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Experimental Exergy Analysis and Optimum Water Load of a Solar Cooker

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Abstract: The energy and exergy efficiencies of a stationary solar cooker equipped with an asymmetric compound parabolic concentrator (CPC) were experimentally evaluated. Experiments were conducted with different water load and at different ambient temperature. It was found that it is preferable that the cooker is directed 30° east of south for an exploitation during morning at a lower ambient temperature with sufficient solar radiation on its intercept area. Also exergy efficiency together with energy efficiency is used to define the optimum water load of the solar cooker. This optimum load is calculated according to 5 kg water/m² intercept area.

Keywords: Energy Efficiency, Exergy Efficiency, Optimum Water Load, Solar Cooker

1. Introduction

Solar cookers have been in use for many years. In recent years, research was focused on the design improvements of solar cookers for more effectiveness, a user-frindliness and a better social acceptance. Many solar cookers were developped in different countries with different designs and in various sizes [1]. Differents authors have also defined and used several parameters to test the performance of solar cookers [8].

Some of them depend on an energy analysis [2, 5, 9] and others on an exergy analysis [6, 7, 10, 14].

Effect of load varfiations on the performances of theses systems was also approached but for the first time in 2015 the concept of optimum load range (OLR) for solar cookers was introduced by Mahavar [8]. This concept is based on an energy analysis. Indeed, the optimum load range is a specific range of load for each solar cooker for which it shows good thermal as well as good cooking performance and has reasonably high efficiency. In the present paper and for the first time a contribution to the determination of the optimum water load of a solar cooker based on an experimental exergy analysis is presented.

2. Experimental Study

2.1. Description of the Studied Solar Sooker

A schematic diagram of the studied solar cooker is presented in Fig. 1 [3]. It consists of a solar cooker that is equipped with a non-imaging line-axis asymmetric CPC and an insulated parallelepipedic box with a vertical transparent glass cover on a side and a horizontal transparent glass cover on the roof. The absorber-plate is bent in right angle in a form of a step. It is laid out, so that its vertical surface is parallel to the glass cover on side by forming a space allowing the circulation of hot air upward the cooker box cavity, which is delimited by the roof glass and the horizontal surface of the absorber-plate, on which are deposited the cooking pots. The absorber-plate has a negligible thermal capacitance (thin plate) and its exposed surface is painted black to increase solar radiation absorption. Two linear parabolic reflectors (upper and lower parabola) are fixed on the glazed walls of the box.

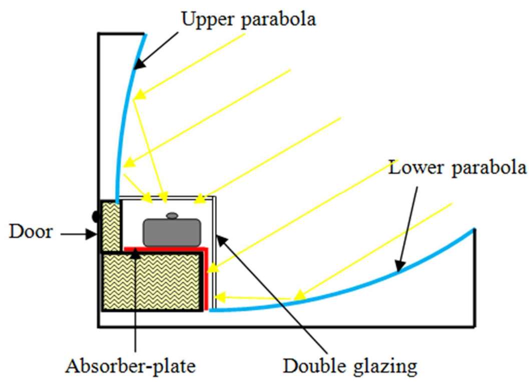

Fig. 1. *Schematic sketch of the stationary box-type solar cooker employing a line-axis asymmetric CPC as booster-reflector and an absorber-plate in a form of a step.*

The two reflectors are arranged so that, incoming solar radiation received by the aperture is reflected towards the absorber-plate. According to the solar altitude angle; the focal spot that is formed by the upper parabola moves on the horizontal surface of the absorber-plate and the focal spot that is formed by the lower parabola moves on the vertical surface of the absorber-plate. A prototype of a box-type solar cooker with an asymmetric CPC of an acceptance angle of 60° was constructed. The internal dimensions of the box receiving the cooking pots are 0.7 m per 0.28 m per 0.14 m height. Its top transparent cover consists of a double glazing of 4 mm thickness, 0.7 m length and 0.3 m width and its side vertical transparent glass cover consists of a double glazing of 4 mm thickness, 0.7 m length and 0.36 m height.

