Experimental Water Heating Studies Of Flat Box And Inclined Box Solar Cooker Designs In Ghana

Emmanuel Yeboah Osei, Araba Amo-Aidoo

Abstract: Experimental water heating studies were performed to study the performance of inclined box and flat box solar cookers under the solar insolation conditions of Kumasi from May to July 2016, 10:00 to 14:00. The local solar insolation and average temperature profiles for the water and ambient were determined for the duration of study. Analytical methods of the ASAE S580.1 NOV2013 test standard were employed to estimate the interval cooking power and standardized cooking power of both solar cookers. The cooking power and efficiency in heating water to the point of maximum temperature were also estimated for both cookers. Generally, the inclined box cooker performed better than the flat box cooker by generating a relatively higher peak water temperature, higher cooking power, and higher efficiency. Further studies have been recommended to improve the design of the cookers and analyze the effect of insulation on the performance of the new cookers under similar solar insolation conditions.

Index Terms: Cooking efficiency, solar cooker, solar energy, solar warming, water heating test.

1. INTRODUCTION

Globally, 4.3 million people die prematurely on a yearly basis due to indoor air pollution caused mainly by cooking or warming food from traditional biomass and kerosene cook stoves [1] [2] [3]. About 2.8 billion people in the world rely on biomass and other solid fuels for cooking or warming food with a substantial fraction of these people living in Asia and Sub-Saharan Africa [1] [4] [5] [6]. It is estimated that this number will get to a higher level of over 3 billion by the year 2020 [1]. The increasing trend of biomass use is a source of concern due to the devastating effects it has on the environment including deforestation, carbon emissions and global warming [7] [8] [9]. These problems have made it necessary for the world to explore other cleaner and sustainable methods of cooking that will safeguard the environment and the health of those within the cooking vicinity. Among these cleaner methods is solar cooking where the sun is the main source of fuel. Solar cooking is a method that makes use of the sun's thermal energy for cooking or pasteurizing food [10] [11]. What makes this technology important is the fact that it is fuelled by a renewable resource, does not produce greenhouse gas emissions, and has the potential to curtail global warming and smoke inhalation from traditional methods of cooking [12]. Different solar cooker designs have been developed with different characteristics [11] [13]. These designs can be generally grouped into panel type, box type, and concentration type cookers [13]. Although, the concentration type cookers generate relatively higher temperatures, the box type cookers are easier to fabricate due to their relatively simple geometry [11]. Furthermore, the concentration cookers need to be continuously adjusted during the day to track the sun in order to be fully functional [14]. Despite the developments in the solar cooking technology, solar cooking has not yet been able to fully replace traditional cooking. This is mainly due to some challenges with the technology where food can only be directly cooked during the sunny hours of the day. Furthermore, the heat generated for cooking or warming food also depends on the intensity of available solar radiation at the cooking location and the cooker design. In view of this, efforts to develop the solar cooking technology will require testing of cooker thermal characteristics in order to inform further technological development and modifications. In this regard, the main aim of this research is to test the heat generation characteristics of inclined box solar cooker (IBC) and flat box solar cooker (FBC) designs in Ghana and ascertain their capacity to warm up a pot of water under the available solar insolation conditions.

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2 METHOD

2.1 Overview of Method

Experimental water heating studies were performed with IBC and FBC designs under tropical solar insolation conditions in Kumasi. The experiments were specifically conducted on Kumasi Technical University Campus, at the location with geographical coordinates (6.69° N, 1.61° W). Both cookers were powered by direct thermal energy from the sun without energy storage. The tests were done with regards to the capacity of the solar cookers to warm up 1 kg (0.001 m^3) of water concurrently. A separate open pot (OP) of 1 kg of water was placed outside in the open sun for comparison purposes. Average solar insolation for the location and temperature readings for the water in both solar cookers and that in the OP were taken at 10 minute intervals for the duration of the tests. The tests were conducted between the hours of 10:00 and 14:00 from May to July 2016. As prescribed by the ASAE S580.1 NOV2013 test standard, the interval and standardized cooking powers for the IBC and FBC were calculated respectively from the tests. In addition, the cooking powers and cooking efficiencies in warming water to the point of maximum temperature were calculated for both solar cookers.

