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The study of heat transfers and thermal performance of different types of solar box cookers

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ABSTRACT

Solar fireplaces are important in remote areas with abundant solar radiation, they are a sustainable and environmentally friendly alternative to traditional cooking methods as they do not emit toxic gases. This study aims to experimentally compare solar box cookers of different designs, materials, and features to understand heat transfer and thermal performance to improve overall efficiency. Four different cases with different materials and features of the box structure are studied: Case 1 - non-tinted wooden sides, case 2 - black tinted wooden sides, case 3 - box with glass sides, and Case 4- black tinted wooden sides and coated inside with aluminum foil. Two designs are compared for each case- one with a front flat mirror and one without. All solar fireplaces consist of an inclined glass facing at an angle to the latitude of Baghdad and a base with black fins. The experiments lasted for three months in various weather conditions including cold, hot, dusty, and sunny days in southern Baghdad, Iraq, positioned at Latitude 33.2°north and longitude 44.42° East. Factors such as the intensity of incident radiation, wind speed, and ambient air temperature are taken into account during the cooking period. The results indicate that the third glass-sided box achieved the highest thermal efficiency of 93.7% after 120 minutes. The rice was fully cooked in just 97 minutes, the quickest time ever seen with this type of solar cooker, and it had a thermal efficiency of 88%. The fourth box, lined with aluminum foil inside, succeeded the third book with Rice reaching ripeness at 110 minutes with an 80.5% efficiency.

1. Introduction

A solar cooker is a device that converts sunlight into heat to cook food. It uses a parabolic mirror or small mirrors to focus the sun's rays, directing them toward the cooking pot [1]. Heat is focused, increasing the temperature of both the container and what is inside. Vapors, oil, or water are options for transferring heat to food. Solar cookers have a slower cooking time compared to traditional methods because they produce less intense heat. They play a crucial role in regions that experience intense sunlight in the middle of the day. Solar cookers are an eco-friendly option for cooking that is sustainable, as they operate without fuel and do not create harmful byproducts. Pollutants are being released into the atmosphere. They consist of mirrors, a thermal collector, and insulation. The correct orientation of the solar cooker is crucial for maximum light use [2]. Thermal performance measures, including efficiency, cooking power, and merit scores, were used to evaluate solar stoves.

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Nomenclature:

A	Area (m^2)
A_b	Area of the base of the pot (m^2)
A_c	Aperture area (m^2)
A_t	The surface area of the lid of the pot (m^2)
A_{vf}	The area of the pot walls wetted by the cooking fluid (m^2)
A_v	Area of the base of the cooking pot (m^2)
A_{ap}	Area of the absorber plate (m^2)
C	Specific heat (kJ/kg °C)
C_{ea}	Specific heat capacity of external air (kJ/kg °C) C_a= 0.718 kJ/kg. °C at constant volume & C_a=1.005 at constant pressure.
C_g	Specific heat capacity of the top surface of the glass C_g= 0.84 kJ/kg. ° C
C_{ap}	Specific heat capacity of absorber plate(kJ/kg °C) C_{ap}=0.450 kJ/kg .°C
C_{POT}	Specific heat capacity of pot (J/kg °C)
C_w	Specific heat capacity of water (J/kg °C) C_w=1.7 J/g. ° C
C	Concentration ratio
C_f	Specific heat of the cooking food (J/kg K)
E	Food energy supplied to food (J)
F'	Heat exchange efficiency factor
h_e	Convective coefficient: external surface of the wall to ambient (J/m^2 K)
H_s	The angle of the clock at sunrise or sunset
h_i	Convective coefficient: internal surface of the wall to interior air(J/m^2 K)
h_p	Convective coefficient: absorber plate to interior air (J/ m^2 K)
$h_{c,\,pair}$	Convective heat transfer coefficient from the absorber plate to the enclosed air (W/m^2 K)
$h_{c,\,vair}$	Convective heat transfer coefficient from the cooking pot to the enclosed air (W/m^2 K)
$h_{c,\,air\text{-}c}$	Convective heat transfer coefficient from the enclosed air to the lower surface of the cooker cover (W/m^2 K)
$h_{c,v\text{-}f}$	Convective heat transfer coefficient from the cooking pot to the cooking fluid (W/m^2 K)
I_{av}	Average solar radiation (W/m^2)
I_b	Beam solar radiation (W/m^2)
Is	Intensity solar radiation on a horizontal surface at the time stagnation temperature is reached (W/m^2)
k	Thermal conductivity (W/m K)
K_{ap}	Thermal conductivity (W/m K)
K_{INS}	Thermal conductivity of the absorber plate (W/m K)
L_i	Thermal conductivity of Insulation (W/m K)
L_o	Lower heating value (J/kg)
m_{ab}	Mass of the absorber plate (kg)
m_{if}	Mass of foam insulation saved (kg)
m_f	Mass of the cooking food (kg) =1.5 kg
m	Mass (kg)
m_{POT}	Mass of pot (kg)
M_W	Mass of wood saved (kg)
T	Temperature (° C)
T_{ea}	Temperature of external air (° C)
T_{ap}	Temperature of absorber plate (° C)
T_g	Temperature of glass cover (° C)
T_{ia}	Temperature of internal air (° C)
T_{pot}	Temperature of Pot cooker (° C)
T_V	Temperature of the cooking vessel (pot) (°C)
t	Time [s]
ts	Reference Time (minutes)
Δt	Time interval (seconds) (unless otherwise specified)
Q`	The rate of usable heat gain (Watt)
Greek symbols	
αv	Absorptivity of the cooking pot
τ_{hr}	Heat retention time (minutes)
τc	Characteristic boiling times (minutes)
η_u	Overall utilization efficiency(%)
ϕ	Longitude (°)
t_s	Reference Time (minutes)
N	Number of days with an absorber temperature over 100 °C
ε_g	Glass transmissivity
σ	Stefan-Boltzmann's constant ($\sigma = 5.6669 \times 10^{-8}$ W/m^2 K^4)
τ_{hr}	Heat retention time (minutes)
α_c	Absorptivity of the cooker cover
α_p	Absorptivity of the absorber plate
α	Plate absorptivity
η_{stov}	Mean efficiency of wood stoves (%)
η_o	Optical efficiency (%)
η_u	Overall utilization efficiency(%)
τs	Specific boiling times (minutes)
i_a	Interior air
a_p	Absorber plate
ea	External air
Subscripts	
g	Glass
n	Number of pots
w	Wood
th	Thickness (m)

These variables cannot be compared since they are unrelated to one another. The review study [3] looked at the box-type solar cooker's performance characteristics and the associated testing procedures to identify any commonalities using measurable criteria. This provides a method for academics to contrast and correlate various performance traits. To ascertain convection coefficients, a box-shaped solar cooker was tested and modeled in Madrid, Spain. Less than 4% of the results from a month's worth of temperature readings were used to validate the heat transport model.

The model, which also approximated the number of days in each location's year, was used to mimic Cook's performance in other nations[4]. Three solar-powered cooker systems based on the assembly were checked and calculated, including a single-stage direct heat pipe connection and a two-stage thermal coupling. The operational reliability was proved during external testing in Marburg, where the average thermal powers of the three systems were 580, 653, and 1220 Watts[5]. The untracked capacitor mounted on an inclined chassis was designed as part of the laboratory model that was developed and built.

The thermal performance of the cooker (The efficiency of the solar box cooker's heat distribution) was compared with that of a typical box-type cooker, it was found that the boiling point and the stagnation temperature were 15-22 °C higher [6]. In India, box-style solar cookers are ideal for boiling water, but they may break down or cook food slower. A study investigated design parameters, an essential factor in solar parabolic collector optimization is optical efficiency, which is the ratio of energy absorbed by the receiver to energy incident on the concentrator aperture [7], and heat capacity to evaluate thermal performance and materials.

