Experimental Assessment on Thermal Performance and Efficiency of Pyra-Box Solar Cooker

AWASH TEKLE
School Of Mechanical and Industrial Engineering, Hawassa University, P.box 05,
Email: awashtek@gmail.com or awashtek@yahoo.com

ABSTRACT
Low-cost Pyra-box type solar cooker was designed, prototyped and tested. The energy efficiency of the cooker was experimentally evaluated. The experiments were conducted in a clear day in Junuary 2014 in Hawassa University, Ethiopia. Details of temperature distributions and their time dependences were measured. Temperature measurements were taken at intervals of 30 seconds with K-type thermocouples connected to a multi-channel digital data-logger. The maximum temperature obtained in a pot containing 500 CC amount of water was 94 °C and 88 ^{o}C for pyra-box and conventional box cooker respectivelly. The second experiment was conducted using oil fluid and the maximum temperature attained within two hours by the pyra-box cooker, Tpc, was 104.81^{o}C. The total overall size of pyra-box cooker was 25% less than the box solar cooker. The average energy efficiency of CSC and pyra- box cooker was about 15.4 % and 26.5 % respectively. At 50^{o}C temperature difference they had 8% energy efficiency difference. Finally pyra-box cooker can increase an average of 11 % thermal efficiency by decreasing 25% total collector area.

Key words: Performance, Pyra-Box, Solar Cooker, Thermal Analysis

1. INTRODUCTION

Energy is one of the basic needs and a means to increase productivity, enhance employment opportunities and improve the quality of life of people. The world energy scenario projects the deepening of the fuel energy crisis, the implications of which would be equally serious for both the developed and developing nations (Mahesh A., 2000). The people in Ethiopia rely on biomass, electricity, and gas, to prepare food and light their houses in remote and dry climates, such as Hawassa (7.05°N and 38.467°E). However, electricity and gas can be costly, lacking, and difficult to obtain, so people increasingly use trees and shrubs as an alternative fuel for heating, boiling water and cooking. Biomass, including wood, dung and crop residues, the source for above 92.4% of Ethiopia's total energy use, is used primarily in the household. An analysis of household energy consumption pattern reveals that the major use is for heating and cooking (Devadas, R.P, 1997). The energy needs of our country are increasing at a rapid rate, and indigenous energy resources are limited and may not be sufficient in the long run to sustain economic development. The combination of high demand aggravated by low use efficiency has contributed to deforestation, rural poverty and energy shortage in Ethiopia (Awash T., 2013). This necessitated the search for efficient and appropriate technologies utilizing renewable sources of energy. The use of solar energy to cook food presents a viable alternative to the use of fuel wood, kerosene, and other fuels traditionally used in developing countries (include Ethiopia) for the purpose of preparing food. The efforts in this direction would not only reduce the demand on the fast depleting fossil fuels but would also restore the ecological balance. Solar cooking can be used as an effective mitigation tool with regards to global climate change, deforestation, and economic debasement of the developing countries (like Ethiopia). In this critical situation solar energy which is pollution free, cost free and available in abundance during most part of the year (13 month sunshine) offers a practical solution to the household energy problems. The earth receives 170,000 million MW of energy from the sun viz., about 18000 times the world's present energy consumption (Singhal, A.K., 1997). In Ethiopia solar energy is abundantly available in most parts of the country. The semi-arid and desert areas in the eastern and northern-central part of Ethiopia have the highest radiation intensity 6.5-7.5 kWh/m2/day, while the other parts of the land have radiation in the range of 4.5-6.0 kWh/m2/day. On such days, it is possible to cook both noon and evening meals in a solar cooker.