2.2 Technical Description of the Solar Cookers

The IBC and FBC were both constructed with wood on the outside, aluminium on the inside, and a single layer of glass cover. The IBC had an inclination angle of 10° to the horizontal. Some characteristics of the two solar cookers are presented in Table 1. Again, engineering drawings of both cookers are presented in Fig. 1 and 2 with dimensions in millimetres. Fig. 3 also shows both cookers during the experiments.

TABLE 1: *Characteristics of the IBC and FBC*

Cooker parameters	**Inclined box cooker (IBC)**	**Flat box cooker (FBC)**
Weight	14.5 kg	13.4 kg
Number of glass covers	1	1
Thickness of glass cover	8 mm	8 mm
Area of glazing	180600 mm^2	176400 mm^2

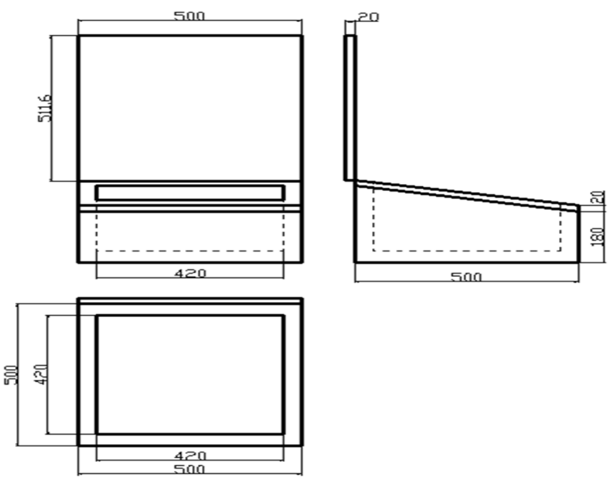

Fig. 1. *Engineering drawing of the Inclined Box Cooker*

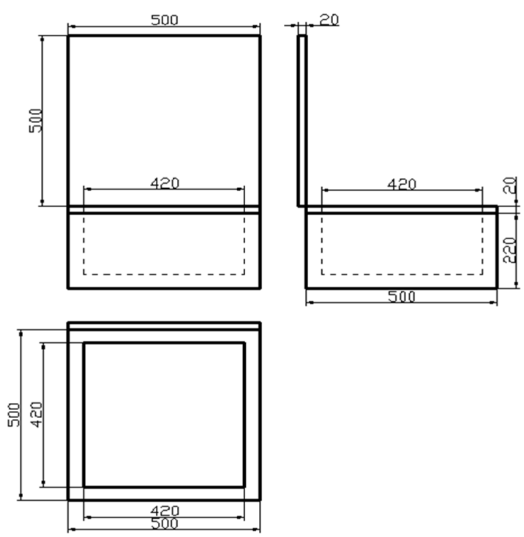

Fig. 2. *Engineering drawing of the Flat Box Cooker*

Fig. 3. *The IBC and FBC during the experiments*

2.3 Analytical Framework

The equations used were adopted from the ASAE S580.1 NOV2013 test standard [15]. The cooking power (*Pi*) for each solar cooker for each 10 minute heating interval was computed according to (1). The standardized cooking power (*Ps*) for each heating interval was calculated according to (3). The temperature difference between the water in each solar cooker and the ambient for each heating interval was calculated according to (4). A linear regression was graphed for standardized cooking power (*Ps*) against temperature difference (T_d). For a single measure of standardized cooking power as specified by ASAE S580.1 NOV2013, the linear graph in this regression was used to estimate the cooking power at a temperature difference of 50°C. The general equation for the linear regression takes the form as expressed in (5). The cooking power and water heating efficiencies for both cookers for the time to reach maximum water temperatures are expressed by (2) and (6) respectively [16] [8]. All the parameters of the various equations are explained in the “Nomenclature and Abbreviations” section.

$$P_i = [m \times C_v \times (T_{w2} - T_{w1})]/(600) \quad (1)$$

$$P = [m \times C_v \times (T_{wmax} - T_1)]/(\Delta t_{max}) \quad (2)$$

$$P_s = P_i \times (700/I_i) \quad (3)$$

$$T_d = T_w - T_a \quad (4)$$

$$P_s = (Slope \times T_d) + Intercept \quad (5)$$

$$\eta = [m \times C_v \times (T_{wmax} - T_1)]/[\Delta t_{max} \times A_{sc} \times I_{av}] \quad (6)$$

3 Results and Discussions

3.1 Solar Insolation Profile

The variation of average solar insolation from 10:00 to 14:00 for the location for the duration of experiment is presented in Fig. 4. The solar radiation generally increased from about 400 W/m^2 at 10:00, peaked at about 650 W/m^2 around 12:00, and gradually declined to 571 W/m^2 at 14:00. The dome shape of the average solar radiation profile for the location agrees with the general solar radiation profiles for other locations for clear days [17] [18] [19].

