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Increasing the Thermal Efficiency of A Solar Cooker Via Blackening The Entire Inner Surface

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ABSTRACT
This study reports the thermal efficiency evaluation of a modified solar box cooker at a project site in Dutsin-ma, Katsina State, Nigeria. The hourly variation of five different temperature measurements as well as standard water heating tests and controlled food cooking tests carried out during the period of 15th-17th April 2018 are also presented. The result of this investigation showed that the efficiency of the device was calculated to be 42.13. This value of thermal efficiency is lower than that of the previously reported work by Bello in Ilorin. However, if the same initial temperature condition of about 65 and 62 were considered, an efficiency of 53.22 would have been obtained which is higher than that of the previously reported work. This high value is predicted to be due to the black paint applied to the entire inner surface of the solar box cooker. It is therefore recommended that this device should be used as a cooking device and alternative to firewood.
Keywords: thermal efficiency, solar box cooker, cooking test, heating tests.

INTRODUCTION

Nowadays' fuel price skyrockets very rapidly so need to search for an alternative cheaper source of energy is a necessity. Therefore, solar energy is becoming a feasible option for us. Solar cookers are rather important applications in thermal solar energy conversion. The use of solar cookers for cooking purposes is spreading widely in most developing countries and particularly in villages and remote areas (Adam, 2018). An advantage of solar cookers especially the box-type cookers is that they do not overcook or burn the food items, and can serve as an oven when closed after the food item is cooked (Adam, 2018)

With current energy problems Nigeria is facing which encompasses gradual decrease in the availability of wood fuel in the rural areas and the problems attributed to the use of it for cooking purposes, irregular availability of fossil fuels (like kerosene, methane gas etc) and lack of steady supply of electricity to use electric stoves for cooking; the obvious alternative is to use solar energy to heat and cook our food in order to meet the need of cooking food for nourishment which is indeed a fundamental need (Nyitar, 2014) This is the best option for Nigerians since Nigeria is blessed with abundant amount of sunshine and that since solar cookers are powered by energy from the sun and which is obtainable virtually always and free of charge, they can be used therefore as alternative cooking devices.(Agbo et al, 2010)

It is a clear fact from various literatures that solar cookers are very promising devices in the upcoming future. However, there are some handicaps concerning the solar cooking technology. Perhaps the most challenging point of solar cookers is that they are slow to heat up. Therefore to improve the sustainability and thermal efficiency of the renewable energy sources, it is important to incorporate some concepts. The aim of this work is to construct a solar box cooker similar to the one constructed by Bello et al, (2010) in ilorin kwara state, Nigeria and then modify it by blackening the entire inner surface of the cooker so as to increase its thermal efficiency.

The project site of this study is Dutsi-ma, a central city of Katsina State which is located in the North western part of Nigeria. The coordinates of Dutsin-ma are: Latitude 12º 27'10''N and Longitude 8º 32'E and altitude 107.4m above sea level (Shamsuddeen 2017).

The city is found in the Sudan Savannah region of the central part of Katsina state which is located in the north western part of Nigeria (NIMET, 2013). Maximum day temperature reaches about 38ºC in the month of March, April and May, and maximum temperature is about 22ºC in December and January (Isa Kaita College of Education, weather station). The area receives 900-1000mm of rain annually (Shamsuddeen 2012). The dry season starts in late October and usually ends by March, while the rainy season lasts from April to early October (Shamsuddeen 2012).

MATERIALS AND METHODS

The materials used for the conduct of this research work are mahogany planks, saw dust, black paint, transparent glass, Plane mirrors, aluminium sheets, crown white wool, glasswool, hinges/rollers, tempered glass, thermocouple, Campbell stokes recorder, PCMs, flat plate, linear focus, central focus collectors, valtzsun photometer pyre geometer, pyradiometer, shading-ring, pyranometer, moving shadow-bar phyrheliometer, black paint, nails, hinges, screws, shelf pins, perforated iron bar, glue, mercury-in-glass thermometer, stopwatch screws and Inclinometer.

