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Construction and Performance Test of Box-type Solar Cooker with Compound Parabolic Reflector

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ABSTRACT
To meet up the ever increasing energy demand all over the world, non-conventional or renewable energy sources have been introduced. Solar energy is one of the major sources of renewable energy and could be used in various purposes like heating, drying, cooking, distillation etc. For cooking purposes solar energy could be used as a substitute of conventional fuels. Box-type solar cooker is popular, simple in design but less efficient. A new type of box cooker design was introduced in the present work aiming to improve the performance. A wooden box with size 0.7m × 0.7m × 0.5m containing five plane glass mirrors, work as reflector for enhancing the incident solar radiation, was constructed. A compound parabolic shape aluminum foil was used as inner reflectors to further concentrate the incident radiation and get higher performance. Cotton was used between the wooden box and inner parabolic reflectors as insulation. Transparent glass was used as cover for creating greenhouse effect inside the box so that heat could be trapped. After developing the solar cooker, experiments were conducted using the solar cooker. Four sets of cooking item (200g rice; 200g rice and 50g lentil; 250g rice and 50g lentil and finally 300g rice and 100g potato) were cooked. Maximum temperature recorded for all loading conditions was in between 80 - 90°C. Among all data, maximum temperature inside the cooking pot was found 90°C whereas minimum temperature was achieved 80°C during the experiments. On average 90 minutes time was required for cooking 200g rice, 105 minutes for cooking 200g rice and 50g lentil, 120 minutes for cooking 250g rice and 50g lentil and 130 minutes for cooking 300g rice and 100g potato.

Keywords: Solar energy, Firewood scarcity, Solar cooking, Box-type cooker, Cooking time.

1. Introduction

Energy is the capability of doing work and there are various forms of energy, like potential energy, kinetic energy, electrical energy, thermal energy, nuclear energy etc. Energy sources can be of two categories, e.g. renewable and non-renewable energy sources. Renewable sources include solar, wind, hydro biomass etc. Non-renewable energy sources are conventional fossil fuels, nuclear fuels etc. They cannot regenerate instantly like the renewable energy sources. But this sources are the most widely used sources in the present world. Consumption of energy is increasing day by day all over the world. Since the 20th century, energy consumption is facing a rapid growth [1]. But the non-renewable energy sources are depleting in nature. Therefore, this rapid increase in energy consumption would result in scarcity of energy. Therefore, finding alternative energy sources are necessary to meet up the increasing energy demand of future. In this case, renewable energy sources could be a great alternative. They are not depleting in nature and could be refilled during a human timescale. Solar energy is one such renewable energy that comes from the sun. It is expected to be one of the most attractive renewable energy sources in the present 21st century because of its nonpolluting characteristics and is practically a limitless supply. Solar energy could either be used in photovoltaic system or as solar thermal energy. Various solar systems have been developed for harnessing the solar thermal energy. Solar collector is used to collect solar thermal energy for water heating or air heating purposes. This type of energy can be used in many domestic, industrial or commercial purposes. Solar heating, drying, distillation, cooking etc. can be performed with solar thermal energy.

In Bangladesh, energy consumption for cooking is significant. The energy used for cooking in the country is basically non-renewable energy. In the urban areas mostly LPG and electricity is used in cooking purposes but in rural areas people mostly depends on biomass energy for cooking. Unplanned use of biomass results in deforestation and ultimately global warming. Also, burning of firewood for cooking creates combustion products that cause environment pollution. Using solar cooker for cooking purpose could be a great alternative to this conventional energy consumption. Solar cooker uses energy from sunlight directly. Cooking operation by solar cooker is accomplished either by trapping the radiation in the form of greenhouse effect or by the concentration of radiation towards the cooking pot. Heat from the sun concentrates toward the cooking pot. When sufficient temperature is achieved inside the cooking pot, cooking can be performed. This system is more environmental friendly as no combustion product is produced. There are different types of solar cooker. Among all these types, mainly three types are most popular. They are box-type, panel type and parabolic solar cooker. Box-type solar cooker consists of an insulated box. This box is used for trapping solar heat. A transparent glass or plastic cover is used to create the greenhouse effect inside the box. By trapping the heat inside the box, cooking temperature is achieved inside the box. Panel type solar

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cooker consists of reflective panels to enhance or concentrate the solar radiation intensity on the cooking pot. Parabolic solar cooker is also known as concentrator cooker. This type of cooker consists of parabolic dish reflector which concentrates solar radiation into the cooking pot. Its concentration ratio is relatively higher than reflective cookers. But this type of cooker needs good solar tracking system. In this work, a box-type solar cooker is designed and constructed accommodating both outer reflector and inner reflector. Thus, this cooker is consisted of compound parabolic inner reflector and flat plane outer reflectors.