The absorber-plate, painted by a non-selective matte black paint, it is made of Aluminium sheet of 0.3 mm thickness and is bent in a right angle in such manner, it so as to present a horizontal surface of 0.7 m length and 0.26 m width and a vertical surface of 0.7 m length and 0.2 m height. The latter is placed at 2 cm from the vertical transparent glass cover. The absorber-plate is insulated, on its rear side, with a glass wool of 0.15 m thickness. On the opposite side of the vertical transparent glass cover, a door is provided to access the cooking pot. The two other box internal side walls are made of Aluminium sheet of 0.3 mm thickness and insulated with a glass wool of 0.05 m thickness. A photograph of the constructed solar cooker prototype is presented in Fig. 2.

Fig. 2. *The stationary box-type solar cooker equipped with an asymmetric CPC.*

2.2. Test Methodology

Experimental tests of the solar cooker were conducted in Adrar which is located in Algerian Sahara at 27° 53’N latitude and 0° 17’W longitude. The cooker was installed at a south oriented stationary position. During each test, three identical cooking pots were placed in the cooker and loaded with water. Ambient temperature, temperature of the water load of each cooking pot and solar radiation on the CPC aperture were measured and recorded at 1 min intervals by using a data logger system. Solar radiation was measured by a class 2 CM11 type pyranometer (range, 0-1400 W/m², accuracy, ±2 W/m²). All temperatures were measured by K type thermocouples (accuracy, ±1.5°C). The temperatures of water in the cooking pots were measured by K type thermocouples which were introduced through a small hole at the lid centre of each pot. The average of these temperatures was taken as the water load temperature.

2.3. Measured Thermal Profiles

As per the International Standard procedure [2], the full water load should be calculated according to 7 kg water per square meter of intercept area. The intercept area of the solar cooker is 0.712m². So the full water load is equal to 5 kg distributed evenly between three identical cooking pots. In this study; experiments were performed for different water loads: 1, 2, 3, 4 and 5 kg and at two different seasons: At winter period with a low test average ambient temperature and at summer period with high test average ambient temperature. The variations of solar radiation and ambient temperature as well as water temperature measured for all tests, under completely clear sky and in absence of wind, are presented in Fig. 3 and Fig. 4. To avoid measurement anomalies as water near boiling, the recorded data were stopped at 96°C in all tests. Tests carried out at high ambient average temperature are presented in Fig. 3. Dates of different loads 1, 2, 3, 4 and 5 kg are 28 Aug. 2012, 29 Aug. 2012, 30 Aug. 2012, 19 Sep. 2012 and 13 Sep. 2012, respectively. During all these tests, the ambient temperature varied between 36.7°C and 42.8°C.

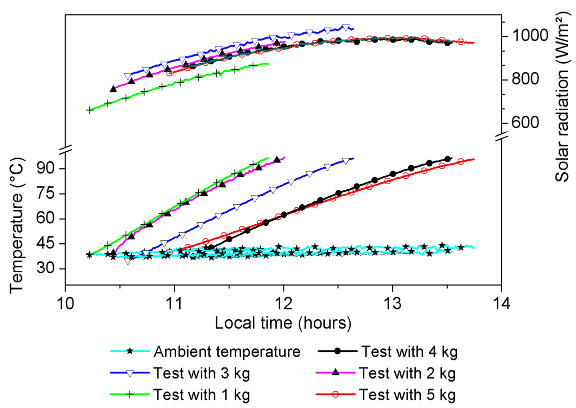

Fig. 3. *Variations of solar radiation, ambient temperature and water temperature during water heating tests with different loads at high average ambient temperature.*