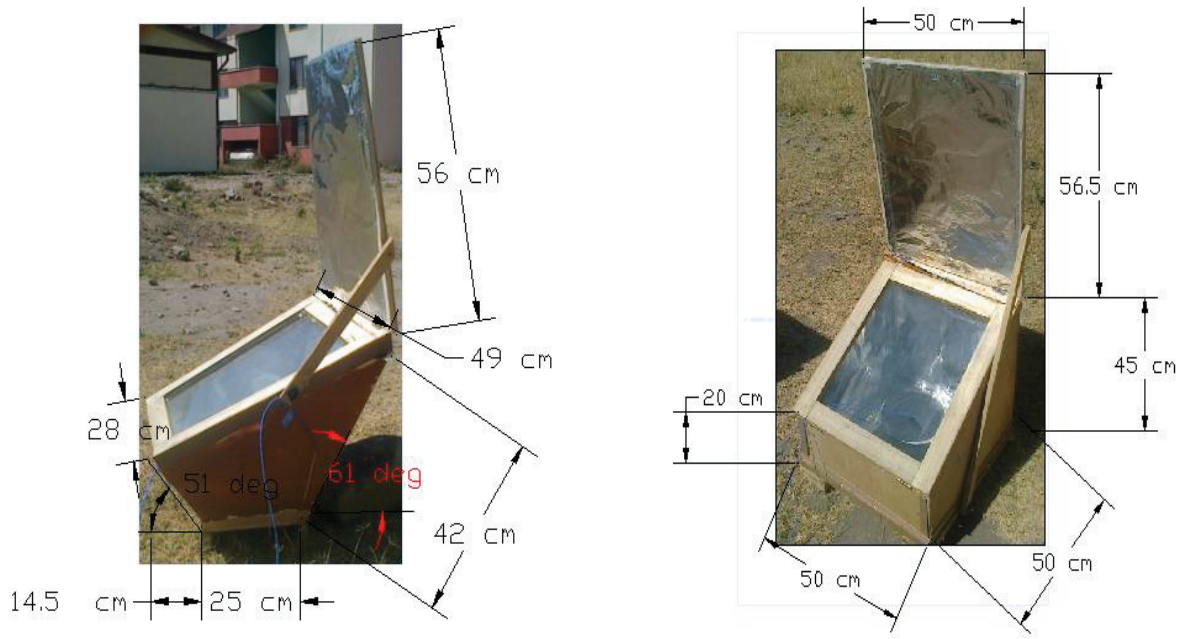
2. MATERIAL AND METHODS

In order to construct an effective solar cooker the choice of materials has to be given considerable thought. The materials chosen must be low cost, able to withstand high temperatures, safe, and effective regarding both the capture and retention of solar energy. A box type solar cooker consisted of an insulated system, glass cover and a top lid, and it has also a foil reflector on its inner side to reflect sunlight into the box when the lid is kept open. The absorber part of the box is painted black and usually one or more than one black painted pots are placed inside the box along with the material to be cooked. These pots are also painted black on the outer surface so that they also absorb solar radiation directly. The thickness of the wood used in constructing the sides and the base of the box is 2cm. These thicknesses are used so that the box will not be too heavy. A solar box cooker is smoke free unlike other forms of cookers which uses smoky cooking fires which results in eye and lung diseases. It consists of three controlled parameters (solar intercept area, overall heat loss coefficient, and absorber plate thermal conductivity) and three uncontrolled variables (insulation, temperature difference, and load distribution) (P.A. Funk and D.L. Larson, 1998). Insulating material (news paper) with five faces and one face of the box fitted with a transparent medium, such as glass or plastic. Glass or plastic allows the box to take advantage of the greenhouse effect and incident solar radiation cooks the food within the box. The general design description of the pyra-box and box solar cooker listed below (Table 2.1).

Table 2.1: Fabrication material selection of pyra- box and box solar cooker

Component	Material	Dimension	Requirements / Remarks
Outer Box	wooden board	2mm thick	Resistant to atmospheric variations
Inner Box reflector	Aluminium foil	0.56 mm thick	Reflectivity - scratch resistant ,and resistant to atmospheric variation
Insulation	News paper	……..	To prevent heat loss from the cooker to the environment
glass cover	Ordinary glass Sheet	3-4 mm thick	glass system must be air tight Transmittance
Pot	Stainless Steel	Sheet 1.2 mm Thick	Dull black painted stable upto 250°C
Absorbor plate	Black sheet metal	1mm thick	Good absorber of radiation