There are several works on box-type solar cooker. Researchers tried different types of box-type solar cooker. But those models contained some lacking. Performance evaluation study of a box type solar cooker was conducted by Adewumi et al. [2]. Efficiency was determined while changing the quantity of reflectors. During sensible heating test, highest temperature reached for water was found 50.4℃ for no reflector, 66.1℃ for one reflector, 75.6℃ for 2 reflectors, 85.3℃ for 3 reflectors and 100℃ for 4 reflectors. Harmin et al. [3] designed a box type cooker with two glazed side, vertical side glazing and a horizontal side glazing. A parallelepiped insulated box with compound parabolic concentrator was used in this case. During the stagnation test, when reflectors were used, maximum temperature of absorber plate and inside air were found 166℃ and 160℃ respectively when horizontal solar radiation was found to be 980 W/m^2 and ambient temperature was found 43℃. Those temperatures were 165℃ and 162℃ respectively when horizontal solar radiation was found to be 695 W/m^2 and ambient temperature was 22.5℃. Those values were again taken removing the reflectors. While no reflector was attached, those temperatures were found 127.7℃ and 120.6℃ respectively when horizontal solar radiation was found to be 719 W/m^2 and in that time ambient temperature was found 18.2℃. It was also found that the stagnation temperature was higher than their previous work. During water heating test with reflector, it was found that time required for achieving boiling point was 150 minutes for 3.5 kg of water and 198 minutes for 4.5 kg of water. When reflectors were removed, the time was found to be about 3 hours for 3.5 kg of water. El Sebaii et al. [4] constructed solar cooker with multi-step reflectors. In this case no outer reflector was used. Inner multi-step reflectors concentrated solar rays towards the cooking pot. In this case, for 1.5 kg water, boiling point temperature was reached after 105 minutes. This experiment was conducted when solar insolation was 741 W/m^2. Maximum mean temperature was found 140.6℃ inside the cooking vessel in 120 minutes.

In the present work a box-type solar cooker was constructed with compound parabolic inner reflectors and flat outer reflectors with a view to getting better performance than the existing models of box-type solar cooker. After the construction, experiments were conducted for cooking food with this cooker. Data like temperature inside the cooking pot, solar intensity, cooking time was measured during the experiments.

2. Working Procedure and Construction

2.1 Working Procedure:

As mentioned before, box-type solar cooker is one of the most common and simple type of solar cooker. Box-type cooker depends on greenhouse effect for cooking. The transparent glass cover allows short wavelength solar radiation to enter into the box but traps the radiation of higher wavelength coming from the objects of low temperature. The box consists of transparent cover as well as reflective surfaces which concentrate and redirect the solar radiation towards the cooking pot inside the box. Inner part of the box was painted black so that it can absorb as much solar radiation as it can. It could be constructed with reflectors or without reflectors [5].

2.2 Design of Solar Cooker:

The size calculation for the box type solar cooker for cooking 300g rice is done according to Joyee and Rahman [6]. Assuming mass of rice, m_r = 300 *g* and mass of water, m_w = 600 g. The specific heat of water is c_{pw} = 4.186 J/kg.K and specific heat of rice, c_{pr} = 1.76 J/kg.K. Assuming also the thermal efficiency, η_{th} = 20%, the average solar intensity, I_b = 450 W/m^2, initial temperature, T_i = 30℃ and final temperature, T_f = 100℃, Cooking time, t = 3600 sec.

Total heat required can be expressed as,

$$Q = Q_r + Q_w = m_r c_{pr}(T_f - T_i) + m_w c_{pw}(T_f - T_i) \quad (1)$$

From Eq. (1), total heat required = 227.97 kJ.

It is assumed that this amount of heat will come from the sun as solar radiation. In terms of solar radiation we obtain,

$$Q = \eta_{th} I_b A_a t \quad (2)$$

From (1) and (2) we get, A_a = 0.71 m^2

So, aperture area need to be 0.71 m^2

For inner parabolic reflector:

Equation of parabola is -

$$x^2 = 4ay \quad (3)$$

Let, focal point will be a = 0.06 m from the vertex and aperture of the system = 0.70 m.

Then the equation for the parabola can be expressed as,

$$x^2 = 0.24y \quad (4)$$

So, for the aperture = 0.70 *m*, height of the parabola from Eqn. (4) would be 0.51 *m*.