3.2 Ambient Temperature Profile

The average ambient temperature profile for the location is presented in Fig. 5. The ambient temperature generally fluctuated between a minimum of 31.5 °C and a maximum of 39.4 °C. The minimum and maximum temperature readings were registered at about 13:20 and 11:40 respectively. The average ambient temperature for the duration was 35.7 °C.

3.3 Water Temperature Profiles

The heating temperature profiles for the water in both solar cookers and the OP in the ambient are presented in Fig. 6. Comparatively, the water in the IBC recorded relatively higher temperatures as compared with the water in the FBC and that in the OP. The temperature of the water in the IBC started out at 34°C at 10:00, increased and peaked at about 58 °C at 12:30, and gradually declined to 56 °C at 14:00. The IBC recorded an average water temperature of 53.4 °C for the duration of study. The temperature of the water in the FBC also started out at 34 °C at 10:00 am, increased and peaked at 56.7 °C from 12:30 to 12:40, and gradually declined to 54.3 °C at 14:00. The FBC recorded an average water temperature of 51.7 °C. The temperature of the water in the OP remained much closer to ambient temperature and had marginal variations from 34 °C at 10:00 to a peak of 38.3 °C at 11:50 and finally to 35 °C at 14:00. The OP recorded an average water temperature of 36.3°C. Table 2 shows the peak and average water temperatures attained by the IBC, FBC, and OP. The peak water temperatures for the IBC and FBC occurred at the same time 12:30, whiles that for the OP occurred relatively earlier at 11:50. This shows that both solar cookers reached peak water temperatures in 2 hours 30 minutes from the beginning of the experiment. Although all three waters started with the same temperature, the peak temperature of the water in the IBC was 2.29% and 51.44% higher than the peak temperatures of the water in the FBC and OP respectively for the period of study. Again the average water temperature in the IBC was 3.29% and 47.11% higher than the average water temperatures in the FBC and OP respectively. Furthermore, the peak and average water temperatures in the FBC were 48.04% and 42.42% respectively higher than those in the OP. Both solar cookers were able to produce relatively higher water temperatures than the OP due to the miniature greenhouse effect created within the cookers. Although none of the cookers was able to attain water boiling temperatures under the weather conditions, the results show that the IBC had better performance over the FBC in producing relatively higher water temperatures. This can be attributed to the glazing inclination of the IBC which enabled it to receive optimal solar insolation as compared with the FBC. The fact that optimally inclined surfaces receive comparatively more solar insolation than horizontal surfaces is consistent with the observations made by [20] [21] [22].

TABLE 2: *Peak and average water temperatures for the IBC, FBC, and OP*

Item	Initial Water Temperature (°C)	Peak Water Temperature (°C)	Time of Peak Water Temperature (GMT)	Average Water Temperature (°C)
IBC	34	58.0	12:30	53.4
FBC	34	56.7	12:30	51.7
OP	34	38.3	11:50	36.3