A black surface is a good emitter and absorber of radiation. B/se a black surface absorbs all the radiation that falls on it, but reflects, and transmits none. The radiation that was transmitted by the glass is absorbed by the black plate and converted to heat (Uhuegbu, Chidi C., 2011). This research has already concentrated on two types of solar cooker. Those are Box and Pyra-box cooker (partial Focusing cooker). The pyra-box, as shown in Figure 3.1(a), has the shape of tapered reverse pyramidal stracture.The experimental tests of the solar cookers were carried out during the successive days from the 04/01/2014 to 06/01/2014. Each experiment starts from 11:00 am in the morning to 13:00 pm in the afternoon. The experimental work was fully carried out in the Thermo-fluid laboratory at the School of Mechanical and Industrial Engineering, Hawassa Universty, Ethiopia. All the experiments were carried out in Hawassa University (7.05° N and 38.467° E). Experiments were conducted between -15^0 and 15^0 hour angle and the solar declination angle (δ), which is defined as the angle between the earth's equatorial plane and the earth sun line, of the experiment site location was -22.78^o upto -22.57^o. And the total declination angle of the research site location and the earth sun line varies form -29.83^o to -29.6^o. The experimental thermal and efficiency analysis was concentrated on testing of two types of cookers; those are box (conventional solar cooker, CSC) and pyra-box solar cooker as shown in Figure 2.1. And the overall dimension, constructing cost and weight of pyra-box was almost three fourth of convensional box cooker (CBC).



(a) Pyra-box solar cooker (b) Box solar cooker

Figure 2.1: Prototyping dimension of solar cookers

During each experiment, both box and pyra-box cookers were placed side by side on the absorber of the solar cooker and loaded with the same mass of water/oil at the same ambient temperature for water/oil heating test. Both the two pots were filled with water and placed in the absorber plate of the cooker, and was closed with Single glazing cover until test end. The cooker was manually oriented according to hour angle at an interval of 5^0(or 20 minute) in order to collect a maximum of solar radiation. The temperatures of the water/ oil in each pot as well as ambient temperature measurements were taken at intervals of 30 seconds with K-type thermocouples connected to a multi-channel digital data-logger computer. Seven thermocouples at different locations were installed on the pra-box and conventional solar cooker. These locations are: (a) Outer glass temperature (or ambient temperature), (b) In side box temperature, and (c) water temperature inside the pot (d) plate temperature. Global components solar radiation estimation was taken analytical estimation for clear sky radiation. Solar radiation incident on the atmosphere from the direction of the Sun is the solar extraterrestrial beam radiation. Beneath the atmosphere, at the Earth's surface, the radiation will be observable from the direction of the Sun's disc in the direct beam, and also from other directions as diffuse radiation. Hottel, et. al. (1976) presented a simple model for the estimation of the transmittance of beam radiation Combined with the Liu and Jordan's model for the transmittance of diffuse radiation was easily computed.

2.1 First and Second Merit Figures

The second testing standard considered is based on Thermal Test Procedures for Box-Type Solar Cookers, by Mullick et al(1987). This standard, presented in a more technical framework than ASAE S580, provides two figures of merit, calculated so as to be as independent of environmental conditions (such as wind speed, insolation, etc.) as possible. The two (first and second) figures of merit are given by the following equations.

$$F_1 = \frac{T_p - T_a}{H_s} \tag{1}$$

And

$$F_2 = \frac{F_1 (MC)_w}{At} \ln \left[\frac{1 - \frac{1}{F_1}\left(\frac{T_{w1} - T_a}{H}\right)}{1 - \frac{1}{F_1}\left(\frac{T_{w2} - T_a}{H}\right)} \right] \tag{2}$$

Where:

T_p = temperature of the absorber plate (stagnation)
T_a = ambient air temperature

H_s = insolation on a horizontal surface (taken at time of stagnation)
M = mass of water
C = heat capacity of water
A = aperture area
t = time
T_{w1} = water temperature at state 1 (initial)
T_{w2} = water temperature at state 2 (final)
H = horizontal insolation (average)

The F1 and F2 merit figures enable the evaluation and future comparisons of solar ovens. The Pyra-box solar oven's thermal performance can be compared by two merit figures which are obtained by experimental testing and are used to improve the pyra-box design.

