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Analysis, design and performance evaluation of a light weight, energy efficient solar cooker

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Abstract

A solar cooker is a device which uses the energy of sunlight to heat food to cook it. Solar cooking is a form of outdoor cooking and is often used in situations where minimal fuel consumption and health is important. In the present work, analysis and design of conventional solar cooker is changed to achieve light weight and more efficient box-type solar cooker that can be used to cook food for four persons. An attempt has been made to optimize the various major parameters such as geometries of box-cooker, heat storage, insulation and mirror boosters so as to make it light weight, energy efficient solar cooker. The designed solar cooker is developed with a casing material made up of highly lightweight Aluminium Composite Panel (ACP), an absorber plate painted with ceramic paint underneath, insulation of glass wool with glaze and reflector. The analysis is done from the sensible heating and cooling curves. The values of the overall heat loss factor (FÚL) are obtained from the sensible heat loss. The general energy balance of the cooker is derived and is used to predict the temperature variation of each part of the cooker under both steady and transient conditions. The performance has been evaluated by the figure of merit F_1 and F_2. The experimental results and theoretical results projects this cooker to be a light weight, energy efficient cooker. These qualities are likely to make this solar cooker to be a socially acceptable solar cooker.

Keywords: Solar Cooker; Energy Efficient; Figure of merit

1. Introduction

Since last many decades, Natural gas has been a really cheap and easily available fuel for cooking and water heating. But due to depletion of natural fossil reserves, the need for alternative fuel has arisen which can replace natural gas in due course of time. Electricity is costly and is unavailable in some rural areas. For families seeking economic solutions for cooking, use of solar cooker is an easy way. Therefore, there is a need for development of feasible solution. Solar water heating solutions are an affordable solution to this problem. But there is a need to develop this way of cooking food for use in community and household applications [4]. Many solar cooker solutions are available in the market, but they are not socially acceptable due to its cost, unaesthetic design and adaptability issues.

2. Design Methodology

Design of solar cooker process requires the estimation of cooking energy requirements, available radiation, and selection of material and loss coefficient of the cooker.

2.1 Estimation of cooking needs: Initially the energy requirement for a family of four persons is calculated by Assuming the total energy required as 1.5 times the sensible heating of food up to 100º C and specific heat of food stuff as 2.7 kJ/kg-K, and food intake of one persons to be 1 kg per day based on actual study in the hostel of SVNIT, Surat.

$$E = m_f \times C_f \times \Delta T$$

$$E = 4 \times 1.5 \times 2.7 \times (100 - 20)$$

$$E = 1295 \text{ kJ/day}$$

Energy required is 1295 KJ/day. Considering two meals per day, energy required per day will be 648 kJ/feed. The meal should be ready up to 12.45 noon, while the meals should be ready in the evening by 5:00 p.m. Assuming feeding time as 9:15 a.m. & 1:30 p.m. and cooking time as 3.5 hrs [9], the rate of use full energy gain in cooker will be:

$$(Q_u)_{\text{required}} = E_c / t_c = 648 \times 10^3 / (3.5 \times 3600) = 51.41 \text{ W.}$$

2.2 Estimation of solar insolation falling on cooker

Estimation of solar insolation has been done according to the ASHRAE model [5].

2.3 Estimation of flux absorbed by absorber plate of the solar cooker.

Based on the above estimations, radiation transmitted through glazing has been calculated by product of transmissivity and absorptivity product and overall heat loss coefficient without reflector and with reflector [3, 18].

