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# Theoretical and Experimental Comparison of Box Solar Cookers with and without Internal Reflector

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**Abstract**

Box solar cookers are commonly built with internal sheet metal painted black as an absorber. In order to increase the performance, a design which incorporates internal reflection is proposed in this paper. The aim of this paper is to report comparisons made between box solar cookers with and without internal reflector. Theoretical modelling of the two types of cookers has been made by considering the radiation, convection and conduction heat transfer employing the thermal network method. The theoretical analysis made was based on steady state heat transfer analysis of the cookers. Experimental comparisons were also made on two cookers having the same aperture area and made from the same type of materials except the internal absorber. The tests were made as per the American Society of Agricultural Engineers (ASAE) procedure.

The result of the theoretical analysis predicts that the performance will be higher in the cooker with internal reflector than the same cooker without reflector. The steady state analysis shows that for the cooker with reflection the temperature of the bottom absorber plate is higher than the cooker without reflector. Similarly, results of dry test and water boiling test show better performance by the cooker with reflector. The standard stagnation temperature and the cooking power were higher in the cooker with reflector as compared to the cooker without reflector. In conclusion, the performance of box solar cookers can be enhanced by making appropriate angle side walls of the absorber and providing internal reflection.



Keywords: Box solar cooker, thermal network method, steady state analysis, dry test, water boiling test

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## 1. Introduction

Solar cooking is one of the cheapest alternatives in countries where there is plenty of sunshine. There are various kinds of solar cooker technologies. One of the simplest technologies is the box solar cooker. Box solar cookers can be used to cook variety of food items. However, box solar cookers have their own limitation. It is not possible to cook food items which need high temperature. Hence, the cookers cannot completely replace other energy sources. It can reduce the dependence on unsustainable use of biomass or any other non-renewable sources. The other limitation is that box solar cookers need sometime which may range 2-3 hours to cook food. Compared to electric or biomass stoves, the cooking time is long. This limitation is probably the most influencing factor for users to accept solar cooking.

Improvements in the performance of box solar cookers will have positive influence in reducing cooking time and hence increase the acceptance by users. In order to make improvements on performance, it is essential to look at theoretical models. Such models can be used to study the effect of changing some parameters on the performance and optimize the geometry, size and materials to be employed. Once such models are developed experimental tests are necessary to validate the models. The modeling discussed in this paper is to look at inner reflectors in enhancing performance.

Reflectors on the sides and in the rear of the box are used to increase solar radiation entering into the cooker. Such reflectors which are commonly made on the outside edges of the box have the advantage of reflecting solar radiation in to the box. On the other hand, the disadvantages are that the reflector materials add weight and cost to the cooker and require more frequent tracking to avoid shading. The back reflector can be kept since it has the additional function of a cover and protection for the cooker glazing when not in use. The outer side reflectors have to be replaced to avoid the above disadvantages. The design which is discussed in this paper is to use all the sides of the box cooker as reflector and the bottom as an absorber.

**Nomenclature**

| | |
|---|---|
| $A_{ap}$ | Aperture area of the cooker [$m^2$] |
| $C_p$ | Heat capacity of water [J/kg $^oC$ ] |
| G | Global solar radiation [W/$m^2$] |
| I | Solar power through aperture of the cooker [W] |
| $P_{bab}$, $P_{sp}$ | Heat input at bottom absorber plate and side plate, respectively [W] |
| $q_{ij}$ | Heat flow between nodes i and j [W] |
| $R_{e,ij}$ | Equivalent thermal resistance between nodes i and j [$^oC$/W] |
| SST | Standard stagnation temperature [$^oC$] |
| $T_{amb,}T_{i,}T_s$ | Temperature at ambient, node i and at stagnation, respectively [$^oC$] |
| η | Efficiency of cooker |

## 2. Literature Review

The time needed for cooking food items using box solar cookers is an important factor in acceptance of the cookers by users. The time needed to cook for different food items are indicated in many reports and user manuals of cookers, for example [1]. Any improvements in the performance of the box cookers will have influence in the cooking time. Theoretical analysis coupled with experiments can provide an optimized option. By making comparison between theoretical and experimental results real situation thermal behavior can be found. For this reason mathematical structured modeling is useful for designing solar cookers.