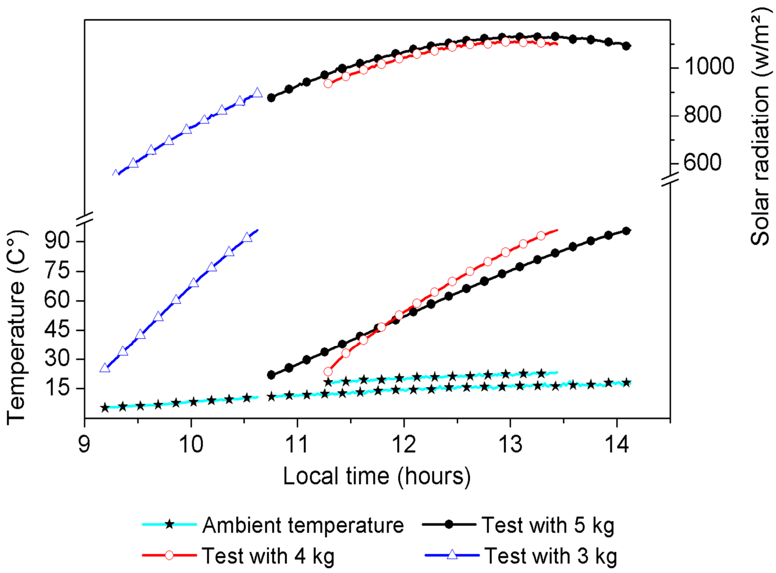

Fig. 4. *Variations of solar radiation, ambient temperature and water temperature during water heating tests with different loads at low average ambient temperature.*

Tests carried out at low ambient average temperature are presented in Fig. 4. Dates of different loads 3, 4 and 5 kg are 8 Jan. 2013, 20 Dec. 2012 and 5 Feb. 2013, respectively. During all these tests, the ambient temperature varied between 5.3°C and 22.6°C. Conditions of the tests carried out at high ambient temperature and at low ambient temperature are given in table 1 and table 2, repectively.

Table 1. *Test conditions for different water loads at high ambient temperature.*

Water load M_w (kg)	Parameters				Date
	Test avg. ambient temp. $\overline{T_a}$ (°C)	Avg. solar radiation $\overline{I_{in}}$ (W/m²)	$\overline{T_{w1}}$ (°C)	$\overline{T_{w2}}$ (°C)	
1	40.3: From 38.3 to 41.9	785.7	33.2	96.4	28 Aug. 2012
2	38.6: From 37.1 to 40.4	796.9	39.5	96.5	29 Aug. 2012
3	38.8: From 36.8 to 39.5	885.5	34.9	96.1	30 Aug. 2012
4	39.2: From 37.1 to 40.3	989.5	37.5	96.2	19 Sep. 2012
5	42.6: From 40.6 to 42.8	960.1	40.1	96.1	13 Sep. 2012

Table 2. *Test conditions for different water loads at low ambient temperature.*

Water load M_w (kg)	Parameters				Date
	Test avg. ambient temp. $\overline{T_a}$ (°C)	Avg. solar radiation $\overline{I_{in}}$ (W/m²)	$\overline{T_{w1}}$ (°C)	$\overline{T_{w2}}$ (°C)	
3	07.5: From 05.2 to 10.6	719.3	25.1	96.1	08 Jan. 2013
4	21.1: From 18.3 to 23.2	1058.2	23.6	96.1	20 Dec. 2012
5	15.3: From 10.9 to 17.7	1064.6	22.1	96.2	05 Fev. 2013

3. Energy and Exergy Analysis

The available solar cookers testing and assessment procedures [2, 5, 9] are based on energy analysis that refer to the first thermodynamique law. Indeed these methods deliver informations regarding the energy quantity without pay intention to quality and energy availability. The exergy analysis is based on the second thermodynamique law; it take into account irreversibility and the quality of the availabe energy [12]. Exergy is defined as the mawimum work that may be supplied by a system at a given ambient temperature. The exergy analysis is a useful method to complement, not to replace, energy analysis. Together they help define the optimum system which satisfies the imposed thermal and economic constraints and minimizes exergy loss [4]. The introduction of the solar cooker exergy efficiency constitutes an other way to evaluate and compare solar cookers performances. For the first time, the exergy efficiency has been introduced for a cylindro-parabolic solar cooker by [10, 11] and later on, other researchers follow up this method to analysis other types of solar cookers [6, 7, 12, 13, 15]. In order to experimentaly evaluate instantaneous energy and exergy efficiencies; water heating tests should be conducted according to international standard recommended by Funk [2]. For each test, the instantaneous experimental energy and exergy efficiencies are calculated. When water is heated until boiling, then for each 600 seconds time interval δt , the instantaneous energy and exergy efficiencies of the cooker are calculated by [6]:

$$\eta = \frac{M_w C_w (T_{w2} - T_{we1})}{I_{in} A_{in} \delta t} \qquad (1)$$

$$\psi = \frac{M_w C_w \left(T_{w2} - T_{w1}\right) - M_w C_w T_a \ln \frac{T_{w2}}{T_1}}{I_{in} \left[1 - \frac{4}{3}\left(\frac{T_a}{T_s}\right) + \frac{1}{3}\left(\frac{T_a}{T_s}\right)^4\right] A_{in} \delta t} \qquad (2)$$

η : Instantaneous energy efficiency;

ψ : Instantaneous exergy efficiency.

Where I_{in} is the solar radiation on intercept area of the cooker, A_{in} is the intercept area of the cooker, T_s is the surface temperature of sun (6000 K), δt is the time interval and, T_{w1} , T_{w2} and T_a are, respectively, the initial and the final water temperature and the ambient temperature for the considered time interval.

Considering all the time intervals during each test, the average energy efficiency η_{en} and the average exergy efficiency η_{ex} are calculated by:

$$\eta_{en} = \frac{M_w C_w \sum_i (T_{w2} - T_{w1})_i}{A_{in} \delta t \sum_i (I_{in})_i} \qquad (3)$$

$$\eta_{ex} = \frac{M_w C_w \sum_i \left[\left(T_{w2} - T_{w1}\right) - T_a \ln \frac{T_{w2}}{T_{w1}}\right]_i}{A_{in} \delta t \sum_i \left(I_{in} \left[1 - \frac{4}{3}\left(\frac{T_a}{T_s}\right) + \frac{1}{3}\left(\frac{T_a}{T_s}\right)^4\right]\right)_i} \qquad (4)$$

4. Results and Discussions

4.1. Effect of Test Average Ambient Temperature on Exergy Efficiency

From the thermal profile of each load the instantaneous energy and exergy efficiencies were calculated by mean of equations (1-2). Variations in exergy efficiency with respect to temperature difference (between water and ambient temperature) for 5 and 4 kg of water in the cooking pots are shown in figures 5 and 6, respectively. For these two loads, exergy efficiency variations are presented for two test average ambient temperatures. For 5 kg water load, tests were carried out on February 5th, 2013 at a test average ambient temperature of 15.3°C and on September 13rd, 2012 at a test average ambient temperature of 42.6°C and for 4 kg water load, tests were carried out on Decembre 20th, 2012 at a test average ambient temperature of 21.1°C and on Septembre 19th, 2012 at a test average ambient temperature of 39.2°C.

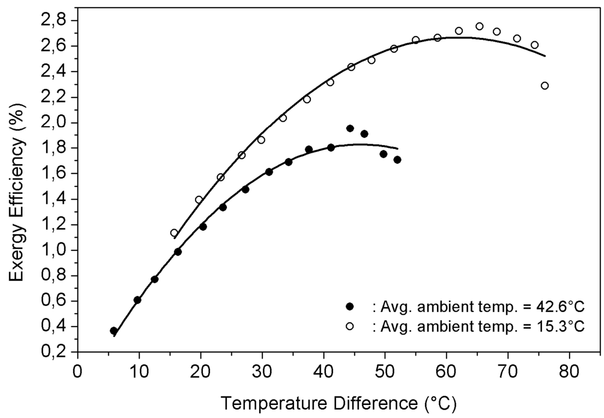

Fig. 5. *Variation of instantaneous exergy efficiency with temperature difference for 5kg water load at two different test average ambient temperatures. (42.5°C on September 13th, 2012 and 15.3°C on February 5th, 2013).*