Without reflector,

$$Q_U = [S - U_o(T_{pm} - T_a)]\ \mathrm{W/m^2}$$
$$Q_U = [496.7 - 4.0887(120 - 20)]$$
$$Q_U = 87.83\ \mathrm{W/m^2}$$

With reflector,

$$Q_U = [S - U_o(T_{pm} - T_a)]\ \mathrm{W/m^2}$$
$$Q_U = [723.25 - 4.0887(120 - 20)]$$
$$Q_U = 314.38\ \mathrm{W/m^2}$$

2.4 Estimation of cooking area

Without reflector,

$A_c = (Q_u)_{required} / Q_{useful}$

$A_c = 51.42/87.83 = 0.585\ m^2$

With reflector,

$A_c = (Q_u)_{required} / Q_{useful}$

$A_c = 51.42/314.38 = 0.1635\ m^2$

2.5 Available Cooking area from pot

$$A_c = 2 \times \frac{\pi}{4} \times d^2 + \pi \times d \times H$$

With the use of 4 pots of 160 mm diameter available cooking pot area with reflector = 0.3015 m^2

With reflector, available cooking area is more than required whereas available cooking area without reflector is less than required cooking area. So, we chose to design the cooker with reflector.

Table 1 : Weight analysis of commercial cooker

surface	materials	Area (m^2)	Weight (kg)
Outer box	GI sheet	0.59	5.727
Absorber tray	Al	0.2386	2.57
Glazing assembly	Glass	0.23	1.725
Cooking pots	Al	0.33604	1.81
Insulation	Glass wool	0.019116	0.48
Absorber coating	Black Board Paint		
Reflector	GI sheet(1 mm thick)	0.0225	2.015
		Total =	14.327

New model is designed with the reflector so that it satisfies the cooking energy requirements and based on that final specifications of the new model are decided [10].

Table 2 : Weight analysis of New designed cooker

surface	materials	Area (m2)	Weight (kg)
Outer box	ACP	0.59	4.3
Absorber tray	Al	0.2287	0.62
Glazing assembly	Glass	0.219	1.64
Cooking pots	Al	0.33604	1.81
Insulation	Glass wool		0.93
Absorber coating	Matt black paint		
Reflector	ACP (2 mm thick)	0.0225	1.183
		Total =	10.483

Table 1 & 2 gives weight analysis of commercial cooker and present cooker.

Figure 1 gives the photographic view of new model of the cooker designed in prsent work.

Fig. 1 New developed solar cooker.

3. Fabrication of a solar cooker

After the optimal combination of materials to be used for solar cooker is achieved, complete fabrication of the box type solar cooker has been carried out and is described in the subsequent text in stepwise manner.

Step 1: Absorber tray

1. For the absorber plate the Al plate of dimensions 340*340*70 i.e. of area is required. However fabrication tolerances at the time of cutting and bending of sheet, the area of sheet can be slightly higher.
2. The dimensions of base is 340*340 and top dimension of the plate is 460*460 Aluminium absorber plate is cut and bent in appropriate manner to achieve this dimensions.
3. After preparing the absorber tray is to provide black matt paint on the surface. On the bottom of the absorber plate, a ceramic paint has been applied to reduce the bottom losses.
4. Surface preparation: It is prepared by removal of the dust and impurities by mechanical and chemical cleaning. Mechanical cleaning includes polishing and buffing. Polishing is done to remove small amounts of metal by means of abrasives. It produces a surface that is free of larger imperfections left by grinding and is carried out prior to buffing. Next to mechanical cleaning is chemical cleaning of contaminants. The contaminants consist of oils and grease of various types, waxes and organic materials.

Step 2: Housing and Cover system

1. For outer body frame dimension 500*500, ACP panel is taken to make a box of desired dimension.
2. For the insulation, glass wool (k=0.0484, ρ=32kg/m^3) is used.
3. Aluminum frame is used instead of wood frame with proper dimensions.
4. After making groove space in frame, both inner and outer glass is fitted by using glue and is left for 5-6 hour for complete sticking.
5. Absorber tray is fixed above another frame fitted inside housing body.
6. Glass frame is joined with the housing body with the help of hinge.
7. At last, one handle on top wood frame and one hook in housing body is attached by screw in such a way that after opening of top frame sufficient opening remains for keeping and removal of cooking pot before and after cooking operation.

INSTRUMENTATION

To measure mean plate temperature, glass cover temperature, inside air temperature and cooking food/water temperature. Thermocouples are used.

1. **Selection of thermocouple**.