Theoretical modeling of the box solar cookers can be done using different methods. Numerical methods such as finite difference, finite element and computational fluid dynamics (CFD) are the alternative techniques. However, the complexity and computational time are high for the methods such as CFD [2]. The analogy between the equations of heat transfer and electrical circuit can be used quite easily for the steady state modeling of the cookers. The method is based on the similarities between the diffusion equation for thermal analysis and electrical circuit analysis. The method is called thermal resistance network modeling [3, 4]. In this method voltage is analogous to temperature while current is analogous to heat flow. Hence the nodal analysis method used in solving electrical circuit problems can be implemented in a spreadsheet to solve for nodal temperatures.

Experimental procedures for performance testing are recommended in international standards. The two widely reported in literature are the American Society of Agricultural Engineers (ASAE) [5] and European Committee on Solar Cooking Research (ECSCR) [6]. The standards describe the conditions during testing, controlled variables, instrumentations and performance parameters.

## 3. Methodology

### *3.1 Description of the cookers*

The cookers are made from the same types of materials. The outer box is made of wood, the inner box is made of metal sheet and the upper cover is made of double glazing. The only difference is in the geometry of the inner metal box. For the cooker without reflector the metal box is painted black all around the inner surfaces. For the cooker with reflector the sides and front are shaped at 60 degree slope and the surfaces are covered with reflecting film. Figure 1 shows the schematic diagram of the cookers. For the cooker without reflector inner metal box is shown in solid lines and for the cooker with reflector inner metal box shown in dashed lines. The aperture area remains the same for both designs. Table 1 shows dimensions and materials used for the fabrication of the cookers.

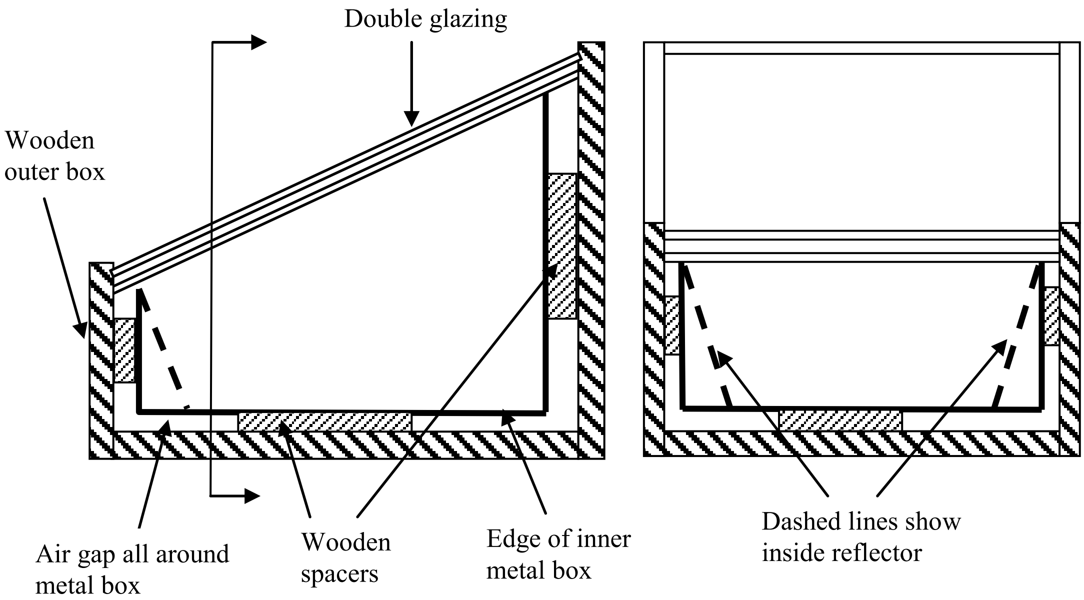


Figure 1 Schematic drawing of the cookers showing the difference between the two designs.

Table 1 Dimensions and materials of the cookers

| | | |
|---|---|---|
| Overall size | Width<br>Length<br>Height at front<br>Height at back<br>Aperture area | 0.43 m<br>0.48 m<br>0.15 m<br>0.35 m<br>0.142 $m^2$ |
| Outer box | Wood | Thickness 50 mm |
| Inner box | Steel sheet | Thickness 1.5 mm |
| Glazing | Glass<br>Spacing between upper and lower glazing | Thickness 4 mm<br>10 mm |

### *3.2 Theoretical modeling*

In order to simplify the modeling the following assumptions are made.