The technique was found to sound after comparing predicted values to trial outcomes [8]. A portable Fresnel lens was used that acts as a condenser for a solar cooker. Manual tracking of the sun's zenith and Zenith angles. In addition to solar elevation or height, the solar zenith angle is the angle formed by the sun's rays and the vertical direction. It is equal to latitude minus solar declination angle, and it is at its lowest during solar noon. Ancient seafarers used this angle to navigate the oceans. Usually, it is used to find the Sun's location on Earth's surface along with the solar azimuth angle [9]. The increased ability of the cooker to concentrate sunlight on the mains when direct radiation is 712 W / m^2. Experimental tests [10] proved that the maximum temperature of the system under no-load conditions can reach 361 ^{o} C. Aluminum fins have been used in box-style solar stoves for home cooking in tropical countries. Heating of water was carried out in four cylindrical metal cooking containers with fins of 25, 35, and 45 mm in length. The results showed that the 45 mm finned design outperformed the conventional uncoated vessel in terms of thermal performance and boiling point [11]. A parallelepiped solar cooker with one reinforced Mirror has been created for effective cooking in cold weather. The Cooker consisted of a trapezoidal chamber at the top and a longer sloping southern wall, which reduced the sides facing east and West. The Cook's cooking performance measures were compared with those of stoves placed horizontally. The results showed that the tilt cooker has superior cooking performance [12]. The energy efficiency of the Fresnel lens of the magnifier equipped with a solar cooker was evaluated. The energy efficiency and the amount of Energy gained from the sun were improved by 10% and 8.52%, respectively, and the concentration of rays increased by 48.7% while reducing the reasonable heating time by 16 minutes [13]. To enhance the thermal performance, a hybrid solar box cooker was created and tested in western Uttar Pradesh, India. Heat transfer is accelerated and cooking periods are shortened, the cooker has a built-in trapezoidal channel and components when cooking, heat is delivered to the food by radiation (roasting marshmallows on fire), convection (passing icy water across food that is frozen to speed up the melting cycle), and/or conduction (cooking meat on a cooking pan lying on a heater) [14].

For heat transfer, rate of heat transfer is equal to temperature difference divided by heat flow resistance of medium [15]. To enhance thermal performance, a 200-watt halogen light and 450 hollow copper balls were used. solar box cooker produced a cooking power of 60.20 W, a thermal efficiency of 45.11%, and a total heat loss coefficient of 6.01 W/m^2 ^{o}C [16]. In remote rural areas, methods have been proposed to help with the development and efficacy assessment of solar cookers. The panel cooker was found to be the most technical possible choice. It has a typical cooking power of 46.85 W and a stagnation temperature of over 75 ^{o} C. The plate cooker's thermal efficiency was 8.13 [17]. Direct solar radiation absorbers, air heaters, and a combination of direct and indirect solar radiation have been used in solar drying. It was concluded [18] that the amount of solar energy and the design parameters depended on how well the food processing and cooking systems operated. The temperature of the hot air and the surrounding environment determine how long it will take to dry and cook. The solar cooker could complete cooking tasks without supervision thanks to using one additional reflector, which reduced tracking towards the sun for three hours. 1485 MJ of the fuel equivalent year was saved, with a payback period that varies depending on the replaced fuel (1.66–4.23 years) [19]. The solar cooker is designed for Fred Wade and has a compact size, practical design, affordable lightweight hybrid insulation, and lightweight polymer glass. Under various load conditions, the cooker has reached a high plate stagnation temperature of 144 ^{o}C [20]. A test method for developing design parameters to gauge a box-style solar cooker's thermal efficiency was proposed. Experiments conducted outside on a double-glazed cooker with a fibre body produced two figures of merit. The cooker's optical efficiency (F' η_o) and heat capacity (MC) [21] were calculated using linear regression analysis. In Razavi Khorasan Province, Iran, a study addressed [22] aspects that have an impact on the development, production, and implementation of solar energy projects. The effective marketing of solar cookers has been positively influenced by such elements as capital, financial assistance, economy, technology, infrastructure, and interactions. The design, construction, and evaluation of the efficiency of solar stoves are carried out by comparing the cooking time and energy costs with the costs of firewood, coal, kerosene, and electricity. Materials including satellite dishes, frames, steel, and aluminium foil were used to build the stoves. Stoves performed better when cooking various dishes [23]. The influence of the amount of solar energy and design parameters on how well food processing and cooking systems operate has been studied. The effect of the performance of dryers and cooking boxes on the distribution of temperature, mass, and ingredients of food was investigated [24]. Compared to conventional stoves, experiments conducted on an autonomous solar cooker powered by renewable photovoltaic energy have revealed - significant gains in cooking temperature, boiling periods, and heating speed. According to estimates, the thermal efficiency was 86%, which was a 59.2% improvement over conventional stoves [25]. The solar cooker Quonset has a dome-shaped transparent polymer glass and two cooking compartments. The thermal performance of the cooker was evaluated, and a mathematical model was provided for verification. QF (The heat it takes for food to cook) increased the cooking efficiency when used with water or glycerine, from 6 to 35% and 9 to 92%, respectively, according to the numerical results [26]. Researchers [27] evaluated the thermal performance of a box-shaped solar cooker using Fresnel lens magnifiers. The cooking power increased by 46.87 W at a temperature difference of 50 degrees Celsius and by 0.11 to 0.12 cm^2 / W when using a Fresnel lens. Researchers [28] have explored the application of porous media and barriers in solar air heaters. They talked about how various materials and barriers affect heat transfer and fluid motion and presented numerical and experimental analyses on flat solar air collectors. The results indicated that porous barriers improve heat transfer and assembly efficiency. In our current research, the Iron clamp has been developed as a base for a pot as a barrier that increases the surface resistance to absorb the heat of the Solar Beam. Gas bottles for cookers in Iraq have become expensive due to transportation costs from city centres to rural areas where solar cooker experiments were done. For low-income families unable to buy traditional fuel, a solar cooker offers a valuable and practical alternative. It is simple to use, saves money, safeguards the natural world, and enhances the well-being of communities. Marketing such cookers at competitive prices and involving local carpenters could create a successful business venture. For such cookers to be cost effective, it is crucial to enhance their thermal performance and use locally available cheap materials so that they compete with other available choices. Therefore, the present study aims to improve the thermal characteristics of solar cookers by comparing various solar box cookers in terms of design, material and features. The experiments were conducted over three months in different climates. The effects of parameters such as intensity of the incident radiation, wind speed, and ambient air temperature on cooker thermal performance are examined during the cooking period.

2. Methodology

A solar-powered cooker is a gadget that turns sunshine into energy to cook meals. It is made up of a mirror with a parabolic shape or a group of tiny mirrors that concentrate light from the sun to a single central point, aiming it toward the cooking pot. This is the spot where the heat from the sun is focused, increasing the warmth of the dish and what is inside. The meal can be cooked by applying heat through vapors, oil, or water. Since a solar cooker's heat output isn't as strong as that of a torch or traditional oven, cooking with one requires longer than cooking with straight heat from the

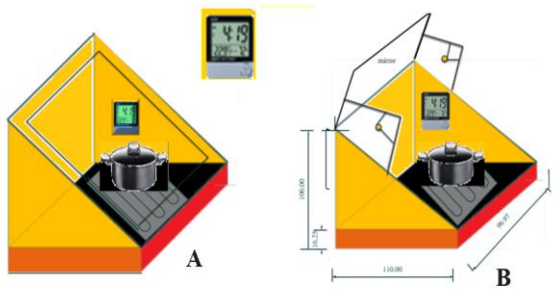

Figure 1. A Solar cooker with a black base with fins, the angle of inclination of the glass cover is 33.2 º from the horizon, uncolored wooden sides. A) Without a flat mirror; B) Equipped with a flat mirror above the side facing the sun.