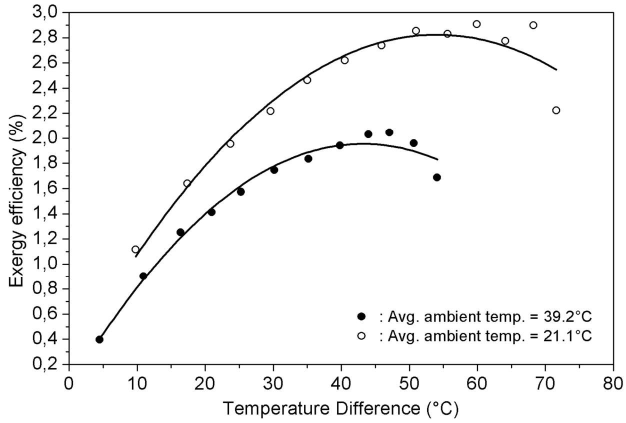

Fig. 6. *Variation of instantaneous exergy efficiency with temperature difference for 4kg water load at two different test average ambient temperatures. (21.1°C on December 20th, 2012 and 39.2°C on September 19th, 2012).*

It can be observed from figures 5 and 6 that the various curves have the same trend, but the exergy efficiency is larger at low ambient temperature. For the same water load, the peak exergy efficiency is atteind at high temperature difference when the test is carried out at low ambient temperature. It signifies that one needs more input energy to raise water temperature with solar cooker at hot environnement conditions. Then it is preferable that the cooker is directed 30° east of south (two hours before noon at a stationary position) for an exploitation during morning with sufficient solar radiation on its intercept area and at a lower ambient temperature compared to afternoon provided that the cooker is well insulated.

4.2. Impact of Load Variation on Exergy and Energy Efficiencies

Conditions of the tests carried out at high ambient temperature are given in table 2. The ambient temperature remains approximately constant during all the testing conditions. For each water load 1, 2, 3, 4 and 5 kg the test average ambient temperatures ($\overline{T_a}$) are 40.3°C, 38.6°C, 38.8°C, 39.2°C and 42.6°C, repectively; it differed by ±2°C. During all tests the average solar radiation ($\overline{I_{in}}$) was almost equal with a maximum difference of ±100W/m².

For each water load of the tests carried out according to the conditions given in table 1 the instantaneous energy and exergy efficiencies were calculated by mean of equations (1-2). The energy efficiency and exergy efficiency dependance on the temperature diffrence for different water loads is presented in figures 7 and 8, repectively. It can be observed that irrespective of the water load, the energy efficiency of the solar cooker decreases linearly with time as the temperature difference rises and its exergy efficiency varies in step with solar radiation and present a peak during each test. Indeed; the exergy efficiency increases from a low starting value to a maximum of 0.89%, 1.59%, 1.87%, 1.80% and 1.81% respectively for a water load of 1,2,3,4 and 5 kg and then decrease as the temperature difference rises and the thermal losses increase. Because during each test, the ambient temperature remains practically constant so the increase in temperature difference is due to the increase in water temperature and then the thermal losses increase.

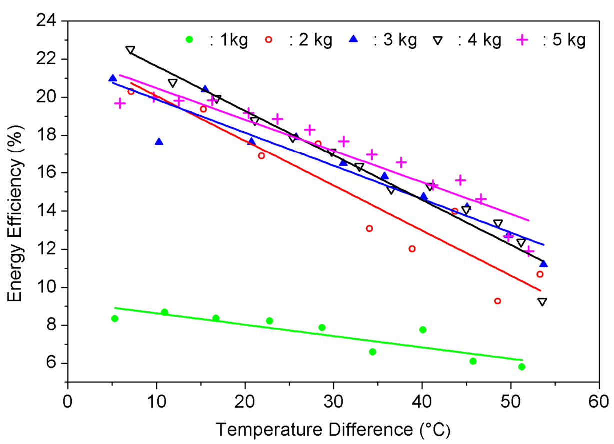

Fig. 7. Variations in instantaneous energy efficiency with temperature difference for different water load. Dates of different loads 1, 2, 3, 4 and 5 kg are 28 Aug. 2012, 29 Aug. 2012, 30 Aug. 2012, 19 Sep. 2012 and 13 Sep. 2012, respectively.