   Type J thermocouples are chosen for their high sensitivity of 40-50 mv/^{0}C.

2. **Calibration of a thermocouple**

   The relation between temperature difference and emf for iron constantan is given by the relation

   emf = $C_1(T_1-T_r) - C_2(T^2-T_r^2)$

   Where C_1 and C_2 are constants.

   T=Temperature of measuring junction

   T_r=Temperature of reference (cold) junction

   A calibration of the thermocouple is carried out with its reference junction at ice point.

3. **Fixing of thermocouples**.

   Thermocouples are fixed on inner surface of outer glass cover to measure mean temperature of outer glass cover under load and no load condition and were also fixed on top and bottom of the absorber tray, side walls of the housing and inside cooking pots. In total 32 thermocouples were placed.

4. Experimentation

Thermal performance test was taken for newly developed solar cooker by finding out figure of merit F1 for no load condition and figure of merit F2 for load conditions [2]. The first figure of merit depicts optical efficiency and is the ratio of optical efficiency to heat loss factor; it is evaluated by a stagnation test without load.

$$F_1 = \frac{\eta_o}{U_{LS}} = \frac{T_{PS} - T_a}{I_{GS}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

Where

η_o = the optical efficiency,

I_{GS} = insolation on the horizontal surface at the time the stagnation temperature is reached (in W/m^2)

U_{LS} = the heat loss factor at stagnation

T_{ps} = the stagnation plate temperature (^{0}C)

T_a = the ambient temperature (^{0}C)

To evaluate the second figure of merit, F2, the solar cooker without the reflector but with a full load of water and utensils is kept in the sun. Initial water is kept at an average temperature between ambient and the boiling point. Temperature and solar radiations are measured until the temperature reaches 95^0 C [16].

The second figure of merit, F2, is calculated using the equation [1,2]

$$F_2 = \frac{F1(MC)_W}{A(t_2-t_1)} X \ln \left\{ \frac{1-\left(\frac{1}{F1}\right)\left[\frac{T_{W2}-T_a}{I_G}\right]}{1-\left(\frac{1}{F1}\right)\left[\frac{T_{W1}-T_a}{I_G}\right]} \right\} \ldots\ldots\ldots\ldots \quad (2)$$

Where

F_1 = the first figure of merit from the stagnation test;

$(MC)_w$ = the product of mass of water and specific heat (J/^{0}C)

A = the aperture area of the cooker of the cover plate (m^2);

$t_2 - t_1$ = the time taken for heating from Tw1 to Tw2 (sec).

T_a = the average ambient temperature during the time period $t_2 - t_1$ (^{0}C)

I_G = the radiation during the time period $t_2 - t_1$(W/m^2)

It is assumed that the global radiation, IG, remains constant during the test. This assumption introduces some error into the data.

5. Results and discussions

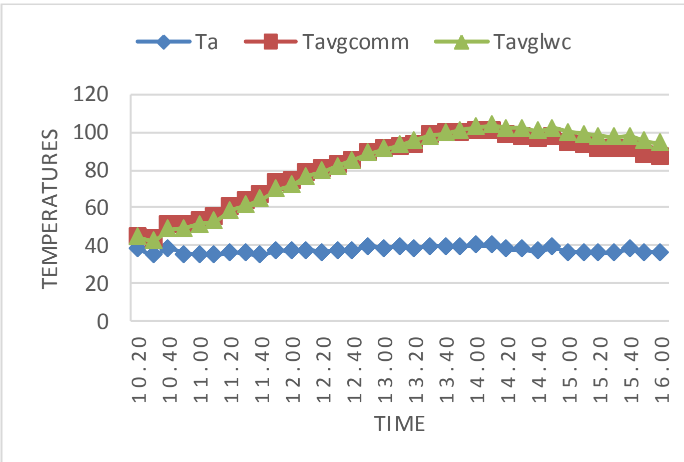

Fig. 2 Comparison of light weight cooker with commercial cooker. The experiments were conducted at Surat (21.15 N, 72.85 E)