Construction Procedure

As earlier mentioned, this work is a modification of the solar box cooker constructed by Bello et al (2010) and other researchers. In the original design only the absorber plate below the box was painted black, the inner walls of the box were left reflecting. However, in this work, the researchers painted the entire inner surface of the box black. A trapezoidal shaped inner box of dimension of 30cm x 30cm x 20cm bounded by an outer box measuring 80cm x 60cm x 30cm was constructed for the study. The two boxes are made from mahogany planks. Aluminium sheet of thickness 0.5mm is glued to the inner box, the aluminium sheet is painted black so that it may significantly retain the heat needed for cooking in the sunny periods, and a heat storage tank for storing phase change chemical material is attached to the inner box in order to store heat from the collectors for cooking at night. Finned absorber plate are used for heat transfer to the food in the cooking vessel, For the insulation of the cooker, saw dust used to fill in the space between the inner and the outer boxes, so also, glass wool and crown white wool are used for insulating the side walls of the cooker and reducing heat losses from the absorbing plate to the environment respectively. For the glazing, two transparent glass panes of thickness of 4.0mm each are fitted on top of the cooker with a space of 10mm between them so that greenhouse effect which is the basis of operation of the solar device is created. A big plane mirror of thickness 4.0mm with measurement of 60cm x 60cm is used as a reflector. The reflector consists of a wooden frame which was sized to form a cover for the box when not in use. The box was inclined at a suitable angle of inclination to ensure that maximum irradiation falls on it.

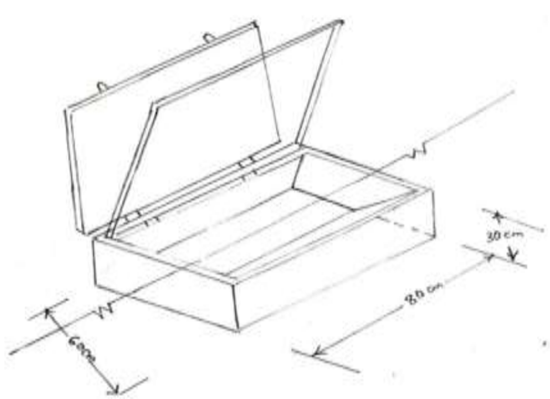


Fig 1a: Isometric view of the solar box cooker

Fig.1b: Outer and inner view of the solar box cooker

Principle of operation of Solar Cooker

The operation of a solar cooker is based on the phenomenon/principle of the greenhouse effect. According to this principle, when an energetic short wave solar radiation falls on a glass cover, the glass surface gets heated up. The incident solar radiation I, will then be partly reflected, party absorbed and party transmitted by the glass cover to an absorber plate called a solar collector placed below the transparent cover in accordance with the relation (Idris, 2013):

$$I = r_\lambda + a_\lambda + t_{\,1} I = r_\lambda + a_\lambda + t_{\,1} \qquad (1)$$

Where:

r_λ = reflectivity at a particular wavelength,

a_λ = absorptivity at a particular wavelength and.

t_λ =transmissivity at a particular wavelength.

The transmitted solar radiation is re-radiated by the solar collector to the space between the glass cover and the solar collector (absorber plate) as long wavelength infra-red solar radiation, which is no more able to pass through the glass cover to the atmosphere. Consequently, this trapped solar radiation between the glass cover and the absorber plate is then transferred as thermal energy to the desirable materials like cooking pot and its contents placed on the absorber plate for cooking a required food item or heating water.

Experimental Procedure

The solar cooker was positioned in an open space at Isa Kaita College of Education Dutsin-ma, Katsina State. The thermal system was placed facing southwards where there were no tree shade of any sort so as to maximize the solar radiation falling on it. The cooking device was allowed to heat for about 10 minutes before inserting the load. The device was exposed to direct sunlight to allow incident solar energy fall on it while the reflector was adjusted manually at regular intervals of 30 minutes to ensure that the reflected rays covered the entire glazing surface.

The performance tests conducted were: (i) water heating tests which involves temperature tests that involve temperature measurements connected with photo-thermal system for the period it takes to heat the water as well as (ii) controlled cooking tests.

During the experimentation on the cooking and water heating tests, the following temperature readings were observed and recorded:

ambient temperature, Ta

insulator temperature,Ti

working fluid (water) temperature,Tw

absorber plate temperature,Tp and

cooking chamber temperature,Tc.

For the water heating tests, a black painted aluminium pot of mass 0.2kg containing 500cm3(0.5kg) of water was placed on the absorber plate of the solar box cooker and placed out door for observations. Similarly, for the controlled cooking tests, the food to be cooked plus 750cm3 of water contained inside the black painted pot were placed in the box and the unit was placed outside for necessary measurements to be observed and recorded. The various temperature and time measurements were measured on hourly basis from 11:00 hours to 17:00 hours using mercury-in-glass thermometers and a stop watch throughout the period of the study.