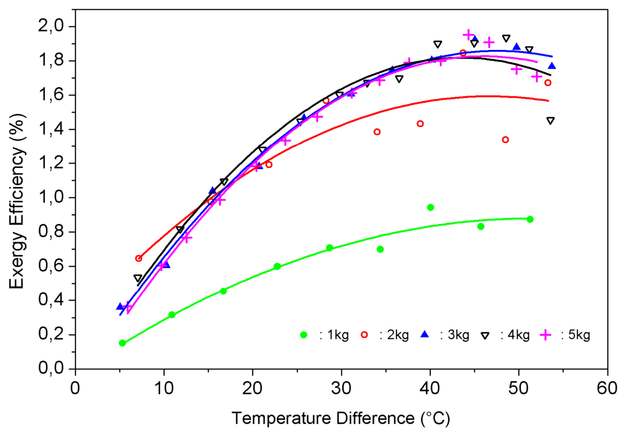

Fig. 8. Variations in instantaneous exergy efficiency with temperature difference for different water load. Dates of different loads 1, 2, 3, 4 and 5 kg are 28 Aug. 2012, 29 Aug. 2012, 30 Aug. 2012, 19 Sep. 2012 and 13 Sep. 2012, respectively.

4.3. Determination of the Optimum Water Load

Figures 7 and 8 show that for the same temperature difference both the energy and exergy efficiencies vary according to the water load during each test. For each test the average energy efficiency and the average exergy efficiency were calculated by mean of equations (3) and (4), repectively. The dependence of these two parameters according to the water load is presented in figure 9. This figure shows that the optimum of water load is located in the range delimited by the optima relative to both efficiencies. According to the two efficiencies curve fitting, this range is 3.74 - 3.77 kg. Thus the optimum water load is lower than the full load as recommended by International Standard procedure [2]. The optimum water load should be calculated according to 5 kg water/m² intercept area. Intercept area is defined as the sum of the reflector and the eperture areas projected onto the plane perpendicular to direct beam radiation.

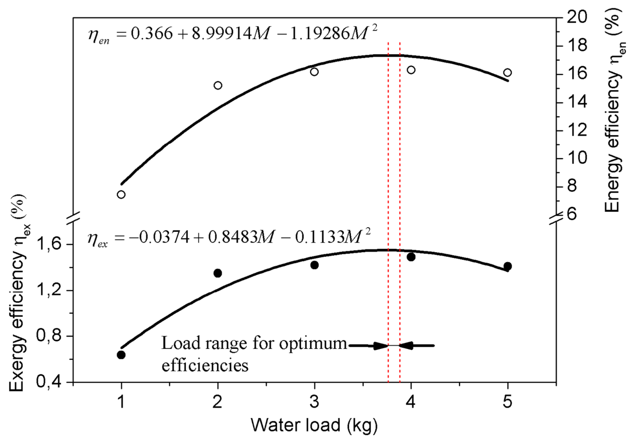

Fig. 9. Variations of test average efficiencies with water load.

For each water load the characterisitic boiling time, as proposed by [5], is calculated by mean of the following relation:

$$t_c = \frac{\Delta t A_{in} \overline{I_{in}}}{M_w 900} \quad (5)$$

Where Δt is the required time (minutes) to achieve at boiling temperature and $\overline{I_{in}}$ is the test average solar radiation on intercep area of the cooker.

The results are presented in table 3. It can be observed, in agreement with what was previously shown, that the best charcteristic boiling time is obtained with a load close to 4kg.

