

# Numerical study on the effect of configuration of a simple box solar cooker for boiling water

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**Abstract.** In this work, a numerical study is carried out to investigate the effect of configuration of a simple box solar cooker. In order to validate the numerical results, a simple a simple solar box cooker with absorber area of  $0.835\text{ m} \times 0.835\text{ m}$  is designed and fabricated. The solar box cooker is employed to boil water by exposing to the solar radiation in Medan city of Indonesia. In the numerical method, a set of transient governing equations are developed. The governing equations are solved using forward time step marching technique. The main objective is to explore the effect of double glasses cover, dimensions of the cooking vessel, and depth of the box cooker to the performance of the solar box cooker. The results show that the experimental and numerical results show good agreement. The performance of the solar box cooker strongly affected by the distance of the double glass cover, the solar cooker depth, and the solar collector length.

## 1. Introduction

Solar energy is a potential renewable energy resource and it will play an important role in fulfill future energy demand. The globe is yearly exposed by 3,400,000 Exa-Joule of solar energy. This energy can fill the present energy consumption of the world only with 1 hour 15 minutes of irradiation [1]. In the present time, only a tiny little portion of the human energy consumption filled by solar energy. However, according to REN21, since 2030 solar energy utilization will increase significantly. Recently, studies on solar energy have increased significantly [2]. Solar industry is developing constantly in all over the world because of increasing energy demand and also limitation on major energy source the fossil fuel. Indonesia has a big potency of solar energy and constant in every year [3]. Typically, solar energy is harvested in solar photovoltaic and solar thermal method. In the solar thermal method, the solar energy can be used as heat energy for solar drying process [4], solar adsorption refrigeration [5], solar desalination [6,7,8], solar water heater [9], solar cooker [10], etc.

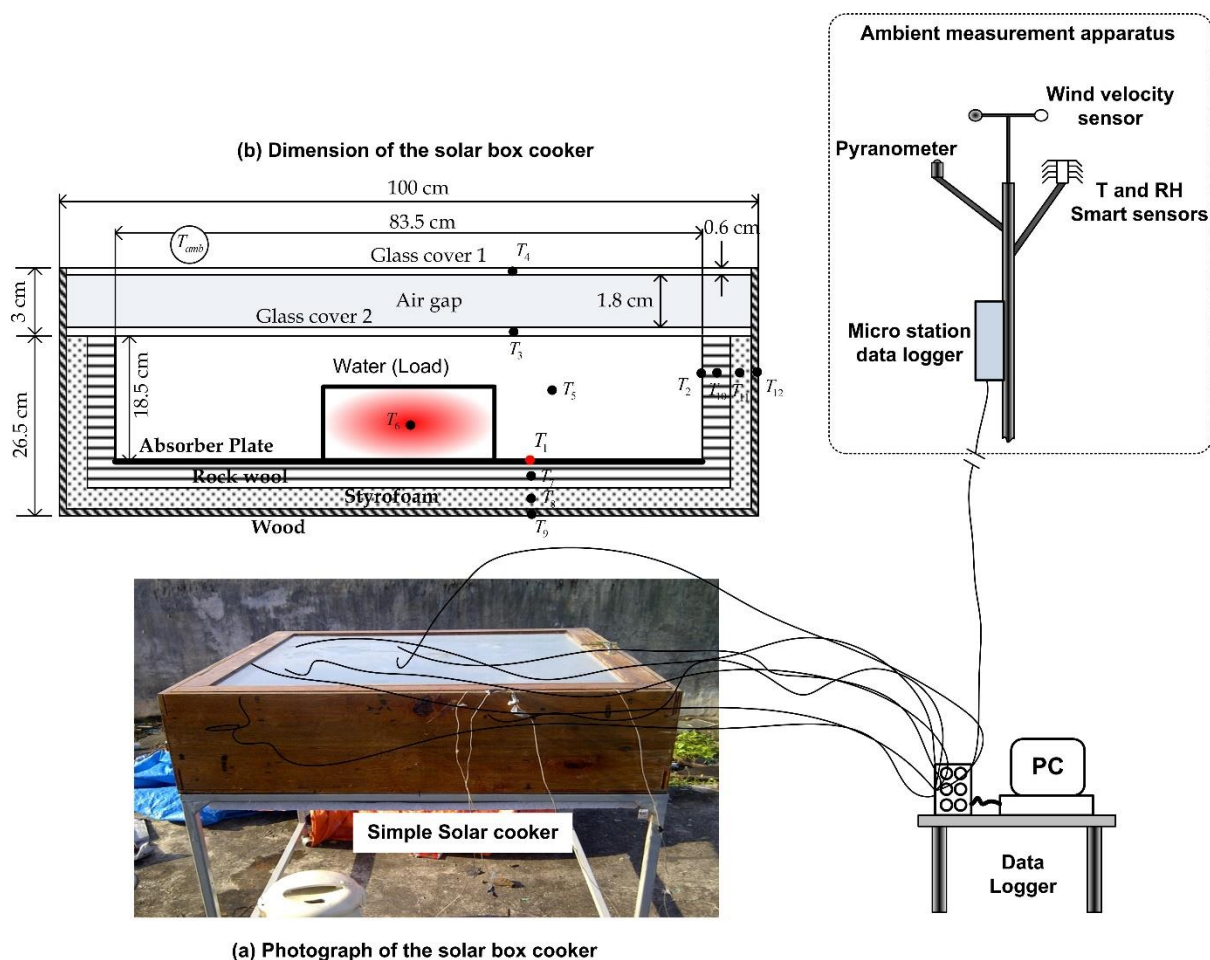
There are many types of solar collector are found in literature. Flat-plate type solar collector is the simplest solar collector and it is very popular [11]. In the flat-plate type of solar collector a double glass cover is typically employed to reduce the heat loss from the top. Studies on the heat transfer characteristics and heat loss from a flat-plate type solar collector can be found in literature. Varol and Oztop [12] carried out a comparative numerical study on natural convection in inclined wavy and flat-plate solar collectors. It was revealed that flow field and thermal fields were affected by the shape of the air space (cavity) and heat transfer rate increases in the case of wavy cavity than that of flat cavity. The influence of inclination to the flat-plate and wavy solar collectors has also investigated [13]. Kumar [14] studied free convective heat transfer in trapezoidal profile of an enclosure of a box-type solar cooker. It



