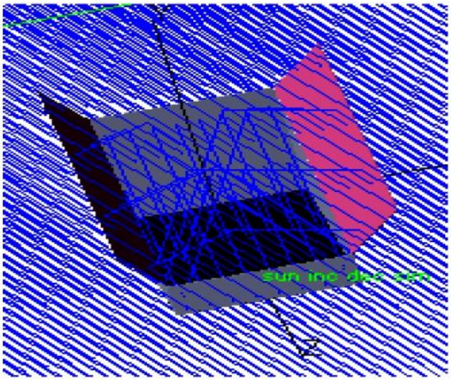

Fig. 6: Simulation ray trace of box solar cooker
with two reflectors for tracking in east-west plane

The simulation results of the solar cooker in December month at noon in Ghardaïa site's (Fig. 7) with two reflectors for tracking the sun during the day show that the distribution of concentrated solar energy is not uniform like the precedent case, the distribution is more concentrated in the side of the absorber because the sunlight fall at normal incidence on the reflectors surface. With choosing correct tilt angles, the east facing reflector is used for morning and the west facing reflector is adapted for afternoon utilization.

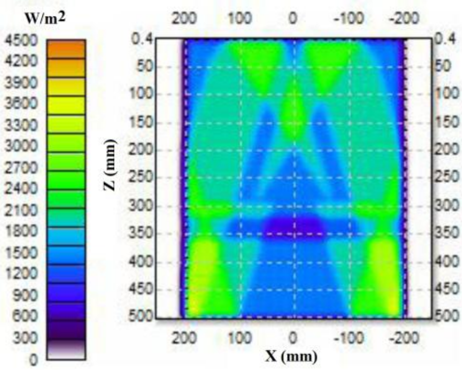

Fig. 7: Simulation results of two reflectors box solar cooker
with respect to east-west sun direction

5.4 The combined design

A combination of north-south and east-west facing reflectors are suggested to improve the design performances. The ray trace of the sunlight representing the combined design allowing the seasonal and diurnal tracking of the sun with the corresponding tilt angles is shown in figure 8:

The final simulation results of the solar cooker in December month at noon in Ghardaïa site's (Fig. 9) show that the combination of the four reflectors increases the collected energy on the plate absorber which improves the optical performances of the cooker. The concentration ratio is so height (> 3000 W/m^2) on the overall plate absorber surface, this case is important in winter season when the solar elevation is low and the need of cooking increase.

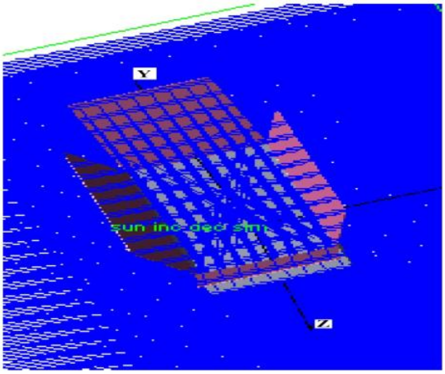

Fig. 8: Simulation ray trace of box solar cooker with four additional reflectors

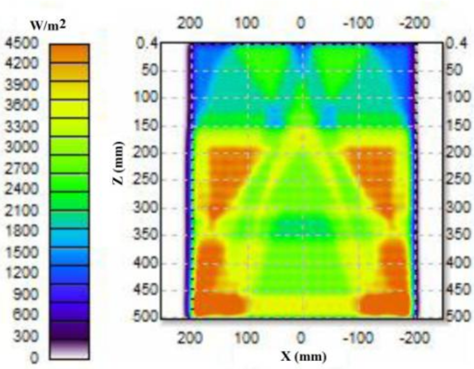

Fig. 9: Simulation results of concentrating irradiance on the box solar cooker absorber for winter season

6. CONCLUSION

A design of solar cooker with tracking mirror reflectors has been studied and the optical performances of the cooker are analyzed. The results of this study show that:

- The north-south facing reflectors are used to track the seasonal variation of the sun and the east-west facing reflectors are allowed to the tracking during the day.

- The distribution of concentrated solar energy is uniform on the plate absorber of the cooker in the case of north-south tracking which is suitable for cooking temperatures.

- The combination of the four reflectors increases the collected energy which improves the optical performances of the cooker and the concentration ratio is so height. This is very important for cooking in winter season when the solar elevation is low.

The results obtained from the simulation of the solar cooker are very promising. In our future works prototype design will be built for testing and validation of simulation results.

REFERENCES

[1] H.M. Toonen, '*Adapting to an Innovation: Solar Cooking in the Urban Households of Ouagadougou (Burkina Faso)*', Physics and Chemistry of the Earth, Parts A/B/C, Vol. 34, N°1-2, pp. 65 – 71, 2009.

[2] U.S. Mirdha and S.R. Dhariwal, '*Design Optimization of Solar Cooker*', Renewable Energy, Vol. 33, N°3, pp. 530 – 544, 2008.