Arc length of a parabola can be expressed as [7], arc length =

$$\frac{1}{2}\sqrt{q^2 + 16p^2} + \frac{q^2}{8p}\ln\left(\frac{4p + \sqrt{q^2 + 16p^2}}{q}\right) \quad (5)$$

With, p = 0.51 m and q = 0.7 m, the arc length of the parabola for this dimensions is 1.29 m and width of the box = 0.7 m. The area of parabolic surface is equal to the arc length × width = 0.90 m^2. Let, absorber plate will be 0.06 m from the vertex. From Eq. (4) we obtain by putting y = 0.06 m, absorber plate will be of 0.24 m in width. From Eq. (5) we obtain with p = 0.06 m and q = 0.24 m, Arc length below the absorber plate = 0.28 m; Surface area below absorber plate = arc length × width = 0.19 m^2. So, the surface area will be = 0.9 - 0.19 = 0.71 m^2.

2.3 Construction of Proposed Model

To construct the proposed box-type solar cooker, at first 0.7m × 0.7m × 0.5 m wooden box was constructed. Inside part of the box was made compound parabolic. For this a structure was made to parabolic shape and then aluminum foil was attached to the parabolic structure which would work as inner reflector. Between wooden box and inner parabolic reflector, cotton was packed as insulation. Although cotton has not impressive insulating property, but it cost is relatively low. On the top of the box, glass cover was placed. This cover was placed in such a way that it could be removed while cooking pot need to be placed inside the box or taken out from the box. It was kept in mind that, the glass cover should be air tight. Three flat silver coated mirrors were hinged on top of the box. There were two trapezoidal mirrors also. These two mirrors were also hinged on top of the box. Those mirrors reflected solar radiation inside the box. Those mirrors were hinged in such a way that they could be manually adjusted with the sun's position while cooking. The cooking pot was also black painted so that it can absorb much of the solar radiation. The photographic view of the final product is shown in Fig. 1.

Fig. 1: Box-type Solar Cooker

3. Experimental Setup

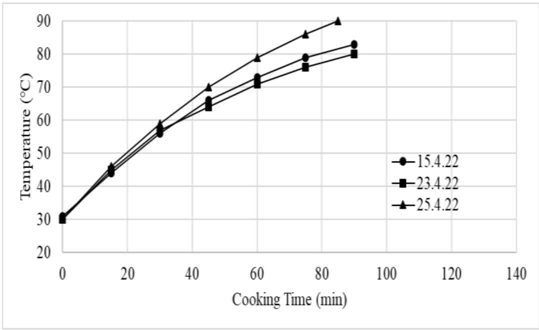
To conduct the experiment, at first the cooker was put under direct sunshine. Pyranometer was set in such a place where there was no obstacle for the solar radiation. Thermocouple wire with temperature indicators were connected with the AC line so that they can be placed inside the box when necessary. The outer reflectors were adjusted according to sun's position so that the maximum amount of solar radiation enter into the cooker. Required amount of water was taken inside the cooking pot. The cooking pot was placed inside the cooker. When temperature of water inside the cooking pot rose up to 70℃, rice and other items were added to the water. Outer reflectors were adjusted after some time intervals so that maximum solar intensity could be achieved. Temperature inside the box was measured at 15 minutes interval from the temperature indicator. Global solar intensity was measured at 15 minutes interval also. The procedures were followed until the cooking is completed. Maximum temperature inside the box was measured by this procedure. Time required for achieving the maximum temperature was also measured. Time to cook was also measured. It is to be mentioned that for each set of cooking, three times the experiments were conducted and the average was taken though radiation was not remain constant.