was revealed that the values of convective heat transfer and top loss coefficient for rectangular enclosure are lower by 31-35% and 7 %, respectively. Those studies reveal that investigation on the flat-plate type solar collector has come under scrutiny. In this study, a flat-plate type solar collector that is used in a simple solar box cooker is studied numerically. The objective is to explore the effect of the configuration of the box cooker to the performance. The configuration in here includes dimensions of the solar cooker components. The results are expected to supply the necessary information in developing an effective and efficient solar box cooker.

## 2. Method

In this study, an experimental apparatus has been designed and fabricated to provide experimental data that can be used to perform numerical validation. The developed experimental apparatus is depicted in figure 1. It is a flat plate solar collector with double glasses cover in the top with absorber area of  $0.835 \text{ m} \times 0.835 \text{ m}$ . In order to decrease the heat loss, the envelop of the solar box cooker made of a series of insulation material rock wool, styrofoam, and wood. The figure shows the dimensions and configurations of these material. The load to the box solar cooker is water and it is placed in a cylindrical cooking container and located in the middle of the collector. The cooking container is made of aluminum with diameter and height of 30 cm and 12 cm, respectively.



**Figure 1.** (a) Photograph of the solar cooker and (b) computational domain

## 2.1 Numerical Method

In this study, the solar box cooker is divided into 12 components. It is assumed that temperature and properties of each component are uniform. Figure 2(b) shows the dimensions and temperature notation of every component. To each component, the energy conservation is applied. The energy conservation for absorber plate gives:

$$m_p C_p \frac{\partial T_1}{\partial t} = \tau^2 \alpha I A_p - FC_{15}(T_1 - T_5) - FR_{13}(T_1 - T_3) - FR_{12}(T_1 - T_2) - \frac{1}{R_{17}}(T_1 - T_7) \quad (1)$$

where  $m_p$  [kg] and  $C_p$  [J/kg K] are mass and specific heat of absorber plate. The parameters of  $I$  [W/m<sup>2</sup>],  $\alpha$ , and  $\tau$  are solar irradiance, absorptivity and transmission coefficients of the glass cover, respectively. The hot air inside the solar box cooker is assumed to be one substance with a homogeneous temperature of  $T_5$ . Thus, energy conservation to the air yield to:

$$(\rho V_{ol})_{air} \frac{\partial T_5}{\partial t} = FC_{15}(T_1 - T_5) - FC_{52}(T_5 - T_2) - FC_{53}(T_5 - T_3) - FC_{56t}(T_5 - T_6) - FC_{56w}(T_5 - T_6) \quad (2)$$