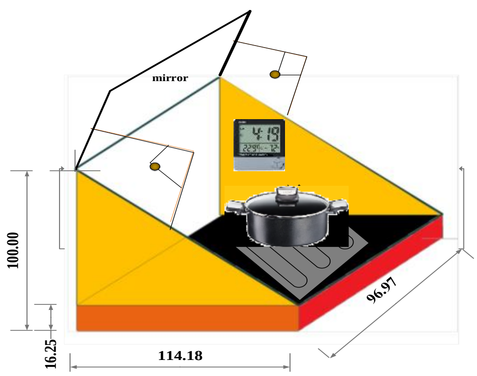

Figure 1B. Shows the real dimensions of the cook in all 8 types

Figure 2. Photos of the box solar cooker from the front, back and side and open to see inside

sun. It is crucial to utilize the solar cooker in regions that receive high solar radiation and exactly during the height of the day, while the sun's rays are at their zenith. Solar cookers are a sustainable and environmentally friendly alternative to traditional cooking methods, as they do not use fuel or produce harmful emissions to the environment. The solar cooker consists of several basic elements: mirrors or solar reflectors, a thermal collector, and insulation. These elements work together to accumulate and concentrate sunlight for cooking food. Proper orientation of solar medicine towards maximum light use is crucial. The introduction of a solar cooker may take a short time from traditional electricity stress due to the relative thermal strength generated by the sun compared to conventional sources. The device of this study is a box solar cooker with an inclined glass face at an angle of view of the city of Baghdad equipped with a fin base. The dimensions of the cooker (110 cm * 96.97 cm * 100 cm) are length, width, and height respectively, as seen in Figure 1-A. Rice with mushrooms was cooked in it and the air temperature readings inside the box were taken every half hour after the first hour the rice was stirred, and all the rice grains are cooked evenly.

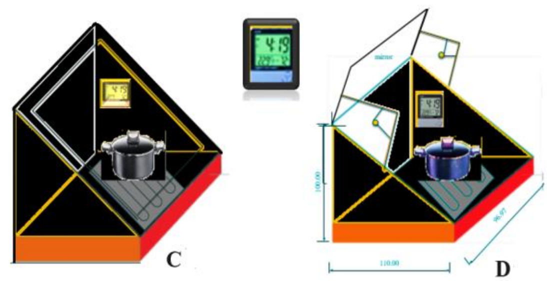

Figure 3. Solar cooker with a black base with fins, the angle of inclination of the glass cover is 33.2° from the horizon, its three wooden sides have been painted dark black. C) Without a flat mirror; D) Equipped with a flat mirror above the side facing the sun.

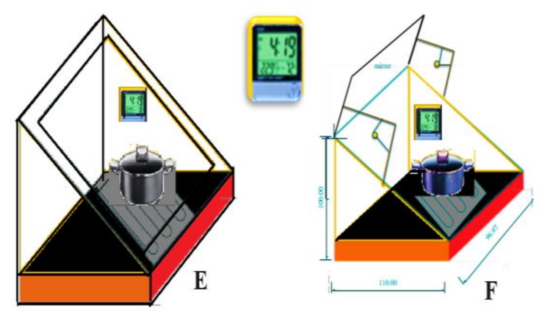

Figure 4. Solar cooker with a black base with fins, the angle of inclination of the glass cover is 33.2° from the horizon, each of its three sides is the glass from which the sun's rays penetrate the interior. E) Without a flat mirror, F) Equipped with a flat mirror above the side facing the sun.

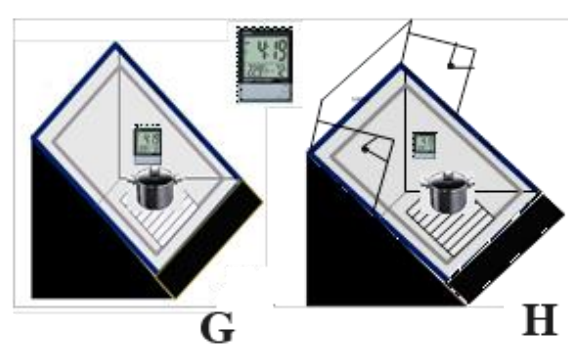

Figure 5. Solar cooker with an aluminum base with fins, the angle of inclination of the glass lid is 33.2° from the horizon; its three wooden sides are sheathed from the inside with aluminum foil and from the outside black. G) Without a flat mirror; H) Equipped with a flat mirror above the side facing the sun.

Figure 6. Weather station

Figure 7. Solar radiation

After that, a flat mirror was installed, which was installed on the side facing the sun. The temperature and ripening time data were also documented Fig. 1B, which was provided with a flat mirror. Then the three sides are painted black, the mirror is removed, and the readings are taken Fig. 3C. All these readings are written in an Excel table to compare the temperature of the air trapped inside the box, which, when heated, forms convection currents that transfer heat from it to the pot and from the pot to the rice by conduction. After that, the mirror is reinstalled on the side facing the sun and the readings are recorded Fig. 3D. The last stage replaces the wooden sides with glass and records the readings, Fig. 4E, then installs a flat mirror and records the readings, Fig. 4F. The wind speed and the intensity of the incident solar radiation are taken into account. And calculate their effect on the period of maturation of food. Fig. 3C, the box cooker with three sides painted black on the outside is used, then those sides are wrapped from the inside with aluminum foil [22], and even the base with fins is coated with aluminum or can be painted in a bright silver color, as aluminum disperses the solar rays from the window from the glass cover to the inside of the box and reflects them to hit the food container as a heat wave that cannot get out of the glass, so the heat is trapped inside the box and the temperature rises. As for Fig. 5 H, a flat mirror was connected with the Fig. 5G device at an angle of latitude of Baghdad to reflect the sunlight falling on it to the box through its glass lid to increase the amount of heat gained by the air inside the box and increase its temperature, which helps the food ripen faster.

Figure 6. Digital thermometer devices that show temperature and humidity

3. Analytical analysis

An insulator wooden box solar cooker is being developed and tested. Foam, see Table 1, is used as a thermal insulator that greatly reduces the transfer of heat to the atmosphere. The cooker's base is foam-insulated wood, painted in a dark black color that does not shine. The purpose of using a dark black color that doesn't reflect light on the base of the solar cooker is to enhance its capacity to absorb and hold heat from the sun. Dark shades absorb additional sunlight and transform it into heat energy, which is crucial for effectively cooking food in a solar oven. Moreover, selecting a non-reflective color helps the solar cooker retain heat within its insulated base, boosting its thermal efficiency. Above the base, a thermal radiator obtained from an old refrigerator (waste) is set. The radiator of which acts as an absorber. The radiator is dyed dark black. Solar radiation is carried out through the glass cover to heat the air inside the box, so convection currents are formed) as air molecules accelerate in their movement by increasing the distances between them due to heat) that transfer heat to the radiator (absorbent surface) and the walls of the black pot. Then the heat is transferred by conduction from the radiator and the walls of the pot to the food inside (rice with mushrooms). The temperatures inside the cooker box are recorded using a digital thermometer used in the research can be installed inside the box cooker, it measures the air temperature inside the box and the relative humidity, see Fig. 8.