3.4 Cooking Power

Variations of cooking power and standardized cooking power with time for each 10 minutes interval for the IBC and FBC as calculated from (1) and (3) are shown in Fig. 7. The interval cooking power and interval standardized cooking power for both cookers followed a similar varying pattern. The interval cooking power for the IBC and FBC registered peak values of 36 W and 34 W respectively at 10:40 (40 minutes into the experiments). The interval standardized cooking power for the IBC and FBC also registered peak values of 58 W and 55 W respectively. However, both solar cookers had consistently declining cooking power after 12:30. This trend was the result of waters within both cookers loosing heat during that time period. In calculating for the sensible cooking power for both cookers in heating water from the initial 34 °C to the maximum temperature, (2) was used. Since the experiments began at 10:00 and both cookers reached maximum water temperatures at 12:30 (see Table 2), the time frame in this regard was 9000 seconds. The sensible cooking powers for both cookers are presented in Table 3. IBC and FBC had sensible cooking powers of 11.16 W and 10.56 W respectively. Regression graphs of standardized cooking power (3) against temperature difference (4) as specified by ASAE S580.1 NOV2013 test standard for the IBC and FBC are shown in Fig. 8 and 9 respectively. From both figures, the standardized cooking power decreased with increasing temperature difference. From Fig. 8, the linear regression for the IBC yielded the equation "y = -0.858 x + 22.206" which could be translated to "$P_s = -0.858T_d + 22.206$" based on (5). Likewise, from Fig. 9, the linear regression for the FBC yielded the equation "y = -0.789 x + 19.154" which could also be translated to "$P_s = -0.789T_d + 19.154$". Therefore from both regression equations, the standardized cooking powers for the IBC and FBC at temperature difference of 50 °C are -20.7 W and -20.3 W respectively. However, the standardized cooking powers for the IBC and FBC are positive for temperature differences below 25 °C and 24 °C respectively. The negative values for standardized cooking power as calculated above mean that at a temperature difference (T_d) of 50 °C, where the water in the cooker is 50 °C hotter than the ambient temperature, increased heat losses cause both solar cookers to begin to move towards a trend of eventual declining water temperature. This general behaviour of both solar cookers is related to their designs and how well both cookers are able to convert the available solar radiation into heat and retain this heat for cooking at high cooker-interior temperatures. Experiments conducted by [23] where different solar cooker designs were tested on different days found that the solar cooker with poor insulation and small solar intercept area consistently depicted similar behaviour with the average regression equation being "Ps = -2.46T_d + 84.75" and the standardized cooking power at T_d of 50 °C was negative. The IBC and FBC had outer wooden bodies and interior black-coated aluminium sheet linings without any extra insulation material to minimize heat losses especially at high cooker-interior temperatures. From the observation in [23], the lack of adequate heat insulation for the IBC and FBC is one of the reasons for the losses in standardized cooking power at T_d of 50 °C.

3.5 Efficiency

Using (6), the efficiencies of both solar cookers in heating water to maximum temperature are presented in Table 3. From the computations, IBC and FBC had efficiencies of 10.84% and 10.50% respectively. Again, the efficiency of the IBC was a little higher than that of the FBC due to the IBC's inclination which made it receive more optimal solar insolation.

TABLE 3: *Sensible cooking powers and efficiencies of solar cookers*

Solar Cooker	Sensible Cooking Power (W)	Efficiency
IBC	11.16	10.84 %
FBC	10.56	10.50 %