Where  $FC$  [W/K] is a factor to represent convective heat transfer from any surface. The subscript 1, 5, 2, 3, 6 refer to surfaces shown in Figure 1. And 6t and 6w refer to the top surface and the container wall surface of the container, respectively. The double glasses cover is made of glass with similar emissivity ( $\varepsilon$ ) and thickness. The energy conservation gives:

$$m_g C_g \frac{\partial T_4}{\partial t} = (1 - \tau) I A_g + FR_{34}(T_3 - T_4) + FC_{34}(T_3 - T_4) - FR_{4s}(T_4 - T_{amb}) - h_w A_g (T_4 - T_{amb}) \quad (3)$$

$$m_g C_g \frac{\partial T_3}{\partial t} = (1 - \tau) \tau I A_g + FC_{53}(T_5 - T_3) + FR_{13}(T_1 - T_3) + FR_{23}(T_2 - T_3) - FC_{34}(T_3 - T_4) - FR_{34}(T_3 - T_4) \quad (4)$$

Where  $h_w$  [W/m<sup>2</sup> K],  $A_g$  and  $T_{amb}$  [°C] are convective heat transfer coefficient from the top glass to the ambient air and temperature of the ambient air, respectively.

As mentioned that the load for box solar cooker is water. In the process the cooking vessel and water receive the heat convectively from the air inside the solar box cooker through side wall and top wall of the vessel. The top surface of the cooking vessel also acts as a solar collector and it receives solar heat flux. Heat transfer from the absorber plate to the bottom and radiative heat transfer from the wall of the container are neglected. The temperatures of the container and the water are assumed homogenous. Thus, energy conservation in the container gives:

$$(m_f C_f + m_c C_c) \frac{\partial T_6}{\partial t} = FC_{56w}(T_5 - T_6) + FC_{56t}(T_5 - T_6) + \tau^2 \alpha I A_{ct} \quad (5)$$

Where the subscript  $f$  and  $c$  represent water and the container, respectively.

The temperature difference in each material of the wall of the solar box cooker is taken into account. The temperature of every material of the bottom wall of the solar cooker is also shown in Figure 1. Energy conservation in the rock wool, styrofoam, and wood show the following equation.

$$m_{rw} C_{rw} \frac{\partial T_7}{\partial t} = \frac{1}{R_{17}}(T_1 - T_7) - \frac{1}{R_{78}}(T_7 - T_8) \quad (6)$$

$$m_{st} C_{st} \frac{\partial T_8}{\partial t} = \frac{1}{R_{78}}(T_7 - T_8) - \frac{1}{R_{89}}(T_8 - T_9) \quad (7)$$

$$m_{wd} C_{wd} \frac{\partial T_9}{\partial t} = \frac{1}{R_{89}}(T_8 - T_9) - FC_{9a}(T_9 - T_a) \quad (8)$$

Where the subscript  $rw$ ,  $st$ ,  $wd$ , and  $a$  refer to rock wool, styrofoam, wood, and ambient, respectively. Furthermore, the energy conservation in every material of the wall of the solar box solar cooker (inner plate, rock wool, Styrofoam, and wood) will give the following equations:

$$m_p C_p \frac{\partial T_2}{\partial t} = FR_{12}(T_1 - T_2) + FC_{52}(T_5 - T_2) - FR_{23}(T_2 - T_3) - \frac{1}{R_{210}}(T_2 - T_{10}) \quad (9)$$

$$m_{rw} C_{rw} \frac{\partial T_{10}}{\partial t} = \frac{1}{R_{210}} (T_2 - T_{10}) - \frac{1}{R_{1011}} (T_{10} - T_{11}) \quad (10)$$