Solar Cooker Performance Criteria

In this work, the average global solar radiation value for the months of April, 2018 of 45Wm^{-2} (NIMET, 2013) has been used for the estimation of the thermal efficiency of the solar box cooker. The monthly average extraterrestrial radiation in Jth day of the year was computed using the relation (Bello et al, 2010):

$$\overline{H_O} = \frac{24}{\pi} I_{SC}\left[1 + 0.0334cos\frac{2\pi l}{365} - 3\right] Z\frac{24}{\pi} I_{SC}\left[1 + 0.0334cos\frac{2\pi l}{365} - 3\right] Z \qquad (2)$$

Z= $(Cos\phi Cos\delta Sin\omega_s\delta - \omega_s Sin\phi Sin\delta)$

$$\delta = 23.45Sin360\left[\left(\frac{284+j}{365}\right)\right]\left[\left(\frac{284+j}{365}\right)\right] \qquad (3)$$

Where:

1_{sc}= solar constant taken as $\pm$ 13531.5%Wm^{-2}

J = the Julian day with J = 1st January and 365 on 31st December.

ϕ= latitude of the site of investigation which is Dutsin-ma.

δ= the declination angle of the sun. Usually 15th day of each month is the day on which the solar declination angle, is calculated by Agbo et-al (Agbo et al, 2010) and

ω_s= the sunset hour angle which is given by Olajuyi (Olajuyi, 2003):

$$\omega_s = Cos^{-1}(-tan\phi\ tan\delta) \qquad (4)$$

The monthly average of the maximum sunshine hours per day at the location is given by (Olajuyi, 2003):

$S_{max}=\frac{2\ 2}{1515}Cos^{-1}(-tan\ \phi tan\ \delta)$ (5)

The monthly average clearness index $\overline{K_T}\overline{K_T}$ is given by (Abdullahi et al, 2013):

$\overline{K_T}=\frac{H\ H}{H_0 H_0}$ (6)

Where $\overline{H}$is the monthly average global solar radiation on a horizontal surface.

Cooking power of the solar box cooker

The cooking power can be defined as the rate of useful energy available during the heating period and for a standard cooking test, this can be estimated by:

$p_{sbc}=m.c_p\frac{T_{wf}-T_{Wi}}{600}p_{sbc}=m.c_p\frac{T_{wf}-T_{Wi}}{600}$ (Danmallam, 2011) (7)

Where:
F = final
i=initial
w=water
Equation is divided by 600 to account for the number of seconds in each 10 minutes interval as per recommended by Bashir et al, (1999)

RESULTS

The results of the hourly variations of temperature measurements observed in the period of 15th, 16th, and 17th of April 2018 using the modified solar box cooker are presented in tables 2.1 to 2.3:
Table 2.1: Results of temperature measurements observed with time using the modified solar box cooker 15th April, 2018.

Table 2.1: Results of temperature measurements observed with time using the modified solar box cooker 15th April, 2018.