- The surfaces of the cookers to be modeled are considered as nodal points and hence isothermal.
- The surfaces except the reflector are assumed to be diffuse emitters for thermal radiation.
- The input solar energy is assumed to last indefinitely so that steady state temperatures will be reached.
- Proper tracking is assumed hence the solar radiation strikes the absorber plate at zero angle of incidence.

The cooker is modeled into eight nodal points and the ambient condition is considered as the ninth nodal point. The node numbering and definition is shown below in Table 2. The bottom absorber plate and side plate are separately included to consider the difference in the two designs. In the case of the cooker without reflector the side plate will be an absorber while in the case of the cooker with reflector the side plate will have no absorption and will radiate the incoming solar radiation.

Table 2 Description of nodes.

| Node | Description | Temp. | Remark |
|---|---|---|---|
| 1 | Bottom absorber plate | $T_1$ | Solar energy input to the node $P_{bab}$ |
| 2 | Side plate | $T_2$ | Solar energy input to the node $P_{sp}$ |
| 3 | Cooker inside air | $T_3$ | |
| 4 | Inner glazing | $T_4$ | |
| 5 | Outer glazing | $T_5$ | |
| 6 | Side inner wooden wall | $T_6$ | |
| 7 | Side outer wooden wall | $T_7$ | |
| 8 | Bottom wooden wall | $T_8$ | |
| 9 | Ambient environment | $T_{amb}$ | |

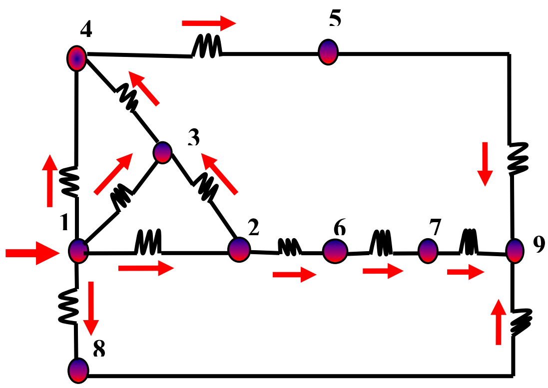


Figure 2 Thermal network model of the cooker.

The thermal network has been developed by considering the heat flow between each combination of nodes. The thermal network model of the cooker is shown in Figure 2. The node numbers and the equivalent thermal resistance between nodes are shown in the Figure. At steady state condition the heat flowing into a node and out of a node are balanced. The following eight simultaneous equations represent the heat balance at nodes 1-8. The eight equations are sufficient to find the unknown temperatures. Node 9 is with known condition of ambient temperature.

Node 1: $P_{bab} + q_{18} + q_{13} + q_{14} = 0$ Node 2: $P_{sp} + q_{21} + q_{23} + q_{26} = 0$ Node 3: $q_{31} + q_{32} + q_{34} = 0$
Node 4: $q_{41} + q_{43} + q_{45} = 0$ Node 5: $q_{54} + q_{5amb} = 0$ Node 6: $q_{62} + q_{67} = 0$
Node 7: $q_{76} + q_{7amb} = 0$ Node 8: $q_{81} + q_{8amb} = 0$

Where $q_{ij}$ represents the heat flow from node i to node j and $P_{bab}$ and $P_{sp}$ are the heat absorbed at bottom absorber and side plate respectively. The heat flow between nodes can be written in terms of the temperature difference $(T_i - T_j)$ and the equivalent resistance between the nodes $R_{e,ij}$ , i.e:

$$q_{ij} = (T_i - T_j)/ R_{e,ij}$$

The heat flow between nodes can be a combination of the three modes of heat transfer: conduction, convection and radiation. Therefore, the equivalent thermal resistance is determined by considering the three heat transfer modes for the specific nodes. The eight simultaneous equations above can be solved for the eight unknown temperatures. This can be done using an iterative procedure since the convective and radiation heat transfer coefficients and hence the equivalent thermal resistances are function of temperature. The iteration was made on an Excel worksheet. The solution method that was used in this work was the "optimize" add-in program with Newton-Raphson algorithm. The details of the procedure may be referred in [7].