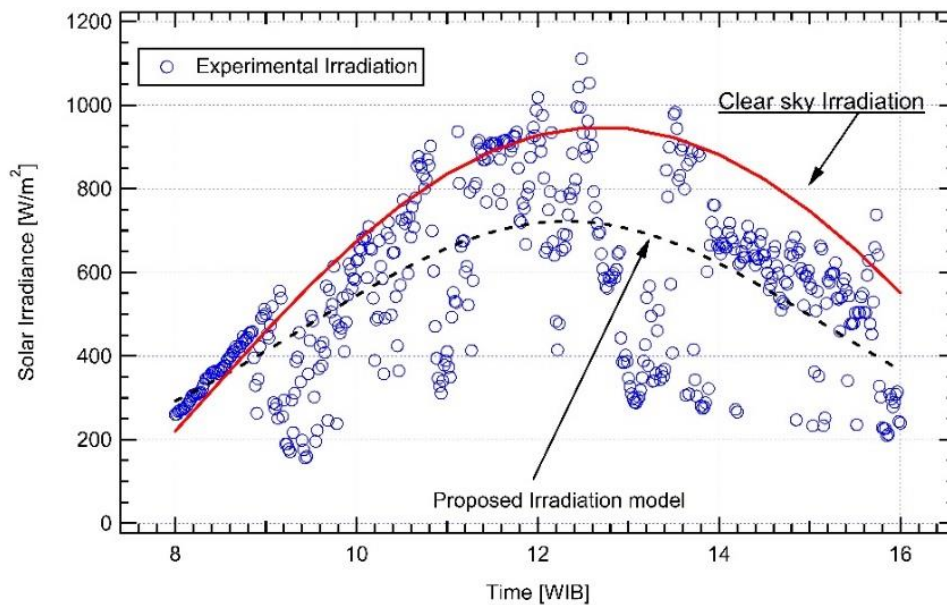
$$m_{st} C_{st} \frac{\partial T_{11}}{\partial t} = \frac{1}{R_{1011}} (T_{10} - T_{11}) - \frac{1}{R_{1112}} (T_{11} - T_{12}) \quad (11)$$

$$m_{wd} C_{wd} \frac{\partial T_{12}}{\partial t} = \frac{1}{R_{1112}} (T_{11} - T_{12}) - \frac{1}{R_{12a}} (T_{12} - T_a) \quad (12)$$

All of the governing equations, equation (1) to equation (12), are converted from partial differential equation form into linier equation system by using discretization technique. Here, the used technique is forward time step marching. In this work, the value of  $\Delta t = 1$  sec is used due to stability consideration. This value shows stability.

### 3. Results and Discussions

#### 3.1. Solar Irradiance and Numerical validation

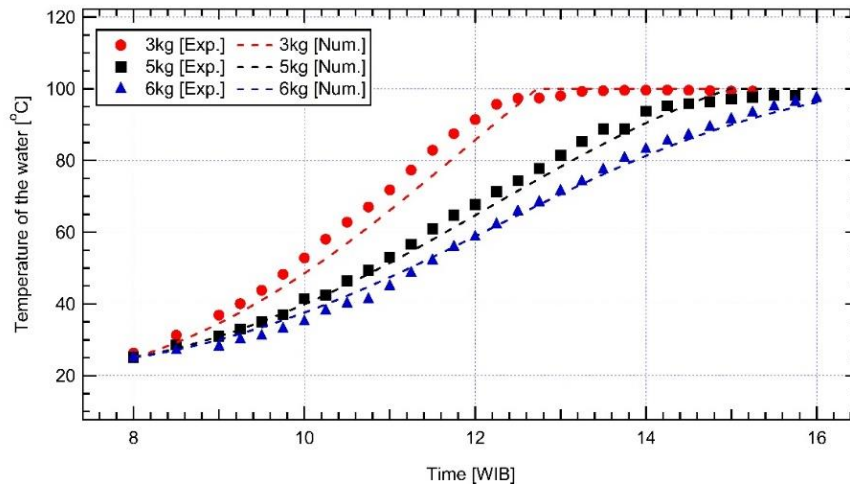


**Figure 2.** Solar Irradiance during experiment and modelled for numerical simulation

As a note, the source of energy for solar cooker is solar irradiation. The solar irradiation during experiment is measured. The measured data will be modelled and used as an energy input to the numerical simulation. The theoretical clear sky irradiance, measured solar irradiance and the modelled one are shown in figure 2. In the modelled one, the maximum solar irradiance is 722 W/m<sup>2</sup> and it occurred at 12.19 of local time. The total solar energy resulted by the solar radiation by the proposed model is 16.2 MJ/m<sup>2</sup>. This shows that the solar energy from measurement and from the proposed model is the same. This model will be used in the numerical simulation as heat flux to the absorber plate of the solar box cooker.