Table 3. *Characteristic boiling time for different water loads.*

Water load M_w (kg)	1	2	3	4	5
Avg. solar radiation $\overline{I_{in}}$ (W/m²)	785.7	796.9	885.5	989.5	960.1
Required time Δt (min)	96	93	122	138	181
Characteristic boiling time t_c (min m²/kg)	59.67	29.31	28.48	27.00	27.49

5. Conclusion

This paper presents results of an experimental analysis of energy and exergy efficiencies of a stationary solar cooker equipped with an asymmetric compound parabolic concentrator. Experiments were carried out with five different water loads and at different ambient temperatures. The experimental exergy analysis showed that it is preferable that the stationary solar cooker is directed 30° east of south for exploitation during morning with sufficient solar radiation and at a lower ambient temperature. Also exergy efficiency together with energy efficiency is used to define the optimum water load of the stationary solar cooker. This optimum load is calculated according to 5 kg water/m² intercept area.

Nomenclature

A_{in}	Cooker intercept area, m²
C_w	Water specific heat, J/kg K
I_{in}	Solar radiation on cooker intercept area, W/m²
$\overline{I_{in}}$	Test average solar radiation on cooker intercept area, W/m²
M_w	Water load, kg
t_c	Characteristic boiling time, min m²/kg
T_a	Ambient temperature, °C
$\overline{T_a}$	Test average ambient temperature, °C
T_s	Surface temperature of sun, K
T_{w1}	Initial water temperature, °C
T_{w2}	Final water temperature, °C
Δt	Time required to achieve at boiling temperature, min
δt	Time interval, s
η	Instantaneous energy efficiency, %
ψ	Instantaneous exergy efficiency, %
η_{en}	Average energy efficiency, %
η_{ex}	Average exergy efficiency, %

References

[1] Cuce, E., Cuce, P. M., 2013. A comprehensive review on solar cookers. Applied Energy 102, 1399-1421.

[2] Funk, P. A., 2000. Evaluation the international standard procedure for testing solar cookers and reporting performance. Solar Energy 68 (1), 1-7.

[3] Harmim, A., Merzouk, M., Boukar, M., Amar, M., 2013. Design and experimental testing of an innovative building-integrated box type solar cooker. Solar Energy 98, 422-433.

[4] Kerim K. A., 1985. Exergy efficiency and optimum operation of solar collectors. Applied Energy 21, 301-314.

[5] Khalifa, A. M. A., Taha, M. M. A., Akyurt, M., 1985. Solar cookers for outdoors and indoors. Energy 10 (7), 819-829.

[6] Kumar, N., Vishwanath, G., Gupta, A., 2011. An exergy based test protocol for truncated pyramid type solar box cooker. Energy 36, 5710-5715.

[7] Kumar, N., Vishwanath, G., Gupta, A., 2012. An exergy based unified tests protocol for solar cookers of different geometries. Renewable Energy 44, 457-462.

[8] Mahavar, S., Rajawat, P., Punia, R. C., Sengar, N., Dashora, P., 2015. Evaluating the optimum load range for box-type solar cookers. Renewable Energy 74, 187-194.

[9] Mullick, S. C., Kandpal, T. C., Saxena, A. K., 1987. Thermal test procedure for box-type solar cookers. Solar Energy 39 (4), 353-360.

[10] Öztürk, H. H., 2004a. Experimental determination of energy and exergy efficiency of the solar parabolic-cooker. Solar Energy 77, 67-71.

[11] Öztürk, H. H., 2004b. Second law analysis for solar cookers. International Journal of Green Energy 1 (2), 227-239.

[12] Pandey, A. K., Tyagi, V. V., Park, S. R., Tyagi S. K., 2012. Comparative experimental study of solar cookers using exergy analysis. J. Therm. Anal. Calorim. 109, 425-431.

[13] Panwar, N. L., Kaushik, S. C., Kothari, S., 2012. Experimental investigation of energy and exergy efficiencies of domestic size parabolic dish solar cooker. Journal of Renewable and Sustainable Energy 4, 23111-23118.

[14] Petela, R., 2005. Exergy analysis of the solar cylindrical-parabolic cooker. Solar Energy 79, 221-233.

[15] Shukla, S. K., 2009. Comparison of energy and exergy efficiency of community and domestic type parabolic solar cookers. International Journal of Green Energy 6, 437-449.