### *3.3 Experimental tests*

Two box cookers made from similar materials described in previous section, were fabricated in the same workshop. The difference was the inner metal box as indicated in section 3.1. The cookers were tested simultaneously following a standard procedure as recommended by ASAE. The test was conducted with measurements of temperature using k-type thermocouple and National Instruments (NI) data logger. The main procedures during testing were:

- Tests were started at around 10:00 AM and were stopped before 2:00 PM.
- The cookers were kept under shading before the start of the tests and brought to receive solar radiation simultaneously.
- Tracking of the cookers was done every ten minutes.
- Thermocouples were attached to the center of the bottom absorber plate during the stagnation test and were immersed into water during the boiling test.
- Half liter of cold water was used at each start of the boiling test.
- Solar radiation measurement was taken from a pyranometer in the nearby campus metrological station.
- Wind speed measurement was not taken. Any influence of wind speed is assumed to affect both cookers equally.

Standard stagnation temperature is found from:

$$SST = (T_s - T_{amb})\ (850\ W/m^2)/G$$

Solar power input I into the cooker was calculated from:

$$I = G\ A_{ap}$$

Cooking power $P_c$ during boiling of mass of water 'm' from initial temperature $T_i$ to final temperature $T_f$ during time 't' is calculated from:

$$P_c = mC_p(T_f - T_i)/t$$

The cumulative efficiency of the cooker after 'n' time intervals is found from:

$$\eta_n = \sum P_{ci}/\sum I_i$$

## 4. Results and Discussion

### *4.1 Results of theoretical modeling*

The set of simultaneous nodal equations were modeled in an Excel worksheet. The constant input data as well as data which vary with temperature were entered using lookup tables. The steady state solutions were then determined using the solver discussed in the methodology section. The results are discussed for each type of cooker as shown in Table 3 (Cooker 1 is without and Cooker 2 is with reflector).

Table 3 shows the temperature at each node for the modeled cookers. The temperature at the bottom absorber is $T_1$ which is expected to be the maximum. For cooker 1 the result shows $T_1$ = 153.8 $^oC$ while for cooker 2, $T_1$ = 177.6 $^oC$. This temperature is the maximum stagnation temperature assuming solar radiation of 800 W/m$^2$ and ambient temperature of 24$^o$C. The standard stagnation temperature predicted by the theoretical modeling is therefore 137.9 $^oC$ and 163.2 $^oC$ for cooker 1 and cooker 2 respectively. This shows that there is significant difference between the two designs in terms of the stagnation temperature. The theoretical modeling predicts that the cooker with reflector can perform much better than the cooker without reflector.

Table 3 Temperature predictions of the nodes

| **Node** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| **Temperature ($^o$C) Cooker 1** | 153.8 | 134.0 | 131.0 | 104.5 | 52.5 | 40.5 | 24.3 | 27.3 |
| **Temperature ($^o$C) Cooker 2** | 177.6 | 159.2 | 150.1 | 121.0 | 59.8 | 44.4 | 24.6 | 26.2 |

### *4.2 Results of experimental tests*

*Stagnation test*

Tests were conducted as per the procedure discussed in the methodology section. Temperature was measured using thermocouples every ten minutes. The plot of temperature and solar radiation for three days of testing are shown in Figure 3. The standard stagnation temperature for each day and cooker design has been calculated and the results are shown in Table 5. The experimental result also indicates that the standard stagnation temperature of the cooker with reflector is higher than the cooker without reflector. The difference is on average about 22$^o$C. In comparison the stagnation temperature of the cookers found from experiment is much less than the theoretical prediction. This is due to an unaccounted heat loss factors in the theoretical prediction such as leakages around the cooker doors and around the edge of the outer wooden box. However, the stagnation test also indicates that the cooker with reflector performed better.