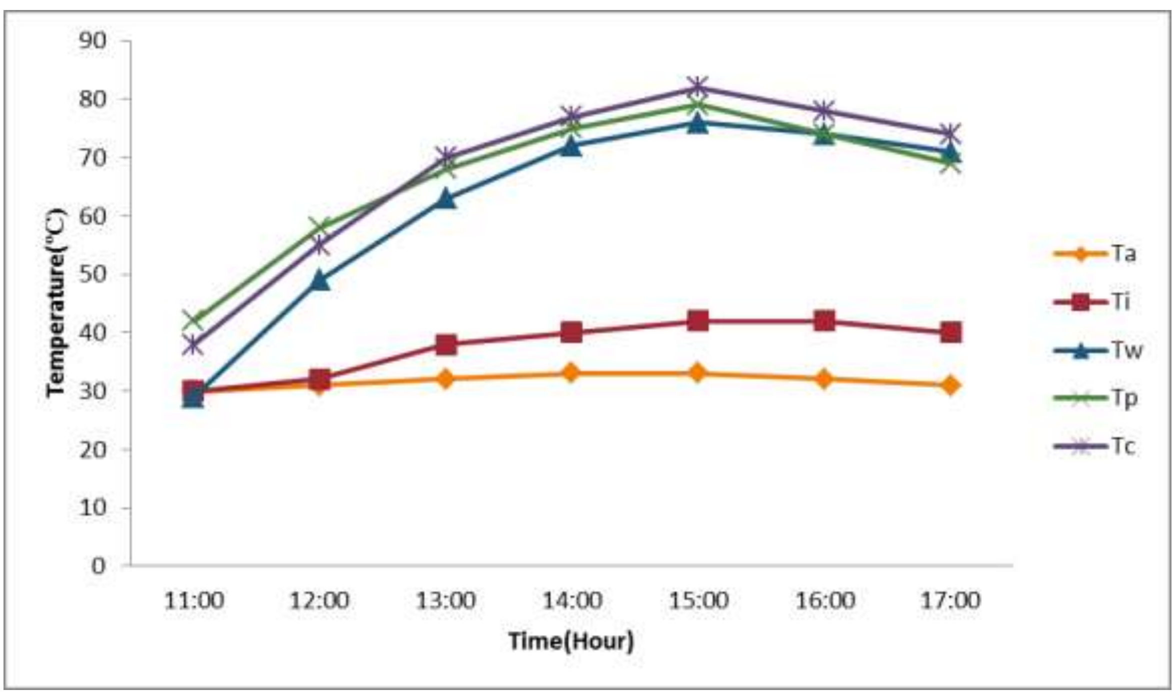
Time(Hour)	T_a(ºC)	T_i(ºC)	T_W(ºC)	T_p(ºC)	T_c(ºC)
11:00	30.0	30.0	29.0	42.0	38.0
12:00	31.0	32.0	49.0	58.0	55.0
13:00	32.0	38.0	63.0	68.0	70.0
14:00	33.0	40.0	72.0	75.0	77.0
15:00	33.0	42.0	76.5	79.0	82.0
16:00	32.0	42.0	74.0	74.0	78.0
17:00	31.0	40.0	71.0	69.0	74.0

Table 2.2: Results of temperature measurements observed with time using the modified solar box cooker 16th April, 2018.

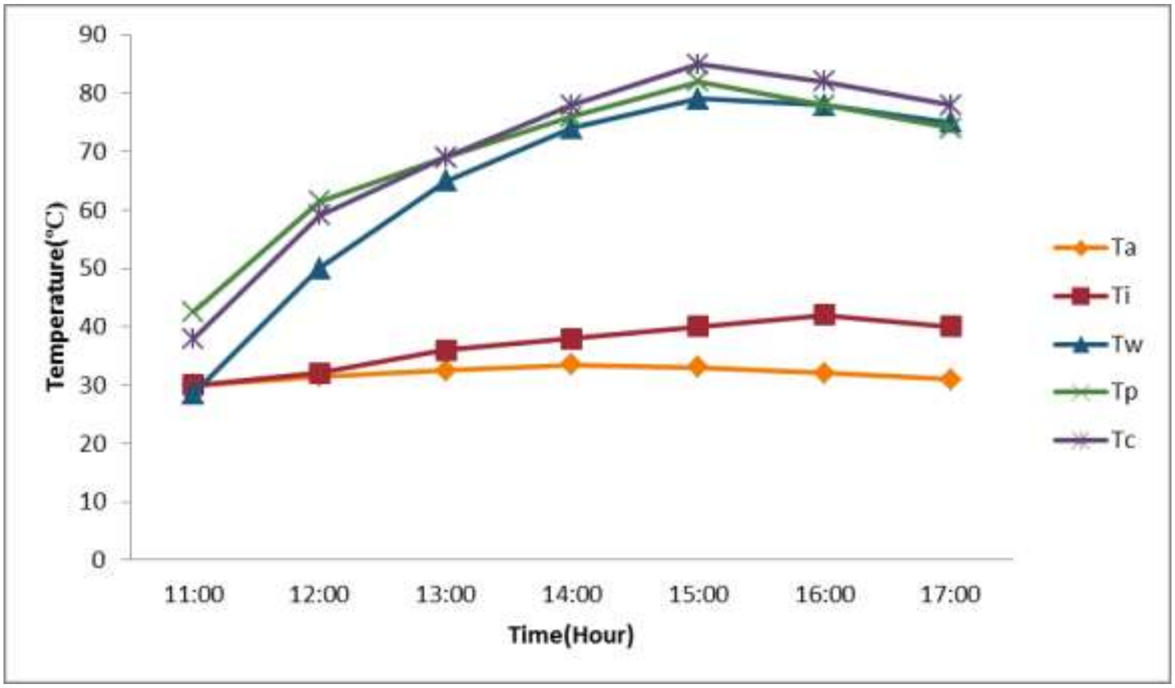
Time(Hour)	T_a (℃)	T_i (℃)	T_W(℃)	T_p(℃)	T_c(℃)
11:00	30.0	30.0	28.0	42.5	38.0
12:00	31.5	32.0	50.0	61.0	59.0
13:00	32.0	36.0	65.0	69.0	69.0
14:00	33.0	38.0	74.0	76.0	78.0
15:00	33.0	40.0	79.5	82.0	85.0
16:00	32.0	42.0	78.0	78.0	82.0
17:00	31.0	40.0	75.0	74.0	78.0