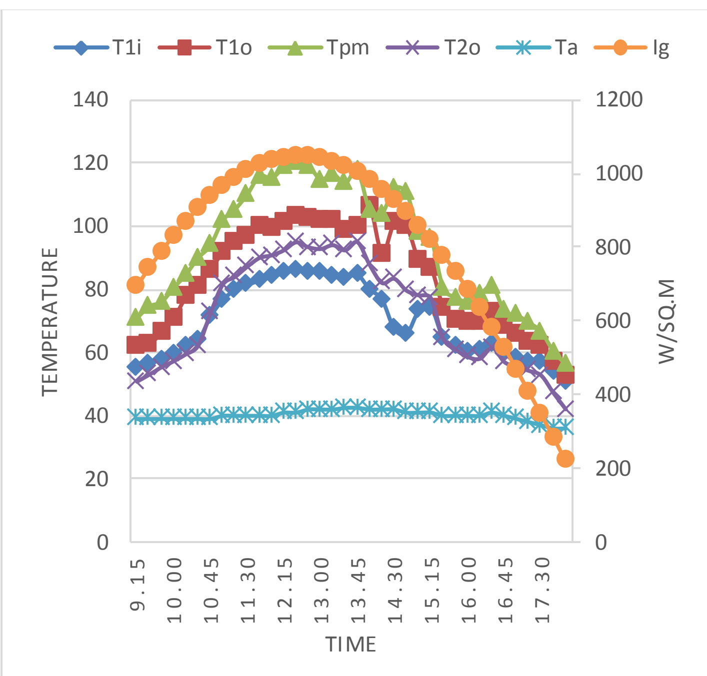

Fig. 3 Temperature profile of various components at no load test.

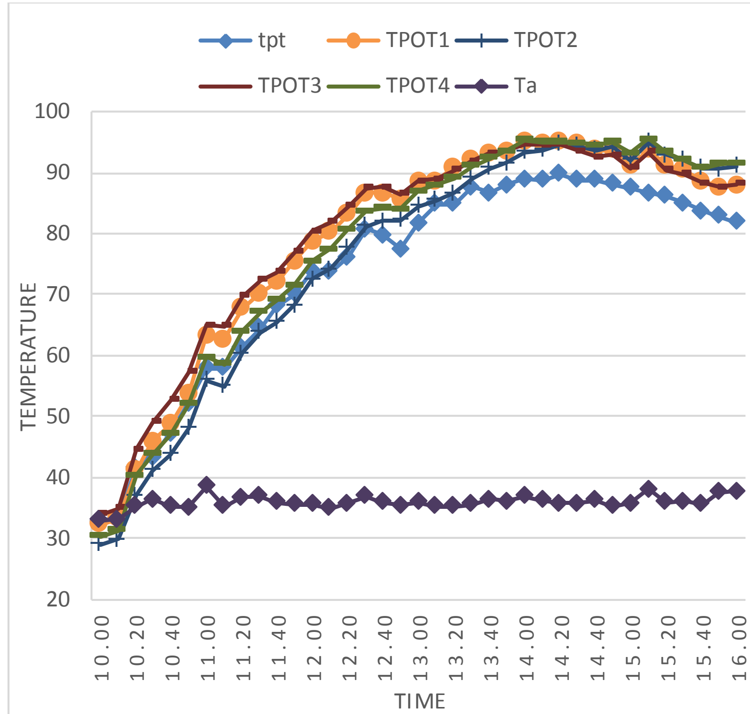

Fig. 4 Temperature profile of pots kept in the solar cooker.(load test with water)