4. Results and Discussion

4.1 Experimental Results:

For the performance test, 4 sets of combination were used. For each set, 3 experiments were taken at various times and various days. In Fig. 2(a), temperature inside cooking pot is plotted against cooking time for 200g rice loading. Three experiments were conducted on 15 April, 2022, 23 April, 2022 and 25 April, 2022. Solar intensity during those days were in between the range from 686.44 W/m^2 to 949.15 W/m^2, from 745.76 W/m^2 to 872.88 W/m^2 and from 822.03 W/m^2 to 906.78 W/m^2 respectively. In Fig. 2(b), temperature is plotted against time required for cooking for 200g rice and 50g lentil. Three experiments were conducted on 17 April, 19 April and 24 April, 2022. Solar intensity on those days were within the range from 703.39 W/m^2 to 915.25 W/m^2, from 677.97 W/m^2 to 940.68 W/m^2 and from 830.51 W/m^2 to 915.25 W/m^2 respectively. Temperature inside the cooking pot vs cooking time for cooking 250g rice and 50g lentil is shown in Fig. 2(c). The experiments were conducted on 19 April, 23 April and 24 April. Solar intensity on those days were between 728.81 W/m^2 and 906.78 W/m^2, 762.71 W/m^2 and 906.78 W/m^2, 794.64 W/m^2 and 964.29 W/m^2 respectively. In Fig. 2(d), temperature inside cooking pot is plotted against time required for cooking for 300g rice and 100g potato. Among the three experiments, one was performed on 25 April, 2022 and other two were performed on 26 April, 2022. Solar intensity on those days were within the range from 855.93 W/m^2 to 906.78 W/m^2, from 762.71 W/m^2 to 923.73 W/m^2, from 838.98 W/m^2 to 940.68 W/m^2 respectively.

(a)



(b)
(c)
(d)

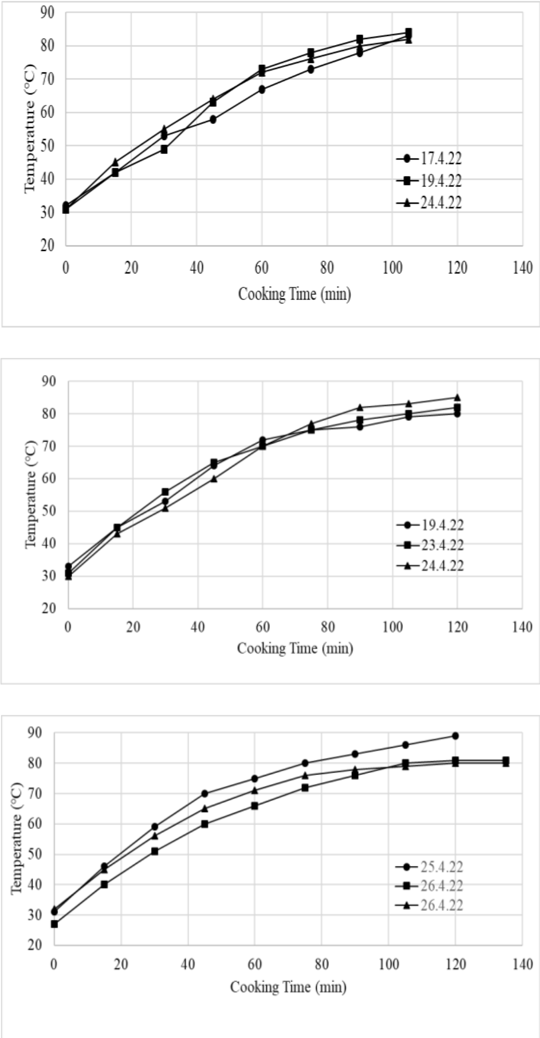


Fig. 2: Temperature vs Cooking Time for (a) 200g Rice, (b) 200g Rice and 50g Lentil, (c) 250g Rice and 50g Lentil and (d) 300g Rice and 100g Potato.

Comparison of four set of experiments is shown in Fig. 3. Average value for temperature and cooking time of three experiments for each set of loads is taken and plotted in a graph.

4.2 Discussion

To test the performance, 12 experiments with four combinations were conducted. Cooking performance was tested during this experiments. Experiments were conducted from 15 April 2022 to 26 April 2022.

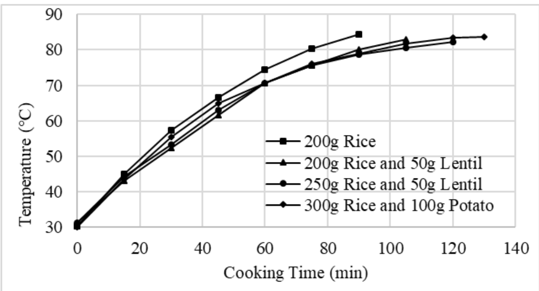


Fig. 3 Comparison of Cooking Time between Different Loads.