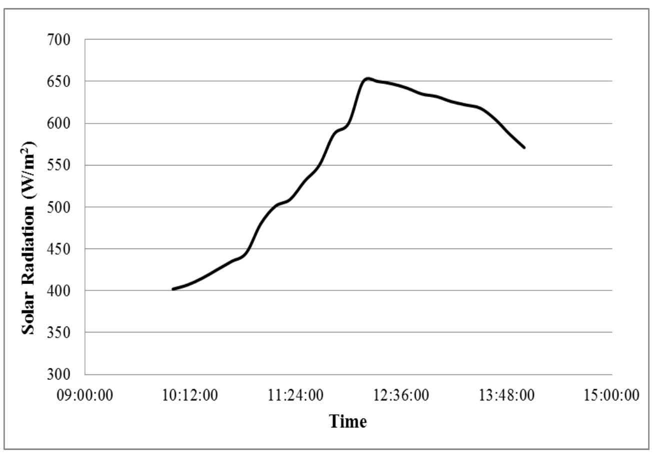

Fig. 4. *Average solar insolation profile*

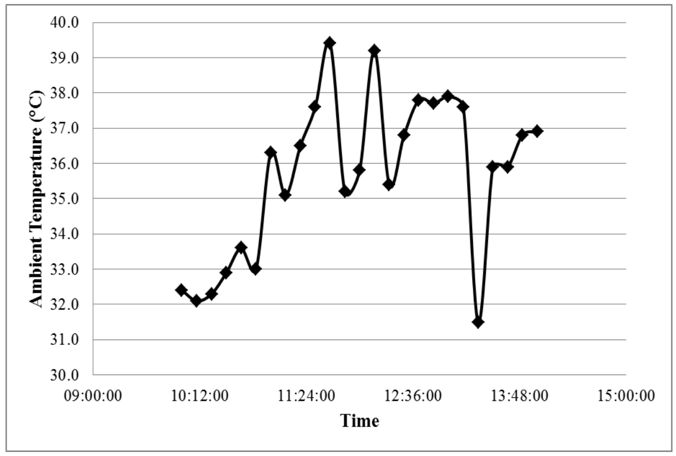

Fig. 5. *Average ambient temperature profile*

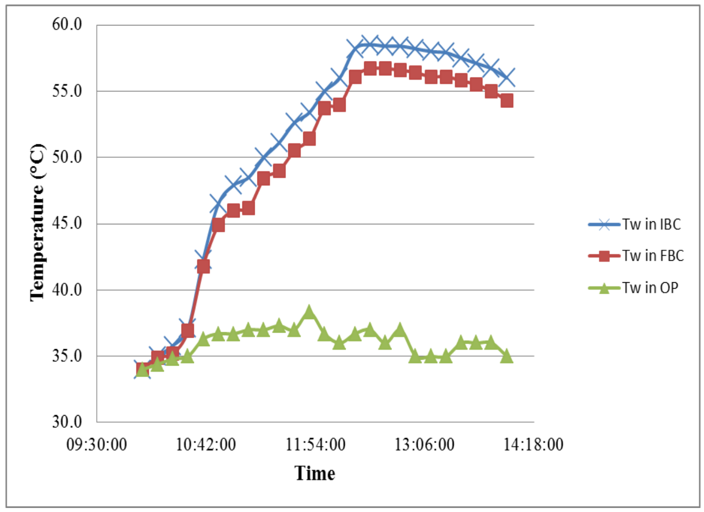

Fig. 6. *Variation of water temperature in both cookers*

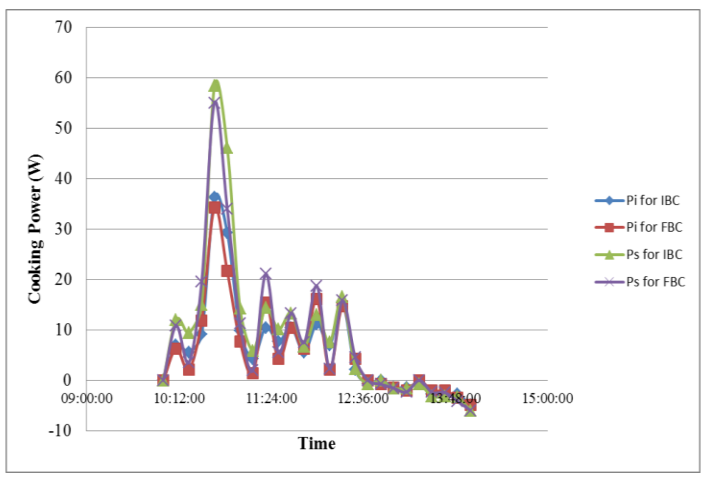

Fig. 7. *Variation of interval and standardized cooking power with time*

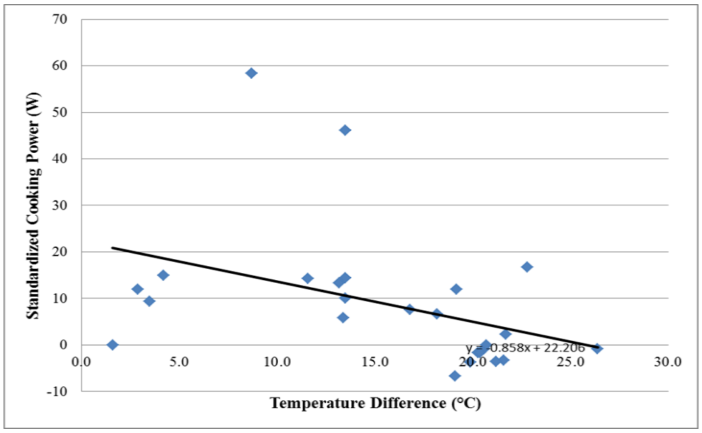

Fig. 8. Standardized cooking power versus temperature difference (T_d) for IBC

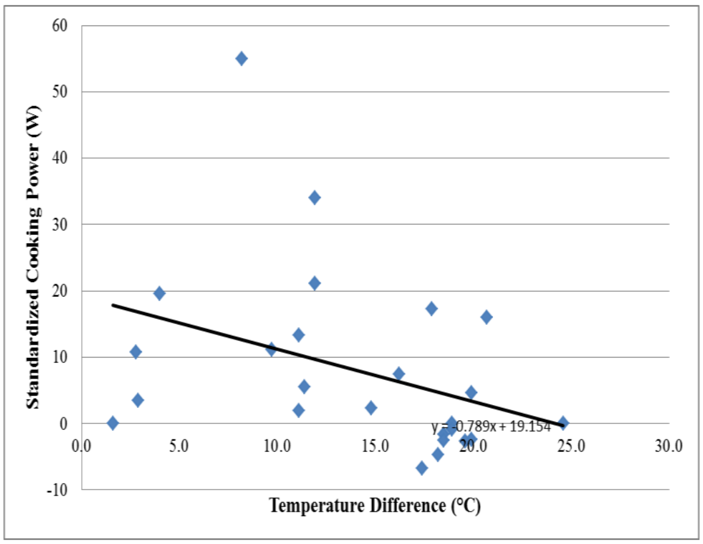

Fig. 9. Standardized cooking power versus temperature difference (T_d) for FBC

4 Conclusions and Further Research

Water warming tests were conducted with IBC and FBC designs in Kumasi from May to July 2016. The minimum and maximum average measured solar insolation was 400 W/m^2 and 650 W/m^2 respectively. The maximum water temperatures achieved were 58.0 °C and 56.7 °C for the IBC and FBC respectively. The sensible cooking powers in heating water to the point of maximum temperature were 11.16 W and 10.56 W for the IBC and FBC respectively. The efficiencies in heating water to the point of maximum temperature were 10.84 % and 10.50 % for the IBC and FBC respectively. From the results, the IBC performed relatively better at warming water than the FBC due to its inclination which enabled it to capture more optimal solar insolation. However, the standardized cooking powers of both cookers from the regression graphs as per ASAE S580.1 NOV2013 test standard procedure only recorded positive values for temperature differences below 25 °C and 24 °C for the IBC and FBC respectively. At a temperature difference of 50 °C, both cookers recorded declined standardized cooking power due to increase in heat losses between the cookers and the ambient which was caused by inadequate insulation. This behaviour was also observed by [23] in comparative experimentations with a solar cooker with inadequate insulation and small solar intercept area for solar insolation capture. With regards to the observations made in this study, the following recommendations are made for further research:

a) Development of new IBC and FBC designs with improved insulation and bigger area for solar insolation capture.
b) Further studies of the impact of insulation on the performance of the improved IBC and FBC designs under similar weather conditions and for comparisons with the results in this research.

Nomenclature and Abbreviations

A_{sc}	glazing area of solar cooker
C_v	specific heat capacity of water (4186 J/kgK)
I_i	average solar insolation for heating interval in W/m^2
I_{av}	average solar insolation for duration of experiment
m	mass of water in kg
η	efficiency
P	cooking power for heating water to maximum temperature
P_i	cooking power for heating interval in W
P_s	standardized cooking power for heating interval in W
Δt_{max}	time to reach maximum water temperature
T_a	average ambient temperature for heating interval in °C
T_d	temperature difference between water and ambient for heating interval in °C
T_{wmax}	maximum water temperature attained in °C
T_w	average water temperature for heating interval in °C
T_1	initial water temperature at the beginning of experiment in °C
T_{w1}	initial water temperature of heating interval in °C
T_{w2}	final water temperature of heating interval in °C

ASABE	American Society of Agricultural and Biological Engineers
FBC	flat box cooker
IBC	inclined box cooker
OP	open pot
W	Watts

References

[1] World Bank. "The State of the Global Clean and Improved Cooking Sector". Energy Sector Management Assistance Program, Technical Report 007/15, 2015. https://openknowledge.worldbank.org/handle/10986/21878

[2] P. Kumar and S. Mehta. "Poverty, Gender, and Empowerment in Sustained Adoption of Cleaner Cooking Systems: Making the Case for Refined Measurement". Energy Research & Social Science, vol. 19, pp. 48 – 52, 2016.

[3] T. Watkins, P. Arroyo, R. Perry, R. Wang, O. Arriaga, M. Fleming, C. O'Day, I. Stone, J. Sekerak, D. Mast, N. Hayes, P. Keller, and P. Schwartz. "Insulated Solar Electric – Tomorrow's Healthy Affordable Stoves?". Development Engineering, vol. 2, pp. 47 – 52, 2017.