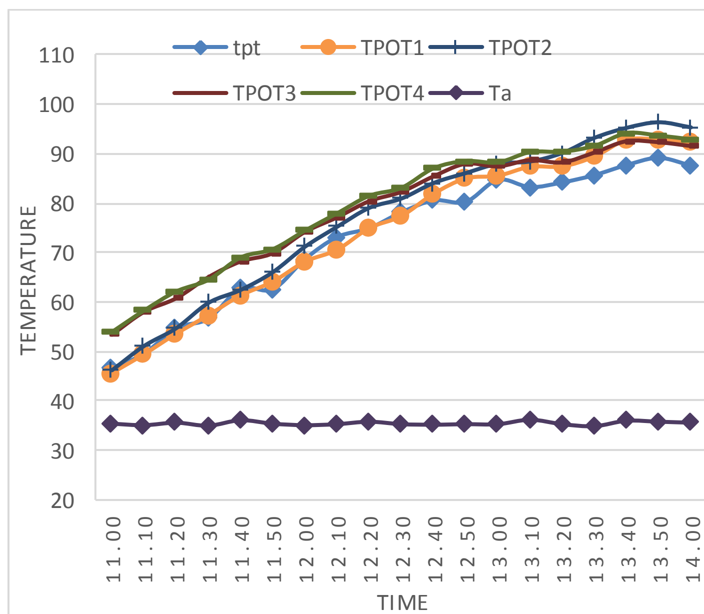

Fig. 5 Temperature profile of pots filled with daal and rice (cooking test)

Figure 3, 4 and 5 shows the temperature profile of various components at no load test, load test with water and cooking test with daal and rice.

Following results were obtained under load and no load conditions

1. The temperature profile is nearly parabolic in all the cases which is quite obvious. The maximum absorber plate temperature obtained under load condition is always less than that obtained under no load condition. This is quite obvious due to heat transfer from the absorber to water. This was also observed by Nahar et al. [15].
2. The results of stagnation temperature shows that the maximum temperature in cooker is always achieved in the vicinity of solar noon. This is also quite obvious because the radiation intensity achieves its maximum value during solar noon. The similar results were obtained by Nahar[13].
3. The mean temperature of air mass, cover plate, absorber plate is found to be less by 25^0C to 27^0C under load condition as compared to that obtained under no load condition, this may be attributed to energy transfer from cooker to load. The similar results were obtained by Reddy and Rao[17].
4. Further the temperature of inner glass is observed to be higher of the order of 30^0C to 40^0C under all experimental sets as compared to outer glass cover. This means there is effective reduction in convection losses due to use of double glass cover system which helps in improving the efficiency of cooker. The similar results were obtained by Kimambo [6].
5. Figure 2 shows the comparison of commercial cooker with newly designed light weight cooker where in the plate temperature of light weight cooker is found to be more than the commercial cooker. Figure of merit F1 of commercial cooker is 0.12 and F_2 is 0.30 while Figure of merit F_1 of light weight cooker is 0.11 and F_2 is 0.34.The useful efficiency of this cooker achieved during cooking test is 19.66%

6. Conclusions

a) The figure of merit F_1 = 0.11 and Figure of merit F_2=0.34 has been obtained during stagnation and load test operation for the cooker. The results shows that the new model of solar cooker meets the requirements of BIS for solar cooker.
b) The actual efficiency of the present cooker during real life cooking test is found to be 19.66%
c) The plate temperature obtained by the newly designed light weight cooker is more than the commercial cooker available in the market and thus establishes its superiority.
d) The weight of the present cooker is 26.83 % less than the commercial cooker and thus establishes this cooker to be a light weight energy efficient solar cooker.

Thus, in nutshell, the experimental results and theoretical results projects this cooker to be a light weight, energy efficient cooker. These qualities are likely to make this solar cooker to be a socially acceptable solar cooker.