3. RESULT AND DISCUSSION

Solar cooker performance experiments were conducted four times in January, 2014. Having suitable clear sky days were a good opportunity to conduct the experiment. Box temperature, ambient air temperature, Base plate temperature and water load temperature were measured during the experiments. For the water boiling tests, a black painted aluminium pot weighing about 0.21 kg containing about 500 CC (0.5kg) of water- was placed on the absorber plate of the pyra-box and box solar cooker covered with the single pane glass and placed outdoor for observations. Pyra-box and conventional box solar cookers, during the heating-up time, had the heating rate of 0.45^{0}C/min and 0.42^{0}C/min respectively.

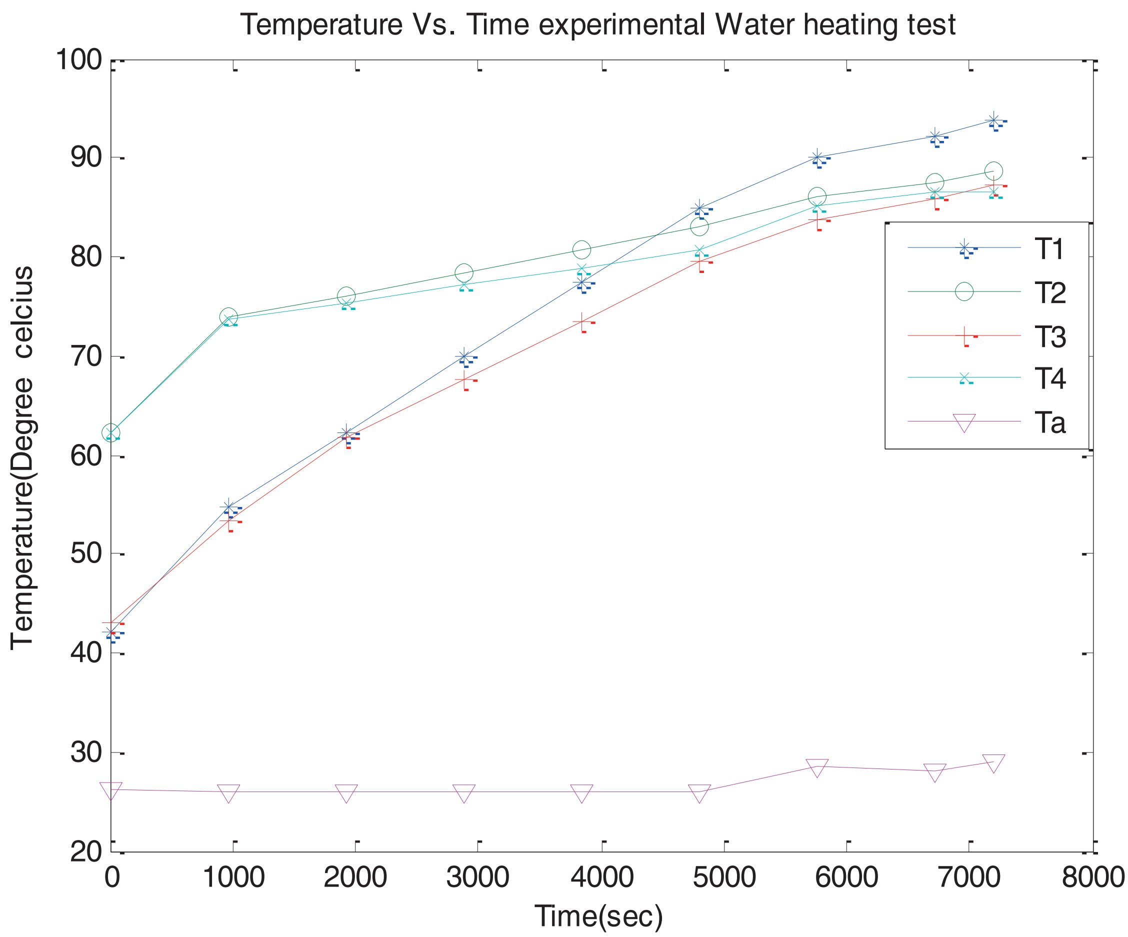


Figure 3.1: Experimental water heating test using pyra-box and conventional solar box cooker