Table 1. Physical properties of the materials used in the manufacture of solar cooker [29]

Material Description	Conductivity (W/m K)	Heat Capacity (kJ/kg K)	Density (kg/m^3)
Steel	050.00	0.480	7800
Copper	200.00	0.418	8900
Aluminium	160.00	0.896	2800
Uf Foam	000.04	1.400	0010
Air	00.030	1.005	1.184
Water	000.60	4.180	0997

The weather station device Fig. 6, is used to measure wind speed, ambient air temperature, and humidity. A device is used to measure the intensity of solar radiation, see Fig. 7. A thermocouple device is used to accurately measure temperatures Five different temperatures were monitored every 10 minutes using the Weather station in Figure 6 used for measuring the ambient air temperature from the outside and the temperature of the glass and the outer walls of the box cooker**.** The temperature of the absorbent surface (T_{ap}), the air temperature inside the box (T_{ia}), the temperature of the wooden walls of the box from the inside (T_w), the temperature of the air surrounding the solar cooker (T_e), and the temperature of the glass cover (T_g). The intensity of solar radiation (I_r) is also measured using a device shown in Fig. 7. The tests were conducted in the southern city of Baghdad, the Tigris district, located on Latitude= 33.31 North, and longitude Lo=44.3 °East. The solar cooker was directed towards the sun all the time.

3.1 The theoretical model

A model of heat flow in a solar cooker was presented that takes into account the relationships between heat balance and heat retention [4]. The focus was all on conduction and convection processes while ignoring the radiation exchange. The convection coefficients were changed to meet the experimental results taking into account convective heat transfer and radiation effects. Heat loss due to air conduction between the cooker and the surrounding environment was also ignored. The current model shows a comparison of the amount of heat transfer and thermal efficiency in eight models of a solar cooker with an insulated wooden base, painted in dark black, and an old refrigerator cooler with fins painted in Black is placed on it that works as an endothermic part and a bowl of food is placed on it that is also selected in black Fig. 1A. Taking into account the relationship between heat balance and heat retention the box for Case 1 is a solar cooker, which will be the standard that compares with the other cases.

3.2 Mathematical background

The solar energy that penetrates through the double-glazing reaches the absorber surface because the inside walls of the solar cooker are coated with a reflected aluminum layer. The absorbent surface distributes heat to the air within the cooker as well as the foam at the bottom of the surface. Eq. (1) depicts the thermal balance of the absorber plate [30]. The heat transfer conducted from the absorber plate to the wall and the glass window by the air within the solar cooker. The thermal equilibrium, [4], of the air within the cooker is shown in Eq. (2).

$$\left.\begin{aligned} I_b\tau_c\alpha_{ap}(A_{ap}-nA_t) &= h_{r,ap-c}(A_{ap}-nA_t)(T_{ap}-T_c)+\\ &+\left(\frac{K_{ap}}{X_{ap}}\right)nA_b(T_{ap}-T_v)+\\ &+h_{c,p-air}(A_{ap}-nA_b)(T_{ap}-T_{air})+\\ &+h_{c,v-air}nA_v(T_v-T_{air})+U_bA_{ap}(T_{ap}-T_a)+\\ &+\varepsilon_p\sigma\alpha_cA_c(T_{ap}^4-T_c^4)+\varepsilon_p\sigma\tau_cA_c(T_{ap}^4-T_s^4) \end{aligned}\right\} \quad (1)$$

$$\left.\begin{aligned} m_{ap}C_{ap}\frac{dT_{ap}}{dt} &= I\tau^2\alpha A_g - h_pA_{ap}(T_{ap}-T_{ia}) -\\ &-\frac{k_{ap}A_{ap}}{th_{ap}}(T_{ap}-T_c) \end{aligned}\right\} \quad (2)$$

The heat transfer conducted from the air within the box to the wood and from the absorption plate (finned) to the bottom of the cooker is included in the equation of the thermal equilibrium of the foam Eq. 3. The heat equilibrium, Eq. 4, for walls made of wood takes into account heat transmission from the foam to the outside air. A conduction heat transfer term through the wood as well as a convective heat transfer term from the outside layer of the wood to the atmosphere makes up the heat transfer from the internal surface of the wood to the external air as Eq. 5 [13].

$$\left.\begin{aligned} m_{ia}C_{Pa}\frac{dT_{ia}}{dt} &= h_pA_{ap}(T_{ap}-T_{ia}) - h_i\left[(A_c-A_{ap})\right.\\ &\left.(T_{ia}-T_c)+A_g(T_{ia}-T_g)\right] \end{aligned}\right\} \quad (3)$$

$$\left.\begin{aligned} m_fC_f\frac{dT_c}{dt} &= h_i(A_f-A_{ap}).(T_{ia}-T_f)+\\ &+\frac{k_{ap}A_{ap}}{th_{ap}}(T_{ap}-T_f)-\frac{k_fA_f}{th_f}(T_f-T_w) \end{aligned}\right\} \quad (4)$$

$$m_wc_w\frac{dT_w}{dt} = \frac{k_fA_f}{th_f}(T_f-T_w) - \frac{A_w}{\frac{th_w}{k_w}+\frac{1}{h_e}}(T_w-T_{ea}) \quad (5)$$

For ambient air (external air) [13]&[31] For the black cooking vessel pot as Eq. (6) [13]. For the black absorbent surface for all cases Eq. (7) [31]. The rate of usable heat gain (Q) by cooking food per unit area is given by the Hottel-Wilier-Bliss model (HWB) as Eq. (8) [26]. The η_o represents optical efficiency, I_{av} represents average total irradiance, U_L represents heat loss factor, C represents concentration ratio, T_{mf}. represents mean food temperature, $\bar{T}_a$ represents average ambient temperature, and F́ represents heat exchange efficiency factor [31]. Where H_s represents the angle of the clock at sunrise or sunset, and Ta the ambient temperature.

$$\left.\begin{aligned} h_{c,p-air}(A_{ap}-nA_b)(T_{ap}-T_{air})+\\ +h_{c,v-air}nA_v(T_v-T_{air}) = h_{c,air-c}A_c(T_{air}-T_c) \end{aligned}\right\} \quad (6)$$

$$\left.\begin{aligned} I_b\tau_c\alpha_vnA_t+\left(\frac{K_{ap}}{X_{ap}}\right)nA_{ap}(T_{ap}-T_v) = \\ h_{cvf}nA_{vf}(T_v-T_f)+h_{c,v-air}nA_v(T_v-T_{air}) \end{aligned}\right\} \quad (7)$$

$$\dot{Q} = \acute{F}[\eta_oI_{av} - (\frac{U_L}{C})(T_{fm}-\bar{T}_a) \quad (8)$$

$$\acute{F} = T_g\sum_{n=1}^{\infty}[(1-A_p)R_g]^n F_{inc} \quad (9)$$

$$\eta_oH_s = U_L(T_{ap}-T_a) \quad (10)$$

F_1 acts as the ratio of optical efficiency to the heat loss factor. The total heating efficiency (η_u), specific (t_s), and characteristic (t_c) boiling durations are essential assessment factors for the thermal performance of various solar cooker designs. The following equations are used to compute η_u, t_s, and t_c as in Eqs. (11-13) [26].

$$\frac{\eta_o}{U_L} = \frac{T_{ap}-T_a}{H_s} = F_1 \quad (11)$$

$$\eta_u = \frac{(MC)_f(T_{f,max.}-T_a)}{\bar{I}_sA_{ap}\Delta t} \quad (12)$$

$$t_s = \frac{\Delta tA_c}{M_f} \quad (13)$$

$$t_c = \frac{t_sI_{av}}{I_{av}^*} \quad (14)$$

$$\eta_o = \dot{Q}_{useful}/\dot{Q}_{sun} \quad (15)$$

When I_{av} is the mean solar intensity (W/m^2) throughout the period t, and I_{av} is an average sun intensity of 900 W/m^2[26]. To calculate the optical efficiency of a solar cooker, the heating power of the cooker is considered as power output, and it is expressed mathematically as in Eq. (9).