Table 5 Results of stagnation test.

| Cooker | Day 1 | | | Day 2 | | | Day 3 | | |
|---|---|---|---|---|---|---|---|---|---|
| | Maximum temperature ($^o$C) | Average radiation (W/m$^2$) | SST ($^o$C) | Maximum temperature ($^o$C) | Average radiation (W/m$^2$) | SST ($^o$C) | Maximum temperature ($^o$C) | Average radiation (W/m$^2$) | SST ($^o$C) |
| Without reflector | 106.2 | 785.6 | 86.8 | 103.9 | 719.3 | 92.1 | 86.7 | 868.6 | 59.4 |
| With reflector | 129.3 | 785.6 | 111.8 | 117.8 | 719.3 | 108.5 | 111.3 | 868.6 | 83.5 |

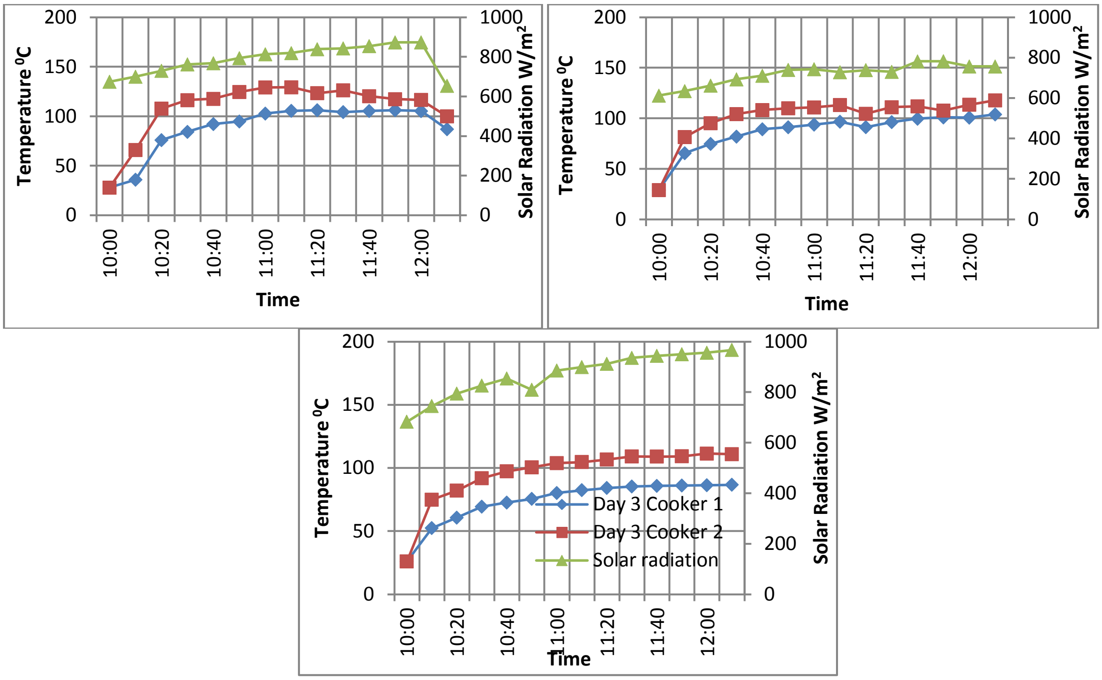


Figure 3 Stagnation tests, top to bottom, Day 1, 2, and 3.

*Boiling tests*

Boiling tests were also done in a similar manner with 0.5 liters of water in a cooking pot inside the cookers. Figure 4 shows plots of temperature and solar radiation data for three different test days (Day 4, 5 and 6). The cumulative efficiency plots for boiling tests of the same three days are also shown in Figure 5.