[3] M. Thirugnanasambandam, S. Iniyan and R. Goic, '*A Review of Solar Thermal Technologies*', Renewable and Sustainable Energy Review, Vol. 14, N°1, pp. 312 – 322, 2010.

[4] S. Kumar, '*Natural Convective Heat Transfer in Trapezoidal Enclosure of Box Type Solar Cooker*', Renewable Energy, Vol. 29, N°2, pp. 211 -222, 2004.

[5] R. Kumar, R.S. Adhikari, H.P. Garg and A. Kumar, '*Thermal Performance of a Solar Pressure Cooker Based on Evacuated Tube Solar Collector*', Applied Thermal Engineering, Vol. 21, N°16, pp. 1699 – 1706, 2001.

[6] S. Kumar, '*Estimation of Design Parameters for Thermal Performance Evaluation of Box-Type Solar Cooker*', Renewable Energy, Vol. 30, N°7, pp. 1117 – 1126, 2005.

[7] A.R. Reddy and A.V.N. Rao, '*Prediction and Experimental Verification of Performance of Box-Type Solar Cooker. Part II. Cooking Vessel With Depressed Lid*', Energy Conversion and Management, Vol. 49, N°2, pp. 240 – 236, 2008.

[8] E.H. Amer, '*Theoretical and Experimental Assessment of a Double Exposure Solar Cooker*', Energy Conversion and Management, Vol. 44, N°16, pp. 2651 – 2663, 2003.

[9] E. Sharaf, '*A New Design for an Economical, Highly Efficient, Conical Solar Cooker*', Renewable Energy, Vol. 27, N°4, pp. 599 – 619, 2002.

[10] A.V. Sonune and S.K. Philip, '*Development of a Domestic Concentrating Cooker*', Renewable Energy, Vol. 28, N°8, pp. 1225 – 1234, 2003.

[11] H.H. Ozturk, '*Experimental Determination of Energy and Exergy Efficiency of the Solar Parabolic-Cooker*', Solar Energy, Vol. 77, N°1, pp. 67 – 71, 2004.

[12] R. Petela, '*Exergy Analysis of the Solar Cylindrical - Parabolic Cooker*', Solar Energy, Vol. 79, N°3, pp. 221 – 233, 2005.

[13] S.D. Pohekara and M. Ramachandran, '*Multi-Criteria Evaluation of Cooking Devices with Special Reference to Utility of Parabolic Solar Cooker (PSC) in India*', Energy, Vol. 31, N°8-9, pp. 1215 - 1227.

[14] N. Kumar, S. Agravat, T. Chavda T and H.N. Mistry, '*Design and Development of Efficient Multipurpose Domestic Solar Cookers/Dryers*', Renewable Energy, Vol. 33, N°10, pp. 2207 – 2211, 2008.

[15] H.M.S. Hussein, H.H. El-Ghetany and S.A. Nada, '*Experimental Investigation of Novel Indirect Solar Cooker with Indoor PCM Thermal Storage and Cooking Unit*', Energy Conversion and Management', Vol. 49, N°9, pp. 2237 – 2246, 2008.

[16] C.R. Chen, A. Sharma, S.K. Tyagi and D. Buddhi, '*Numerical Heat Transfer Studies of PCMs Used in a Box-Type Solar Cooker*', Renewable Energy, Vol. 33, N°5, pp. 1121 – 11299, 2008.

[17] A. Harmim, M. Boukar and M. Amar, '*Experimental Study of a Double Exposure Solar Cooker with Finned Cooking Vessel*', Solar Energy, Vol. 82, N°4, pp. 287 – 289, 2008.

[18] A. Harmim, M. Belhamel, M. Boukar and M. Amar, '*Experimental Investigation of a Box-Type Solar Cooker with a Finned Absorber Plate*', Energy, Vol. 35, N°9, pp. 3799 – 3802, 2010.

[19] J. Hofierka and M. Súri, '*The Solar Radiation Model for Open Source GIS: Implementation and Applications*', Proceedings of the Open source GIS - GRASS users Conference, Trento, Italy, 11-13 September 2002.

[20] B. Gschwind, L. Ménard, M. Albuisson and L. Wald, '*Converting a Successful Research Project into a Sustainable Service: The Case of the SoDa Web Service*', Environmental Modelling and Software, Vol. 21, N°11, pp. 1555 - 1561, 2006.

[21] S.A.M. Ibrahim and M.K. El-Reidy, '*The Performance of Solar Cooker in Egypt*', Renewable Energy, Vol. 6, N°8, pp. 1041 – 1050, 1995.

[22] I. Purohit and P. Purohit, '*Instrumentation Error Analysis of a Box-Type Solar Cooker*', Energy Conversion and Management, Vol. 50, N°2, pp. 365 – 375, 2009.

[23] SolidWorks, SolidWorks Corporation, 300 Baker Avenue, Concord, MA 01742. Available from: http://www.solidworks.com/.