[4] D.B. Rahut, B. Behera, and A. Ali. "Patterns and Determinants of Household use of Fuels for Cooking:

Empirical Evidence from Sub-Saharan Africa". Energy, vol. 117, pp. 93 – 104, 2016.

[5] E. Topriska, M. Kolokotroni, Z. Dehouche, D.T. Novieto, and E.A. Wilson. "The Potential to Generate Solar Hydrogen for Cooking Applications: Case Studies of Ghana, Jamaica and Indonesia". Renewable Energy, vol. 95, pp. 495 – 509, 2016.

[6] R. Suresh, V.K. Singh, J.K. Malik, A. Datta, and R.C. Pal, "Evaluation of the Performance of Improved Biomass Cooking Stoves with Different Solid Biomass Fuel Types". Biomass and Bioenergy, vol. 95, pp. 27 – 34, 2016.

[7] H.M. Toonen. "Adapting to an Innovation: Solar Cooking in the Urban Households of Ouagadougou (Burkina Faso)". Physics and Chemistry of the Earth, vol. 34, pp. 65 – 71, 2009.

[8] A. Harmim, M. Merzouk, M. Boukar, and M. Amar. "Solar Cooking Development in Algerian Sahara: Towards a Socially Suitable Solar Cooker". Renewable and Sustainable Energy Reviews, vol. 37, pp. 207 – 214, 2014.

[9] A. Karimu. "Cooking Fuel Preferences Among Ghanaian Households: An Empirical Analysis". Energy for Sustainable Development, vol. 27, pp. 10 – 17, 2015.

[10] G.D.J. Harper. " Solar Energy Projects for the Evil Genius". McGraw-Hill, 2007. ISBN: 0-07-150910-0.

[11] G. Kumaresan, V.S. Vigneswaran, S. Esakkimuthu, and R. Velraj. "Performance Assessment of a Solar Domestic Cooking Unit Integrated with Thermal Energy Storage System". Journal of Energy Storage, vol. 6, pp. 70 – 79, 2016.

[12] S.B. Riffat, and E. Cuce. "A Review on Hybrid Photovoltaic/Thermal Collectors and Systems". International Journal of Low-Carbon Technologies, vol. 6, issue 3, pp. 212 – 241, 2011.

[13] E. Cuce, and P.M. Cuce. "A Comprehensive Review on Solar Cookers". Applied Energy, vol. 102, pp. 1399 – 1421, 2013.

[14] S.B. Joshi, and A.R. Jani. "Design, Development and Testing of a Small Scale Hybrid Solar Cooker". Solar Energy, vol. 122, pp. 148 – 155, 2015.

[15] ASABE. "ASAE S580.1 NOV2013. Testing and Reporting Solar Cooker Performance". http://www.asabe.org/media/200979/s580.1.pdf, 2013. Accessed 22 February 2017.

[16] N. Kumar, G. Vishwanath, and A. Gupta. "An Exergy Based Test Protocol for Truncated Pyramid Type Solar Box Cooker". Energy, vol. 36, pp. 5710 – 5715, 2011.

[17] J. Twidell, and T. Weir. "Renewable Energy Resources: Second Edition". Taylor & Francis, USA, 2006. ISBN: 9-78-0-419-25330-3.

[18] J.A. Duffie, and W.A. Beckman. "Solar Engineering of Thermal Processes: Fourth edition". John Wiley & Sons, USA, 2013. ISBN: 978-1-118-67160-3.

[19] S.B. Joshi, and A.R. Jani. "Photovoltaic and Thermal Hybridized Solar Cooker". ISRN Renewable Energy, Article ID: 746189, 2013.

[20] P.C. Pande, and K.P. Thanvi. "Design and Development of a Solar Cooker for Maximum Energy Capture in Stationary Mode". Energy Conversion and Management, vol. 27, issue 1, pp. 117 – 120, 1987.

[21] S. Bari. "Optimum Slope Angle and Orientation of Solar Collectors for Different Periods of Possible Utilization". Energy Conversion and Management, vol. 41, pp. 855 – 860, 2000.

[22] U.S. Mirdha, and S.R. Dhariwal. "Design Optimization of Solar Cooker". Renewable Energy, vol. 33, pp. 530 – 544, 2008.

[23] P.A. Funk. "Evaluating the International Standard Procedure for Testing Solar Cookers and Reporting Performance". Solar Energy, vol. 68, pp. 1 – 7, 2000.