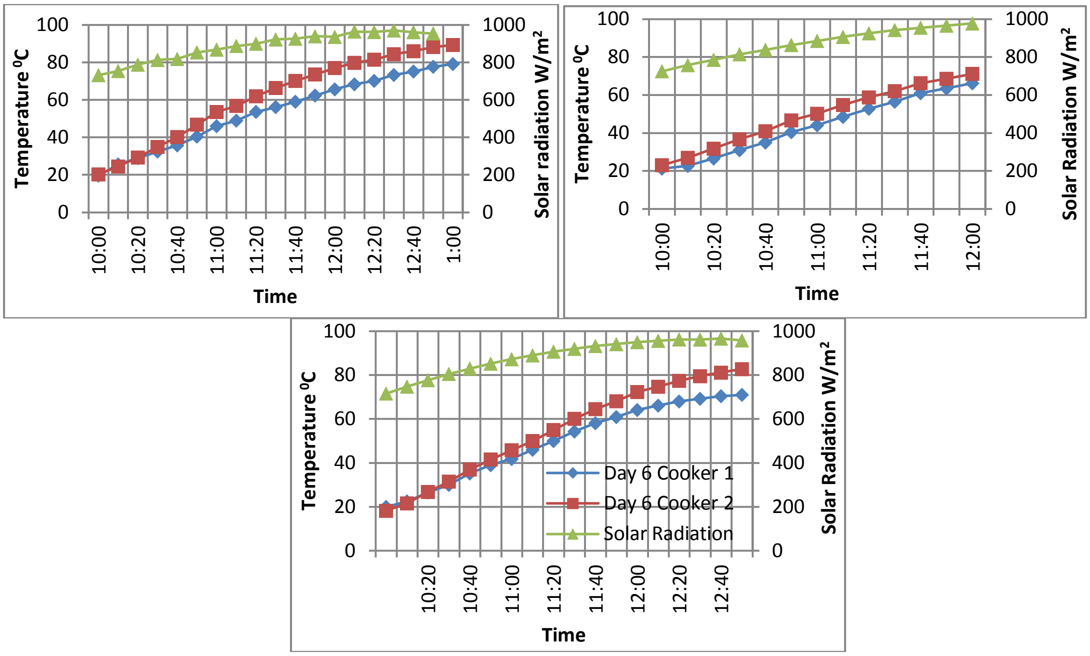


Figure 4 Boiling tests, top to bottom Day 4, 5 and 6.

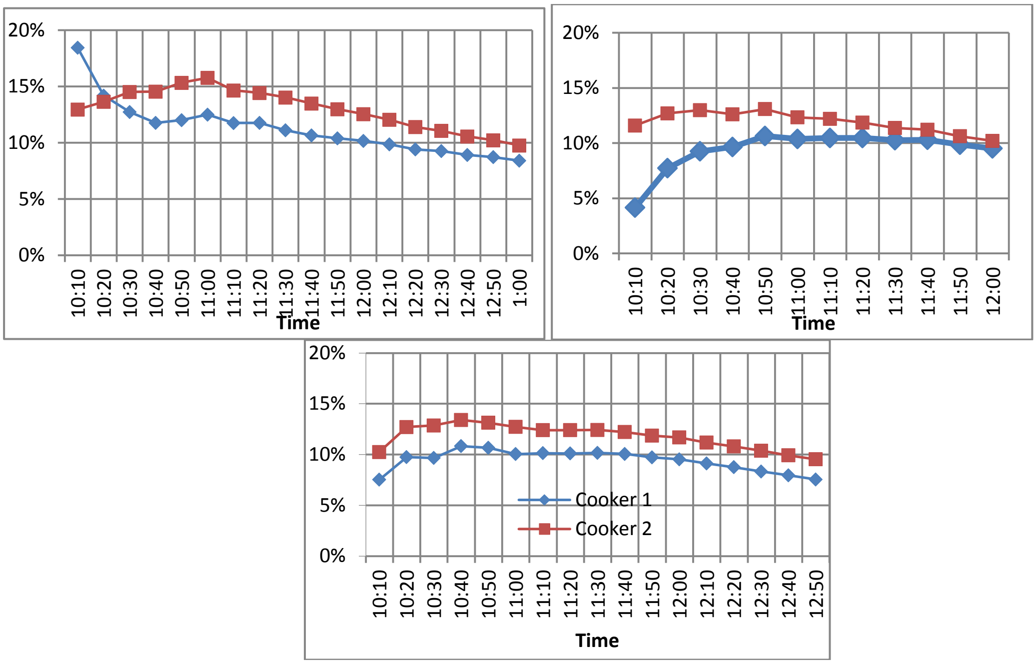


Figure 5 Cumulative efficiencies of the cookers during the boiling test.

## 5. Conclusion

The study has clearly shown that in both the theoretical prediction and experimental tests, the performance of box solar cookers can be enhanced using internal reflectors. The steady state theoretical analysis predicted difference in standard stagnation temperature of about 25$^{o}$C. The experiment on stagnation test also concluded that the standard stagnation temperature was higher by about 22$^{o}$C. However, the predicted stagnation temperature for both the cookers was higher than the experimental value. Similarly the boiling test indicated that the water temperature and the cumulative efficiency were higher for the cooker with reflector. Therefore, the performance of box cookers can be enhanced by making appropriate angle side walls of the absorber and providing internal reflection.

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