4. Results and discussion

The main details in Fig. 9 will be elaborately discussed. The relationship between the intensity of solar radiation (watts per square meter) with time in minutes from nine in the morning to four in the afternoon. It is noted that the highest value of the solar radiation intensity (800-900 W/m2) is between one and three o'clock in the afternoon when the sun's Rays are perpendicular to the Earth. The value increases as the air temperature increases until it reaches a value of more than 1000 W /m2. Increasing the intensity values of solar radiation increases the speed of maturation of food in the solar cooker. In Fig. 10, case A shows the relationship between the temperatures of both the absorbent surface (the base of the box from the inside), the air inside the cooker box, and the air outside the box, the glass lid, and the wood of the box walls with the time interval of food ripening. It turned out that the highest temperature reaches 81 °C on the absorbent surface after 120 minutes of exposure to sunlight, followed by the air temperature inside the cooker box, and reaches 47 °C after 120 minutes.

Table 2 The table below shows the specific heat of some materials[29]

Material	specific heat Joule /(kg. °C)
Water	4180
Olive oil	1971
Aluminum	895
Plain glass	832
Copper	389

The highest temperature of the air surrounding the stove is 39 °C after 120 minutes, followed by the glass temperature reaching 26 °C after 120 minutes. As for the highest grade of wood from the sides, it reaches 16 °C after 120 minutes. The reason for the maximum temperature difference is the heat conduction of the material, so it was found that the Iron billet (Thermal conductivity coefficients of iron =80 (W/ m. K) at 20°C and 1 bar) base is the highest temperature because it has the highest absorption and conduction of heat ,see Table 2.

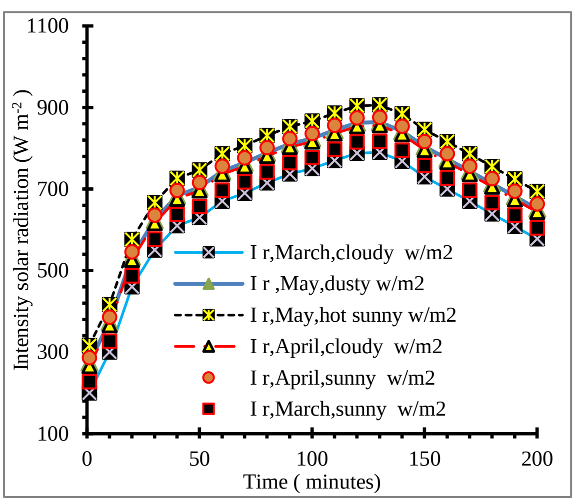

Figure 9. The correlation between the strength of sunlight and the hours of the day (from 9 am to 4 pm)

Figure 11 Case B is the same relationship between the temperatures mentioned in Fig. 10 and the ripening period of rice with mushrooms with different temperature values, where the temperatures have increased (absorbent surface, incoming air, ambient air, wood, and glass) due to the flat mirror that reflects the solar rays falling on it on the glass lid, and from it to the black pot containing the food, where they collide with the glass and are reflected inside and absorbed by the base and the walls of the pot; thus, temperatures increase from Case A between $1-5C^{\circ}$, which increases the speed of maturation of food that has gained heat by conduction from the walls of the pot and by convection from the convection currents formed inside the box from heat waves.

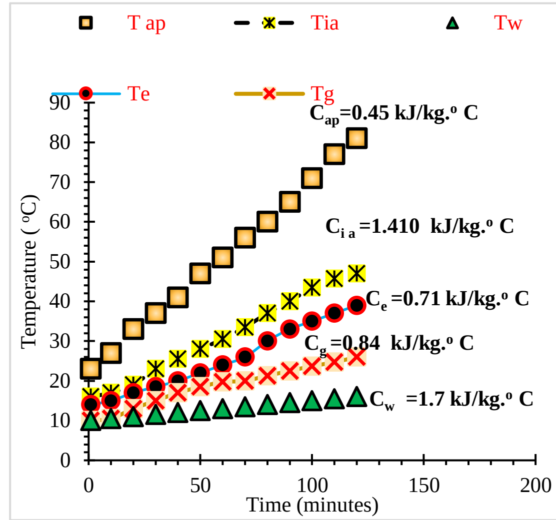

Figure 7. Case A The temperature of the pallet, air inside and outside the box, wood, and glass all impact how long it takes for rice with mushrooms to ripen.

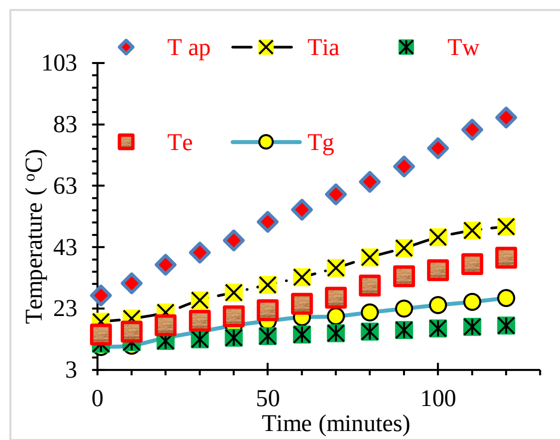

Figure 8. Case B The connection between the temperature of the pallet, the air inside and outside the box, wood, and glass with the maturation time of rice with mushrooms.

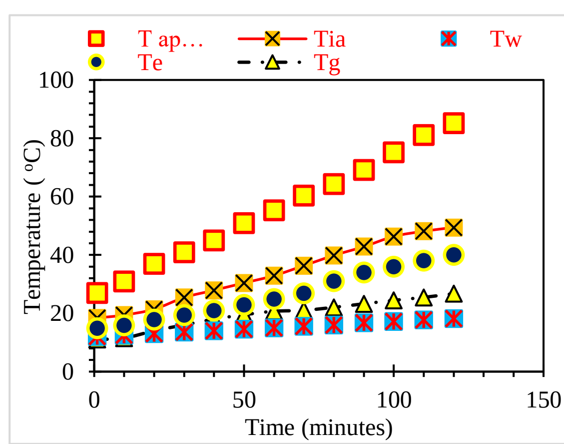

Figure 9. Case C The connection between the pallet temperature, air inside and outside the box, wood, and glass with the ripening time of rice with mushrooms.

There are various reasons why the glass temperature of a solar cooker may decrease, mainly stemming from heat transfer dynamics and environmental influences. Here are a few reasons why this could occur:

1. Loss of heat to the surroundings
   1.1 Radiative Heat Loss: The glass can release heat by emitting infrared energy to the colder environment, particularly when solar radiation is low, like in the late afternoon or on overcast days.
   1.2 Convective Heat Loss occurs when wind or air flow across the glass increases convective heat transfer, resulting in the glass cooling down.
2. Variations in the brightness of the sun
   2.1 Diurnal changes: Solar radiation decreases naturally in the late afternoon or on cloudy days, causing less energy to be absorbed by the glass.
   2.2 Temporary shading, whether caused by clouds, trees, or other objects, can decrease the solar radiation reaching the glass, leading to a decrease in temperature.