Table 2.3: Results of temperature measurements observed with time using the modified solar box cooker 17th April, 2018.

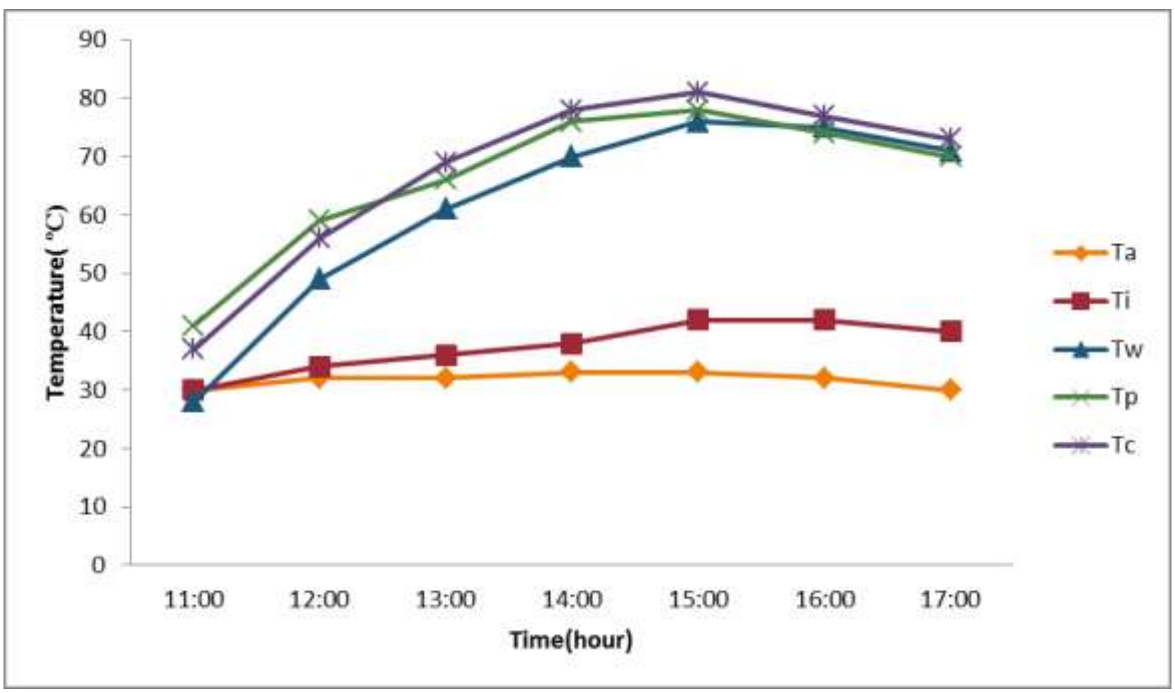
Time(Hour)	T_a (℃)	T_i (℃)	T_W(℃)	T_p(℃)	T_c(℃)
11:00	31.0	30.0	28.0	41.0	37.0
12:00	32.0	34.0	49.0	59.0	56.5
13:00	32.0	36.0	61.0	66.0	69.0
14:00	33.0	38.0	73.0	76.0	84.0
15:00	33.0	42.0	76.5	78.0	81.0
16:00	32.0	42.0	75.0	74.0	77.0
17:00	30.0	40.0	73.0	70.0	73.0



3.1: Graph of Temperature versus Time using the modified solar box cooker on 15th April 2018



3.2: Graph of Temperature versus Time using the modified solar box cooker on 16[th] April 2018



3.3: Graph of Temperature versus Time using the modified solar box cooker on 17[th] April 2018.