The experimental result shows, the optimum water temperature of pyra-box and conventional solar cooker only gets up to 201.2 °F (94 °C) and 188.6 °F (87 °C) respectively. Conventional cookbooks call for high temperatures to shorten the cooking time and for browning. A temperature of 179.6° F (82° C) is hot enough for most kinds of cooking. Remember that water cannot get hotter than 212° F (100° C at see level), but the experiment was conducted above 1652m from the see level and the boiling temerature of water is less than

100oC. Test data shall be recorded while cooking vessel contents (water) are at temperatures between 15 °C above ambient and local boiling temperature using the preheated pyra-box and box solar cooker.

According to Fig. 3.1, it was evident that the pyra-box solar cooker was beter than conventional solar cooker, and developed a temperature of about 54 ^{0}C over the ambient within two hours (11:00 hours to 13:00 hours) after it was set up for investigation. The photo-thermal of pyra-box cooker using water load device later attained a maximum temperature of 93.7 ^{0}C on 04/01/2014 and 92.7 ^{0}C on 05/01/2014. Since the maximum temperature of water test depends on the extensive and intensive thermo fluid property of the environment and location of the research area. So, the second experiment was conducted using oil fluid and the maximum temperature attained within two hours by the pyra-box cooker, Tpc, is 104.81^{o}C. Finally, Payra-box was established that optimum processing water temperature ranged from 92.7 ^{o}C - 94^{o}C, giving an average overall heat transfer coefficient of 12.04 W/m^{2}.K under clear sky conditions.

Table 3.1: Oil heating rate using pyra-box and box solar cooker (500 CC)

Time(sec)	ST-1	ST-2	ST-3	ST-4	ST-5
0	40.47	41.14	40.11	41.47	31.40
600	50.47	51.14	49.10	51.47	31.88
1200	62.34	57.99	62.20	55.51	32.36
1800	79.64	59.12	78.19	58.94	32.30
2400	85.97	60.08	83.97	60.49	32.90
3000	90.52	70.57	87.73	61.89	31.51
3600	94.41	74.90	91.79	63.94	30.30
4200	97.61	71.25	95.01	65.35	29.81
4800	99.91	69.07	97.23	66.46	29.71
5400	102.27	68.77	99.70	67.10	31.37
6000	103.17	67.14	100.95	66.94	30.27
6600	104.23	66.85	102.57	68.24	31.01
7200	104.81	76.09	102.79	65.93	31.29

Under stagnation test, the first figure of merit (F1) of the two solar cookers was obtained 0.1250 and 0.1252 respectively. Thus the obtained value of F1 is (0.1250 and 0.1252) where the allowed standard F1 test that If the value F1 is greater than 0.12, the cooker is marked as A-Grade and if F1 is less than 0.12 the cooker is marked as a B-Grade solar cooker. The performance test F1 is complying with the suggested value by Mullik.