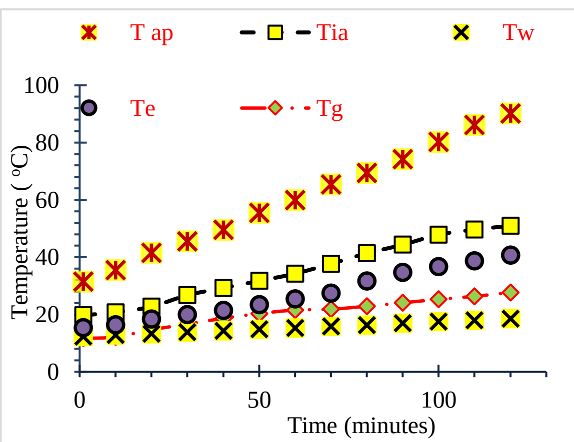

Figure 10. Case D The correlation between the temperature of the pallet, air inside and outside the box, wood, and glass and the maturation time of rice with mushrooms.

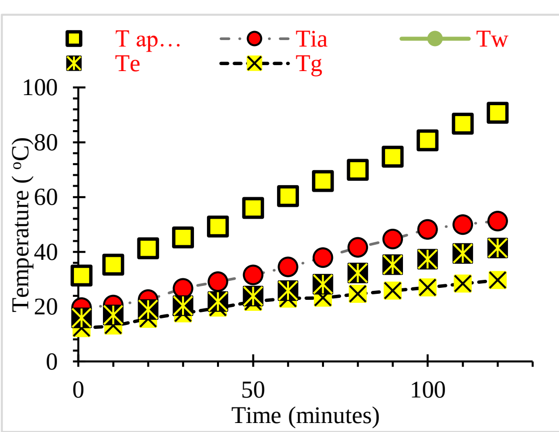

Figure 11. Case E The relationship of the temperature of the pallet (the base of the cooker), the air inside and outside the box, wood and glass with the ripening period of rice with mushrooms

3. Distribution of heat within something.
   3.1 Heat redistribution occurs as the solar cooker's interior heats up, allowing for more uniform distribution of heat within the cooker. The glass, after absorbing a lot of heat at first, could pass on some of this heat to the air and cooking vessel inside the cooker, causing its temperature to drop.
   3.2 Thermal Equilibrium: As time passes, the temperatures of the glass, the air inside the cooker, and the cooking vessel might reach a state of equilibrium. During the heating of the air and cooking vessel, the glass temperature may decrease slightly as part of the balance that occurs.
4. Glass has moderate thermal conductivity, efficiently transferring heat to air and surroundings. Contact with cold air can lower temperature. Thermal mass affects temperature variations, with glass releasing heat faster than it absorbs it after sun exposure weakens.

Heat loss, solar radiation fluctuations, internal heat distribution, glass properties, and airflow impact the glass temperature of a solar cooker. Understanding these factors is crucial for improving solar cooker performance and efficiency. Fig. 12 case C is the same relationship between the temperatures mentioned in Figure 10 and the ripening period of rice with mushrooms with different temperature values, where the temperatures increased (absorbent surface, incoming air, ambient air, wood, and glass) due to the coloring of the wooden walls of the box in a floating black color without a flat mirror. The increase in temperatures was recorded due to the black color, which can absorb heat then store it, which leads to heat transfer from the highest degree part, which is the wall, to the lowest degree, which is the air inside and outside the box, and convection currents are formed that increase the heating of the base and the pot, i.e. absorbed by the base and the walls of the box.

Figure 13 case D represents the relationship between the temperatures mentioned in Figure 10 and the ripening period of rice with mushrooms with different temperature values, as in Figure 3-D, where a flat mirror was connected, the temperatures increased (absorbent surface, incoming air, ambient air, wood, and glass) due to the coloring of the wooden walls of the box in floating black and with the mirror level. Here is the increase in temperature recorded due to the Black color that absorbs heat, as shown in Fig. 12, and the increase in temperature also due to the connection of the plane mirror, as shown in Fig. 11. So the increase in temperatures becomes 1- 9. 5 °C, that is, the increase by 11.11%.

Figure 14 case E represents that the duration needed for rice with mushrooms to mature is dependent on a number of factors, including the temperature of the pallet, the air inside and outside the box, wood, and glass. as in Figure 4-E, where the wood walls are replaced by glass walls, allowing sunlight to penetrate from all four sides. Temperatures (absorbent surface, incoming air, ambient air, wood, glass) increase without attaching the mirror flat. Here is the increase recorded in temperatures due to glass, where the percentage of increase in temperatures became 15.4% that represents the percentage of increase in air temperature inside the box cooker between the first type and the sixth type with glass walls and equipped with a flat mirror.

In Fig. 15 case F shows the relationship between the temperatures mentioned in Figure 10 and time. As can be seen in Fig. 4-F, the solar cooker has four glass sides, and a flat mirror is attached, which leads to recording the highest temperature increase for the absorbent surface, as it reached 97 °C, which is the highest degree for all other cases, as well as for other degrees (the air temperature inside the box reaches the highest 54.5 °C, the air surrounding the box is 43 °C, the walls, and the glass cover are 31 °C), that is, the percentage of increase between 7 to 16 °C by 20% over the first case A. In Fig. 16 case G shows the relationship between the temperatures mentioned in Fig. 10 and time. As can be seen in Fig. 5-G, the solar cooker has black-painted wooden walls. The new thing in this case is aluminum foil is used to wrap the base of the box. This leads to an increase in the temperature of the absorbent surface, where it reaches 94 o C, and the air temperature inside the box reaches a high of 53 o C, the air surrounding the box is 41 o C, and the glass cover is 32 o C, as for the black wallpaper wood) that is the percentage of increase between 5 to 13 o C by 16% from the first case A. Figure 17 case H shows the relationship between temperature and time for the case of the solar cooker shown in Figure 5-H, whose base and sides are coated with aluminum foil and a flat mirror is attached to it, so the results of high-temperature readings are very close to case F, as the aluminum foil acts as a mirror reflecting the solar rays that reach it, but in a scattered reflection and absorbs part of it because it is a good conductor of heat. Since the light waves are converted under the glass cover into long heat waves that do not penetrate the glass, they are reflected from it back to the black absorbent surface with the walls of the black pot of food, which increases the temperatures as shown in Table 1.

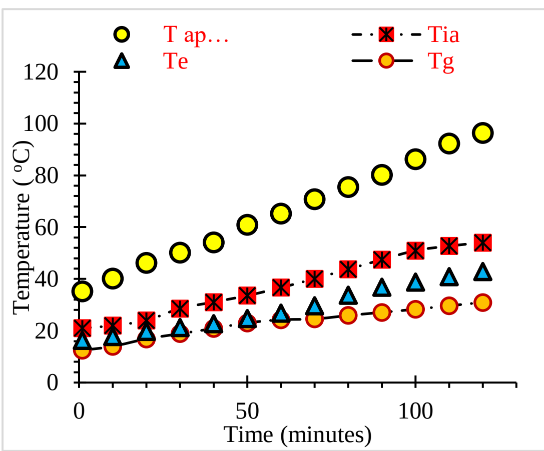

Figure 12. **Case F** The connection between the temperature of the cooker base, the air inside and outside the box, wood, and glass affects how long it takes for rice with mushrooms to ripen.