DISCUSSION

Figure 3.1 indicated that a maximum temperature of the working fluid of about 82 ºC was attained around 14:00 hours (2pm). According to figures 3.2, and 3.3, peak temperature of the working fluid of about 86 ºC, 79 ºC were observed respectively around 15:00 hours (3pm). The results show that a maximum temperature of the fluid of about 86 ºC was attained by the solar cooker in the period of the experiment.

In general, it can be observed that, at the early hours of the day, the temperatures increased rapidly. For the second hour, the rate slows down, peak temperatures were mostly attained around 14:00 hours (2pm) in the month. The temperature of the cooker begins to drop gradually after the peak temperature. Also, it is evident that, the differences between the absorber plate temperature, T_p and cooking chamber temperature, T_c is not quite significant. This is possible a reflection of the good emittance and selective surface properties of the absorber plate.

Efficiency of the Solar Cooker

The efficiency of the cooker is calculated using equation

$$\eta_c = \frac{(m_p c_p + m_w c_w)(\overline{T_w} - \overline{T_a})}{A_C H_T t} \quad (8)$$

Where:

Mass of port, m_p =0.27kg

Mass of water in the pot, m_w=0.5kg

Specific heat capacity of pot, C_p=920Jkg^{-}K^{-1}

Specific heat capacity of water, C_w = 4200Jkg^{-1}K^{-1}

Average water temperature, $\overline{T_w}$ =70.25^{o}C

Average ambient temperature, $\overline{T_a}$ = 34.68^{o}C

Aperture area of solar collector, A_c =0.12m^2

Average global solar radiation, H_T =459Wm^{-2}

Daily time period of investigation, t=3600s

$$\therefore \eta_c = \frac{(0.27X920+0.5X4200)(70.25-34.68)}{0.12X459X3600} = 42.13\%$$

Considering that same initial temperature conditions of the working fluid of about 65°C (in March) and 62°C (in April) were used as in the previously reported, the thermal efficiency would have been:

Mass of pot, m_p = 0.27kg

Mass of water in the pot, $m_w = 0.5$kg

Specific heat capacity of pot, C_p = 920Jkg^{-1}K^{-1}

Average water temperature, $\overline{T_w}$ = 79.41°C

Average ambient temperature, $\overline{T_a}$ =35.32°C

Aperture area of solar collector, Ac = 0.12m^2

Average global solar radiation, H_T = 459Wm^{-2}

Daily time period of investigation, t =3600s

$$\eta_c = \frac{(0.27 \text{ X } 920+0.5X4200)(79.41-35.32)}{0.12X459X3600} = 52.22\%$$

CONCLUSION

The following conclusions have been made from this study:

The thermal efficiency of the solar cooker was found to be 42.13% which is lower than the value of 47.56% obtained by Bello et al (2010) for a similar cooker in the Guinea Savanna Region of Nigeria. However if the same initial temperature condition of the working fluid of 65°C in (April15) and 62°C in (April 17)were used as in the previously reported work, a thermal efficiency of 52.22% would have been obtained. This therefore implies that painting the entire inner surface of the solar box cooker black will give a better performance than painting only the absorber plate below box black.

Since this device can obtain the aforementioned value efficiency; it can be concluded that the device could be used as an alternative to firewood for reduction of indiscriminate cutting down of trees which is the main objective of the research.

RECOMMENDATIONS

Based on the results of this study, the following recommendations are made:

- For the better performance of the device, one or more reflectors should be included as part of the cover to increase amount of insulation on the solar collector.
- Light materials like plywood should be used to construct the box so as to reduce the weight of the box.
- Any future of work of this nature should involve the test of effectiveness of the use of different insulating materials like crumpled newspaper, rice husk or hull, etc to serve as insulators.
- More accurate temperature measuring instrument like thermocouple and platinum-resistance thermometers should be used for conducting the various temperature measurements in future.
- Finally, it is recommended that this device should be introduced in to rural areas and urban poor dwellings so as to reduce the felling of trees as sources of fuel woods for domestic cooking and heating of water. This will undoubtedly check the effects of deforestation on our environment.

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