Nomenclature

A the aperture area of the cooker of the cover plate, m^2
A_C cooking area, m^2
C_p specific heat of cooking utensils, $Jkg^{-1}K^{-1}$
C_w specific heat of water, J $kg^{-1}K^{-1}$
C_f specific heat of food, J $kg^{-1}K^{-1}$
t_{w1} initial temperature of water in utensils, ^{0}C
t_{w2} final temperature of water in utensils, ^{0}C
η efficiency of solar cooker
η_o the optical efficiency
I_{GS} Insolation on the horizontal surface at the time the stagnation temperature is reached (in W/m^2)
S solar radiation available at absorber tray
U_{LS} the heat loss coefficient at stagnation
T_{ps} the stagnation plate temperature, ^{0}C
T_{pm} plate mean temperature, ^{0}C
T_a the ambient temperature, ^{0}C
$T_{avgcomm}$ average temperature of water in commercial cooker, ^{0}C
T_{avglwc} average temperature of water in lightweight cooker, ^{0}C
T_{pt} plate temperature, ^{0}C
$(T_{pot})_{1,2,3,4}$ temperature of pot 1,2,3,4 , ^{0}C
T_{1o} outer temperature of inner glass, ^{0}C
T_{2o} outer temperature of outer glass, ^{0}C
T_{1i} inner temperature of inner glass, ^{0}C
F_1 the first figure of merit from the stagnation test
F_2 the second figure of merit from the load test
$(MC)_w$ the product of mass of water and specific heat, J/^{0}C
E energy Required, J
Q_u power required/ Required rate of energy gain. W
U_o overall heat transfer coefficient, W m^{-2} K^{-1}
T temperature of measuring junction
T_r temperature of reference (cold) junction

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Commonwealth Energy and Sustainable Development Network (CESD-Net)

CESD-Net is a major global initiative in energy and sustainable development. The objective of network is to promote energy and sustainable development in commonwealth countries.
Focussing on Multidisciplinary Research, Promoting Future Low Carbon Innovations, Transferring Knowledge and Stimulating Networking among Stakeholders to Ensure the UK Achieves World Leading Status in Energy and Sustainable Development. https://www.weentech.co.uk/cesd-net/

The 1st International Conference on Energy, Environment and Economics (ICEEE 2016) was held at Heriot-Watt University, Edinburgh, EH14 4AS, UK, 16-18 August 2016. ICEEE2016 focused on energy, environment and economics of energy systems and their applications. More than fifty eight delegates from 31 countries with diverse expertise ranging from energy economics, solar thermal, water engineering, automotive, energy, economics and policy, sustainable development, bio fuels, Nano technologies, climate change, life cycle analysis etc. made conference true to its name and completely international. During conference total 51 oral presentations and six posters were shared between delegates. The presentations showed the depth and breadth of research across different research areas ranging from diverse background. ICEEE2016 aimed:

- To identify and share experiences, challenges and technical expertise on how to tackle growing energy use and greenhouse gas emissions and how to promote sustainability and economical, cost effective energy efficiency measures.

In total 11 technical sessions and two invited talks both from academia and industry provided insight into the recent development on the proposed theme of the conference. Preparation, organisation and delivery of the conference started from July 2015 and further co-ordinated by vibrant team of Conference Centre, Heriot Watt University. Conference organisers would like to acknowledge support from the sponsors particularly World Scientific Publication ltd and its team members for the delivery of the conference. Organisers are also thankful to all reviewers who contributed during peer review process and their contributions are well appreciated. At the end and during vote of thanks following awards have been announced and we would like to congratulate all well deserving delegates.

- Best Paper –Academia: Amela Ajanovic, EEG, TU Vienna, Austria
- Best Paper – Student : Christian Jenne,University of Duisburg-Essen, Germany
- Best Poster – Student: Yoann Guinard, University of New South Wales, Sydney, Australia
- Best Poster – Academia: E. Salleh, Universiti Kebangsaan Malaysia, Malaysia
- Active Participation Award - Yoann Guinard, University of New South Wales, Sydney, Australia

At the end we would like to extend our gratitude to all of you for your participation and hopefully welcome you again during ICEEE2017.

Editors:
Dr. Singh is Senior Scientist at Indian Agricultural Research Institute, New Delhi, India. Her area of expertise are bio energy and bio fuels, environmental engineering, carbon accounting and renewable energy integration for rural development.
Dr. Kumar is visiting faculty at Prince of Songkla University, Thailand. He have 16 years of research and teaching experience in the field of solar energy, drying and energy efficiency.

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