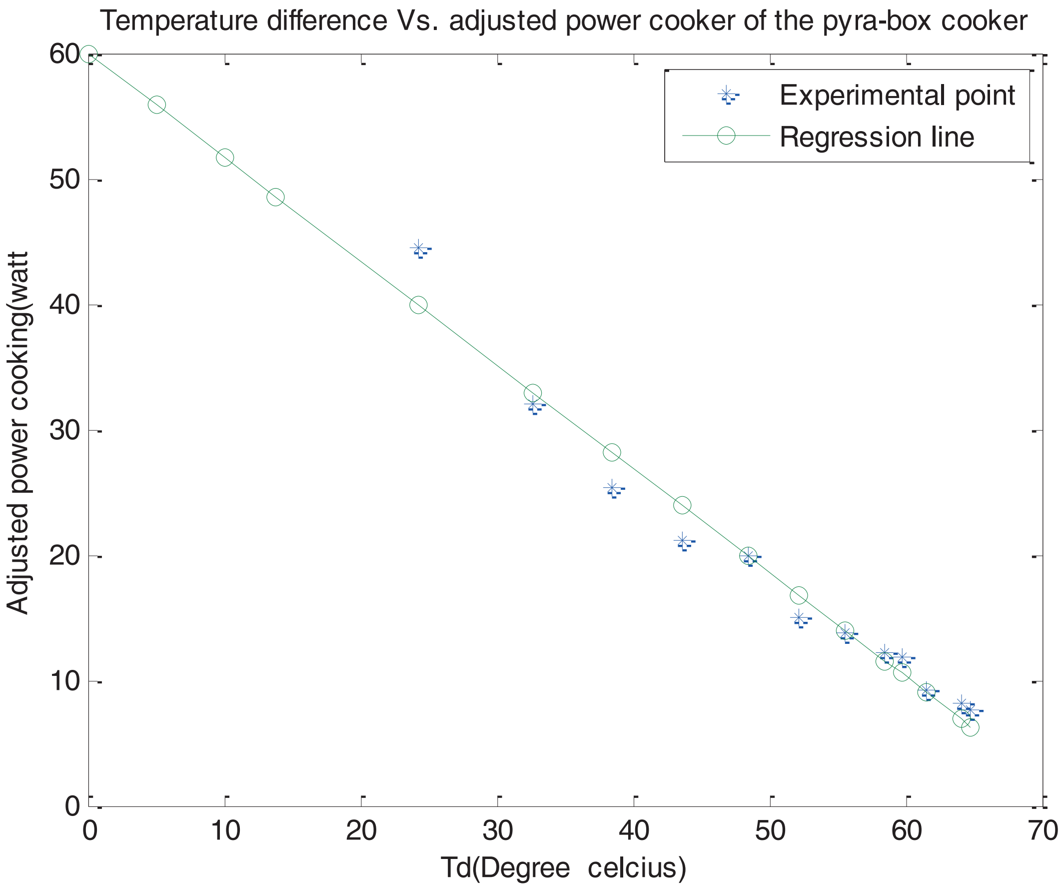


Figure 3.2: Ajusted cooking power plotted over temperature difference and the resulting regression line of pyra-box cooker

To estimate the thermal efficiency of the solar cooking unit, two characteristic values are used: cooking power and efficiency. The cooker power related to the difference between average of load temperature and to the air temperature can have linearly relationship as shown in Fig 4.2 and the regression (R^2) estimated 0.86 which is another indication to confirm the efficiency of the cooker. The result shows that the cooking power of the pyra-box comes out to be higher than that of the conventional cooker; and suggesting that the higher amount of energy is available in the pyra-box during cooking. The cooking powers, Ps, of the pyra-box and box solar cookers at 50°C temperature difference were obtained 36.3 W and 26.9 W per kilogram of water respectively. The regression line obtained for the determination of adjusted cooking power of pyra-box solar cookers is presented in Figure 3.2.

Table 3.2: Water heating merit analysis test using pyra-box and box solar cooker (500 CC)