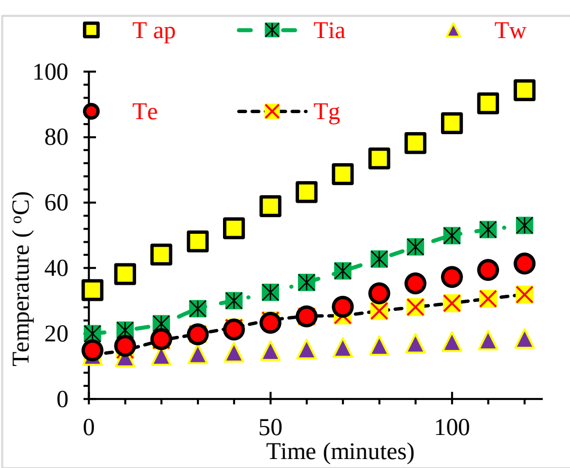

Figure 13. **Case G** The way that the temperature of the pallet (the cooker's foundation), the air inside and outside the box, the wood, and the glass relate to how long rice takes to ripen with mushrooms.

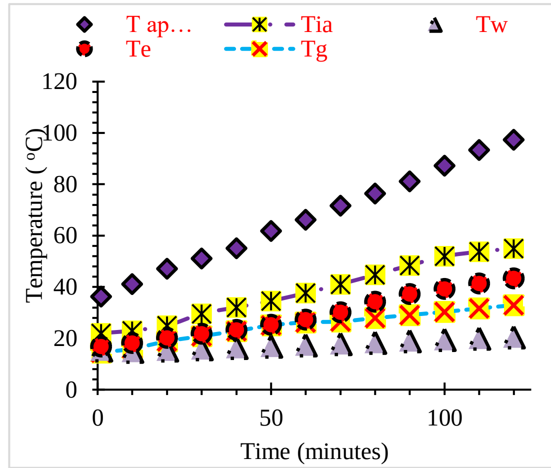

Figure 14. Case H The interaction between the rice and mushroom ripening period and the temperature of the pallet, the air within and outside the box, wood, and glass.

Figure 18 shows the relationship between the cooking pot temperatures for case A-H within 120 minutes. It is noted that the highest recorded degrees are for case F because the walls of the box solar cooker are made of glass and connected to a flat mirror, which increased the temperatures of the absorbing surface due to the influence of solar rays inward from all sides, as well as the mirror reflected the Rays incident on it and carried out from the glass top cover. The temperature values for the cooking pot are shown in Table 2. The heat that the pot first gained from conduction was transferred to it by the heat from the finned absorbent surface. Secondly, the convection currents formed from the movement of hot air inside the box due to the high air temperature by the window rays from the glass, which is the heat transfer by radiation, and the Convection currents are formed after heating the air.

Figure 19 shows the amount of heat gained by the cooking pot which led to the maturation of rice with mushrooms and its relationship to time within two hours. It is noted that case F and followed by case H are the most heat-gaining cases due to the increase in temperature of the pot and the absorbent surface (the finned base of the cooker) as explained in the discussion of Figs. 15-18 G, H, E, F with glass walls with or without the plane mirror and aluminum foil-coated walls with or without the plane mirror**.**

In Table 4, the temperatures of the black cooking pot were recorded in the eight types of cookers a-h over a period of 2 hours for each type.

Typically, the glass temperature in a solar cooker is higher than the air temperature inside the box. Here is an explanation of the reason for this occurrence. Explanation: Explanation: Assimilation of Sunlight: Glass surface. Solar cooker glass allows shortwave radiation to pass through but absorbs some of it, which is the main reason why the glass heats up. The energy directly absorbed heats up the glass surface. The air inside the sealed container under pressure:

The solar cooker box indirectly warms up the air inside. The inside of the cooker is warmed by sunlight passing through the glass and heating surfaces like the dark absorber plate and cooking pot. These surfaces transfer heat to the air through conduction, convection, and radiation

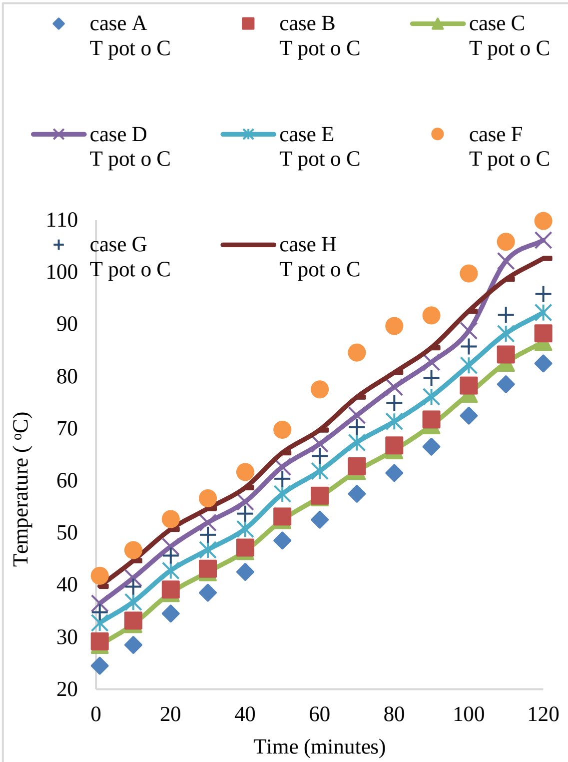

Figure 15. The correlation between the eight examples' (A through H) cooking pot temperatures and the amount of time needed for the rice with mushrooms to mature

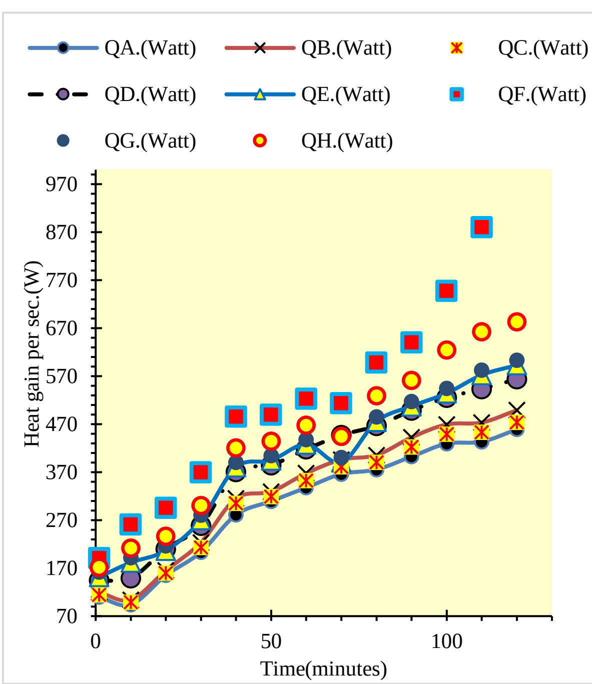

Figure 16. The connection of the cooking pot heat gain per second of the eight cases (A to H) with the time

Table 3. Values of the black-finned absorbent surface temperatures for cases from A-H within 120 minutes

time min.	case A T_{ap} °C	case B T_{ap} °C	case C T_{ap} °C	case D T_{ap} °C	case E T_{ap} °C	case F T_{ap} °C	case G T_{ap} °C	case H T_{ap} °C
1	23	27.9	26.9	34.3	31.3	37.8	33.3	36.3
10	27	31.9	30.9	40.2	35.3	45.2	38.2	43.7
20	33	37.9	36.9	46.2	41.3	51.2	44.2	49.7
30	37	42.9	40.9	50.2	45.3	57.3	48.2	53.7
40	41	46.9	44.9	54.9	49.3	62.3	52.2	59.7
50	47	52.9	50.9	61.7	55.9	69.9	58.9	66.4
60	51	58.1	55.4	66.1	60.4	74.4	63.3	70.8
70	56	63.1	60.4	72.3	65.7	80.6	68.8	76.9
80	60	67.1	64.4	76.9	69.9	85.3	73.5	81.7
90	65	72.6	69.1	81.7	74.6	91.1	78.2	86.4
100	71	78.6	75.1	88.6	80.6	98.	84.2	93.3
110	77	84.6	81.1	94.7	86.7	104.	90.3	99.4
120	81	88.6	85.1	98.7	90.7	108	94.3	103