A numerical validation test has been performed to the method before it is employed to analyse the problem. Three experiments have been carried out. The temperature history of cooking vessel at loads of 3 kg, 5 kg, and 6 kg water were selected for comparison. Here, numerical simulations using the developed method were carried out at the same load as experiments. Temperature history from numerical results and experimental results are shown in figure 3. The figure reveals that for all cases the temperature history from the experiment and numerical result do agree well. In other word, the

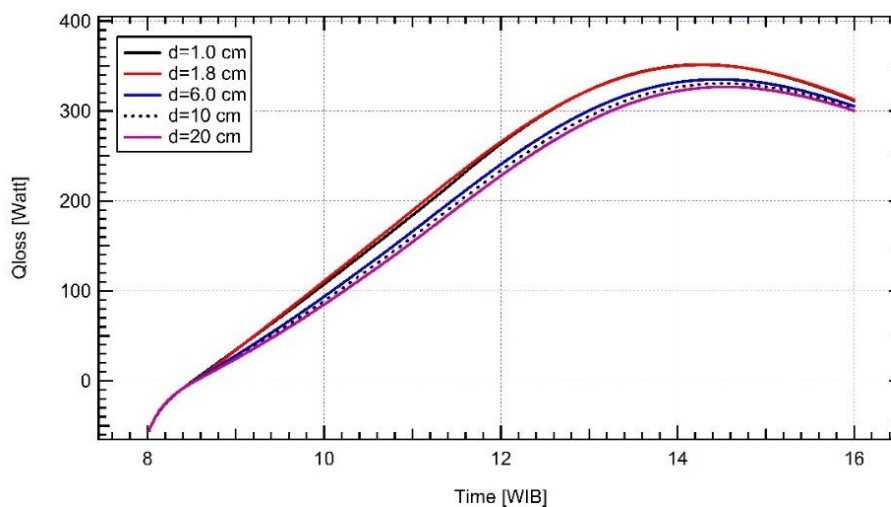
numerical simulation accurately predicts the value of temperature and the boiling time of the water. Based on the above numerical validation, it can be said that the developed numerical method can now be employed to analyse the effect configuration of the solar box cooker for boiling water.



**Figure 3.** Numerical validation of the proposed model

### 3.2. Effect of the distance of the double glass cover

The objective of installing double glass cover is to reduce the heat loss from the solar collector. In this section, the effect of the configuration of the glass cover was investigated in this section. The distance of the glass cover was varied from 1 cm to 20 cm. The heat loss from the solar collector to the surrounding as a function a time at several distances of double glass cover are shown in Figure 4. In general, the heat loss increases as time increasing and reaching a maximum at around 14.00 local time. This is because the temperature inside the solar box cooker increases with increasing time. After reaching the maximum value, the heat loss decreases with increasing time. Here, the temperature is already decreased. It can be seen that the heat loss decreases as the distance of the double glass cover decreased. This suggests that increasing the distance of the double glass cover will decrease the heat loss to surrounding. This fact should be further analysed to search the optimum distance of double glass cover.