Time	Insolation radiation	Water temperature		Ambient Temp.	Plate temperature		first figure of merit		second figure of merit	
t(sec)	I_i	T_1	T_3	T_a	T_{pb}	T_{pp}	F_{1b}	F_{1p}	F_{2p}	F_{2b}
0	591.33	42.02	43.02	26.18	86.29	86.04	0.1016	0.1012	-----	-------
600	593.11	49.81	52.05	26.55	96.29	96.04	0.1175	0.1171	0.3174	0.1692
1200	595.16	57.61	57.09	25.96	104.65	104.52	0.1322	0.1320	0.2760	0.1320
1800	596.25	63.42	60.90	26.38	106.41	106.63	0.1342	0.1345	0.2567	0.1371
2400	597.4	67.79	64.61	26.38	110.20	105.89	0.1402	0.1330	0.2812	0.1436
3000	597.75	72.15	68.33	26.38	107.91	111.81	0.1363	0.1429	0.2169	0.1622
3600	598.14	76.51	72.04	26.38	112.93	115.06	0.1446	0.1482	0.2086	0.1666
4200	597.75	80.88	75.76	26.38	115.36	113.48	0.1488	0.1457	0.2090	0.1771
4800	597.4	85.24	79.47	26.38	117.47	111.99	0.1524	0.1432	0.2361	0.1526
5400	596.25	88.74	82.50	28.04	118.52	107.07	0.1516	0.1325	0.2359	0.1099
6000	595.16	90.93	84.61	28.45	118.21	101.94	0.1508	0.1234	0.3193	0.0689
6600	593.11	92.57	85.87	27.78	118.77	100.14	0.1534	0.1219	0.4277	0.0774
7200	591.33	93.78	87.24	28.96	111.42	100.11	0.1394	0.1203	0.3886	0.2100

Where; Ii= Isolation radiation, T1= pyra-box water temperature, T3= CSC water temperature Ta=ambient temperature, Tpb=CSC plate temperature, Tpp=Pyra-box plate temperature, F1b= first figure of merit of CSC, F1p=firest figure of merit for pyra-box cooker, F2p=Second figure of merit for pyra-box cooker, F2b= Second figure of merit of CSC

In all conditions the cooking power of the pyra-box cooker is higher than that of the conventional solar cooker. According the Basis for the Bureau of Indian Standards Testing Method, the average second figure of merit was 0.28 and 0.14 for pyra box cooker and CSC respectively. The cookers thermal efficiencies at a box cooker range from 8 % to an increasing sharp peak of 21.2% at the maximum solar intensity of the day around 11-12 am with an average overall efficiency around 14.6%. Whereas, pyra-box cooker gave higher water and pot temperatures and thermal efficiency ranged from 12% to 41.2% with an average overall efficiency around 27.6 %.

4. CONCLUSION

The pyra-box solar cooker was found to provide adequate temperatures needed for cooking different kinds of foods and reaches a maximum temperature of 104.8 ^oC for the fluid of oil. Pyra-box cooker has many advantages regarding low price, lightweight and high efficiency with relative to conventional solar box cooker. And the average second figure of merit was 0.28 and 0.14 for pyra box cooker and CSC respectively. Consequently, as it performed well during thermal performance testing, the pyra-box solar cooker should be recommended to use as a domestic cooker.

REFERENCE

AWASH T., "Experimental Investigation On Performance Characteristics And Efficiency Of Electric Injera Baking Pans ("Mitad")" Symposium on Adaption to Climate Change for Water, Energy and Enviroment, Hawassa Univeisty, June 27-28 2013, Vo.1, PP: 311-321

Devadas, R.P., An Option for Cooking – Solar Energy, Proceedings of the Third International Conference on Solar Cookers – Use and Technology, Avinashilingam University, Coimbatore, 1997, P. 15.

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

Mahesh A., Solar Heating and its Applications in India, Renewable Energy Science Series VII Application of Solar Thermal Technologies – Policies and Experience, December 2000, P. 23.

Mullick et al., 1987, Thermal Test Procedure for Box-Type Solar Cookers, Solar Energy Vol. 39, No. 4, pp. 353-360.

P.A. Funk, D.L. Larson, Parametric model of solar cooker performance. Solar Energy, Vol. 62, No. 1, 1998, 63-68.

Singhal, A.K., National Programme on Solar Cooker in India, Proceedings of the Third International Conference on Solar Cooker – Use and Technology, 1997, P. 18

Uhuegbu, Chidi. C, "Design and Construction of a Wooden Solar Box cooker with Performance and Efficiency Test" J. Basic. Appl. Sci. Res., 2011, 1(7)672-678