First combination was with 200g rice only. Three experiments were conducted on 15, 23 and 25th April, 2022. Among those experiments, experiment conducted on 25 April was better than other two experiments. On 25 April, the weather was perfectly sunny. There was a good solar intensity ranged from 822.03 W/m^2 to 906.78 W/m^2. There was no interruption of solar intensity due to cloud. Temperature inside the cooking pot rose to 90℃ on that day. Cooking was completed within 85 minutes. The other two days, there were little bit clouds but cooking was completed without any problem. On both days, cooking was completed within 90 minutes. If the weather is clear and solar intensity is gradually increasing without any fluctuations, much better performance could be obtained on those days. Second set of experiment was conducted with 200g rice and 50g lentil. Three experiments were conducted for this set also. Experiments were performed on 17, 19 and 24th April 2022. On 17 and 19 April, fluctuations on solar intensity were found that resulted in not obtaining much higher temperature inside the cooking pot. On 24 April, experiment was started from 12 pm local time. At that time, solar intensity started to fall slowly which was the reason for not achieving higher temperature. Maximum temperature achieved for this experiment was 82℃ which was lowest among the three experiments. All three experiments were conducted within 105 minutes. But performance could be much higher if there were good, uninterrupted solar intensity. Third set experiment was done with 250g rice and 50g lentil. Three experiments were done on 19, 23 and 24th April 2022. On 19 and 23 April, experiments were conducted from 12.15 pm and 11.45 am local time respectively. During these experiments, after some times, solar intensity began to decrease slowly. On the other hand, on 24 April, experiment was started from 9.45 am local time and solar intensity was increasing gradually during the time of experiment. For each experiment, time required for completing the cooking was about 120 minutes. But for the first two cases, highest temperature inside the cooking pot was 80℃ and 82℃ respectively whereas for the third case, maximum temperature inside the cooking pot was found 85℃. Fourth set of experiments were done with 300g rice and 100g potato. On 25 April 2022 one experiment was performed. On 26 April 2022, two experiments were conducted. On 25 April, weather was very sunny and there was no interruption of solar intensity which brought about decent cooking performance. Even with higher loading, cooking was completed within 120 minutes and maximum temperature was found inside the cooking pot was 89℃ with maximum solar intensity of 915.25 W/m^2. On 26 April, there were some fluctuations in solar intensity. Temperature inside the cooking pot did not rise as high as the temperature found on 25 April. Though foods were cooked properly cooking times were more. For both cases 135 minutes required for proper cooking and temperatures inside the pot were 82℃ and 80℃ respectively. By comparing all four sets, it was seen that, with increasing load cooking time also increased. As mass increased, increase in temperature is delayed. That resulted in increase in cooking time. It was seen that, time required for cooking was minimum for 200g rice and maximum for 300g rice and 100g potato among the four combinations.

Cooking with solar cooker was not easy. As it depended on solar intensity, weather condition played vital role. The project performed well during sunny days with decent solar intensity but during cloudy days it did not perform well. Without any fluctuation of solar intensity the cooker performed very well. It is to be mentioned that the major problem with box type solar cooker will be the maximum temperature attained. Only foods that need boiling could be cooked with this type device. Frying or roasting food could not be performed with box type solar cooker. For that concentrating type solar cooker will be required.

5. Conclusion

The project was aimed to achieve good performance with box-type solar cooker. To achieve good performance, compound parabolic inner reflectors were introduced. After design and construction of the cooker, performance test was done by cooking different types of food with this cooker on different days. The whole work can be concluded as follows:

(i) On average 90 minutes required for cooking 200g rice, 105 minutes required for cooking 200g rice and 50g lentil, 120 minutes required for cooking 250g rice and 50g lentil, 130 minutes required for cooking 300g rice and 100g potato.

(ii) Maximum temperature inside the cooking pot was found 90℃ whereas minimum temperature was achieved 80℃ during the experiments.

(iii) As temperature inside the cooking pot was not so high, only boiling type of cooking could be performed with this cooker and frying or roasting is not tried.

(iv) On cloudy days, cooking could not be performed with this cooker. But during sunny weathers, foods were cooked nicely.

Box-type solar cooker is much feasible to operate than other type of solar cookers. From experiments it was seen that cooking with this cooker was satisfactory. This solar cooker can be a good backup for cooking to the rural people.

6. References

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NOMENCLATURE

m_r : Mass of rice, *kg*
m_w : Mass of water, *kg*
C_{pw} : Specific heat of water, *J/kg.K*
C_{pr} : Specific heat of rice, *J/kg.K*
η : Efficiency of solar cooker
Q : Required heat for cooking rice, *J*
T_i : Initial temperature, *℃*
T_f : Final temperature, *℃*
t : Cooking time, *s*
A_a : Area of aperture, m^2
A_{abs} : Area of absorber, m^2
D_{abs} : Width of absorber pot, *m*
L_{abs} : Length of absorber pot, *m*