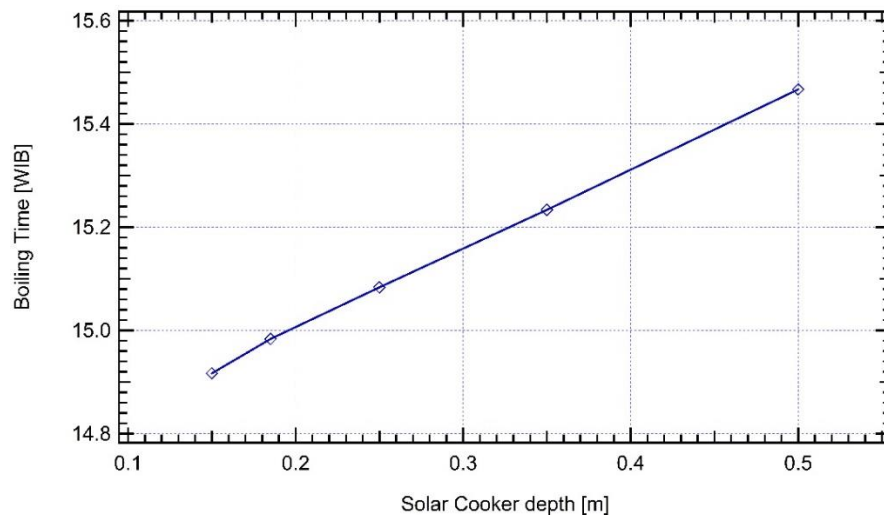


**Figure 4.** Effects of the distance of double glasses cover



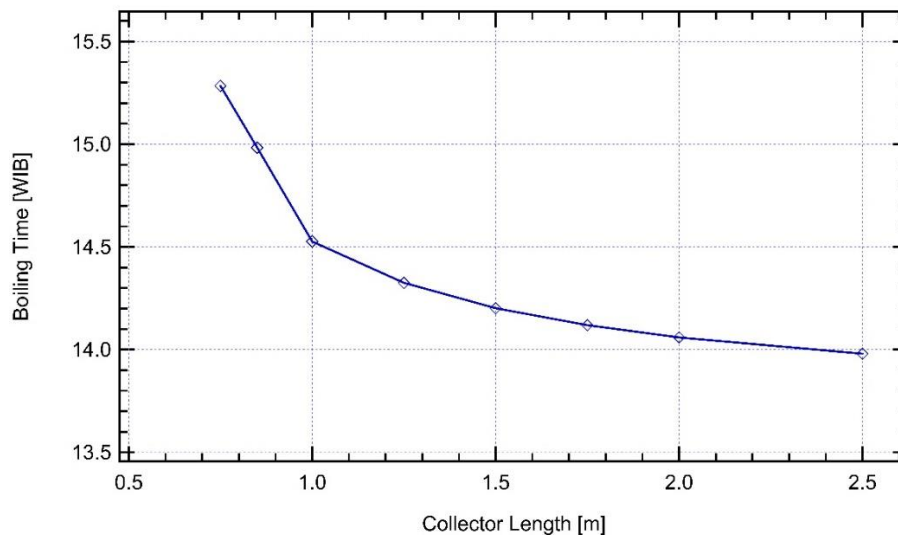
### 3.3. Effect of the Solar cooker depth

The other parameter that is investigated here is the solar collector depth. The original depth of the solar box cooker is 18.5 cm. The simulations have been performed at different depths. The depth was varied from 18.5 cm to 50 cm. The effect of the solar cooker depth to the boiling time is shown in figure 5. The figure shows that boiling time increases with increasing solar cooker depth. This is because the higher solar cooker depth will increase the area of the wall and it will increase the heat loss. In other word, the energy to heat the water in the container will decrease and as a result the boiling time will increase. This suggests that increasing solar cooker depth will decrease the performance of the solar box cooker.



**Figure 5.** Effects of the solar box cooker depth to the boiling time

### 3.4. Effect of the collector area



**Figure 6.** Effects of the collector length

The effect of the collector area to the performance of the solar box cooker is also investigated. In the present solar box cooker, the collector area is made of square plate with original dimension of 0.835 m  $\times$  0.835 m. The length of the solar box cooker was varied from 0.835 m to 2.5 m. The boiling time as a function of solar box cooker to boiling time is shown in figure 6. The figure shows that boiling time

decrease with increasing solar collector length. This is because increasing collector area will increase the solar energy collected by the solar cooker. However, the rate of increasing collector area is decreased. This is because the increasing of collector area also increases the heat loss. Figure 6 shows this fact clearly. The boiling time at collector length 2.0 and 2.5 is almost similar. This fact suggests that there exists the optimum area for maximum performance of solar box cooker.

#### 4. Conclusions

A numerical study has been carried out in order to study the effect of solar box cooker configuration. A numerical method to solve all of the governing equations has been developed. The conclusion of the study are as follows. The increasing of the distance of the double glass cover will decrease the heat loss to surrounding. The increasing solar cooker depth will decrease the performance of the solar box cooker. The boiling time decrease with increasing solar collector length. However, the rate of increasing collector area is decreased. This fact suggests that there exists the optimum area for maximum performance of solar box cooker.

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