Ways in which heat is transferred: Glass is a transparent, long-lasting material used for manufacturing drinking glasses and windows, among other items. The primary reason for the glass heating up is the direct absorption of solar light. Therefore, it can achieve a higher temperature more rapidly. When the cooker comes into touch with hot materials and absorbs the infrared radiation they emit, heat is produced inside the cooker. Air has a reduced capacity for heat absorption and transfer in comparison to solid materials like glass. Therefore, it heats up more slowly and typically does not reach the same high temperature as glass. Transfer of heat and ability to retain heat: A transparent material made from sand that is utilized for windows, containers, and mirrors. Glass has a moderate ability to conduct heat and holds more heat**.** Figure 20 shows the relationship of optical efficiency (equation 14) and time within two hours. It is noted that case F and followed by case H are the most efficient cases due to the increased amount of heat gained by the pot, the absorbent surface, and the air inside the box. As applied in equation 9, optical efficiency increases by increasing the difference between the temperature of the absorbent surface, and the temperature of the air surrounding the box and by reducing the amount of heat lost (thermal losses) from the sides and the glass cover. Figure 21 shows the relationship between the total efficiency, the value of which directly depends on the mass of the food to be cooked and increases with an increase in the temperature difference between the temperature of the cooked food and the air surrounding the cooker, and inversely with the values of both the intensity of solar radiation, the area of the absorbed surface, the ambient temperature of the Cook and the average time required for the maturation of food, where the longer the period for the maturation of food, the less efficiency. Therefore, delta T is a key milestone in determining the preference for one type of box solar cooker over another.

Different climatic conditions during the three months (March, April and May) can affect the warming of the absorbent surface in the solar cooker complex as follows:

1. Sunlit environment: The sun is quite brilliant on apparent sunny skies, which boosts the quantity of energy from the sun that is accessible. This implies that a lot of sunlight will be directed onto the absorbing outer

layer of the solar cooker collector, successfully converting it into as a result, on bright days, the absorbing layer is going to warm up more quickly.

2. Overcast climate: Because of the clouds in the atmosphere, the sun is less brilliant during overcast days. This implies that smaller solar light will be absorbed by the absorbent surface and converted to heat. Therefore, during gloomy days as opposed to sunny ones, the outside temperature of the absorbing layer will be reduced
3. Dusty environment: Sand and dust can collect on the surface of the solar cooker as well as in the atmosphere during dusty weather. This buildup might make it more difficult for solar light to reach the absorbing surface, which would lower the quantity of solar energy collected and have a detrimental effect on the absorbent surface's heating.
4. High temperatures with high storms: The wind may help to somewhat chill the absorbing area on hot days with strong gusts. Strong winds may Disperse the heat generated by the absorption of solar light, reducing the temperature rise of the absorbent surface slightly. In general, climatic conditions such as the brightness of the sun, clouds, dust, air temperature, and wind affect the amount of solar energy received and thus the rise in the temperature of the absorbing surface in the solar cooker Collector. As shown in Figs. 22 and 23.

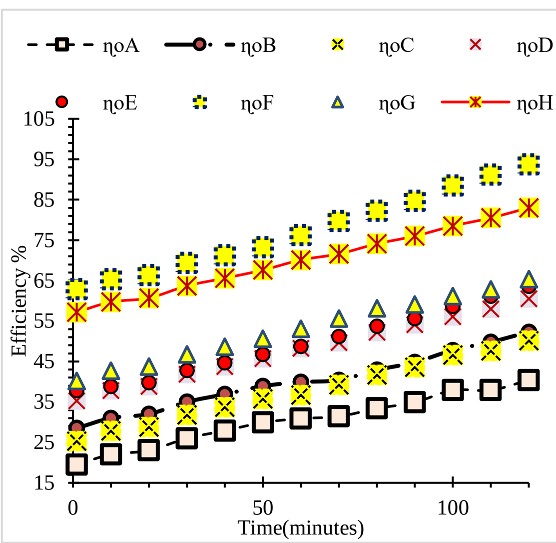

Figure 18. The association between the optical efficiency of the eight cases (A to H) with the time

Table 4. Physical properties of materials [32]

Material	Density kg/m³	Melting Point °C	Reflectivity	Absorptivity	Conductivity W/(m•K)
Aluminium	2700	660.3	0.85	0.07	237
Glass	2500	1400	0.05	0.90	0.78
Stainless Steel	8000	1371	0.65	0.35	16.3
Copper	8960	1085	0.75	0.25	401
Silver	10490	961.8	0.97	0.02	429

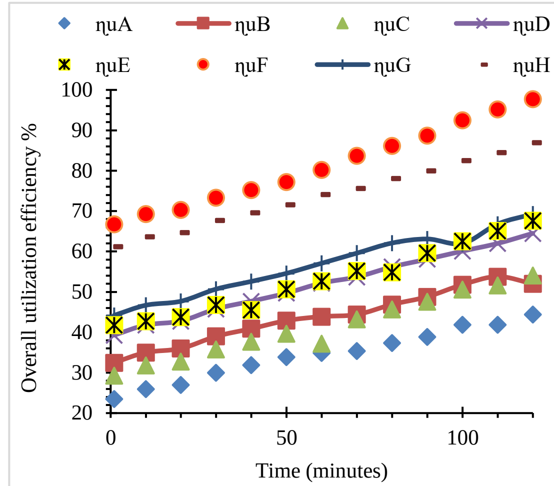

Figure 17. The affiliation between the Overall utilization efficiency of the eight cases (A to H) with the time

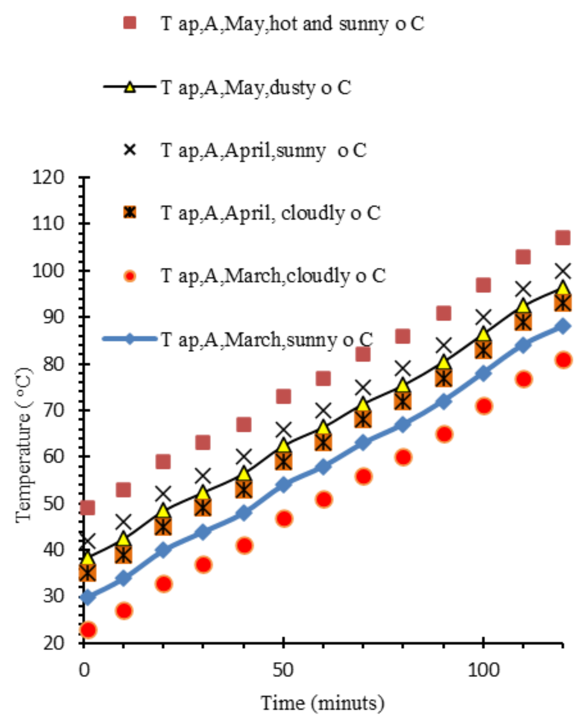

Figure 19. Case A. The correlation between the temperature of the absorber plate in ° C and the duration of two hours in varying weather conditions

The research focuses on the uncertainties in measurements caused by bias and precision errors, emphasizing the difficulty of accurate estimations in outdoor settings. A method suggested by [33] is used to calculate bias error uncertainty more precisely.

Table 5. Estimate the temperatures of the black-colored cooking pot for cases from A-H within 120 minutes

Time (Min.)	case A T_{pot}	case B T_{pot}	case C T_{pot}	case D T_{pot}	case E T_{pot}	case F T_{pot}	ase G T_{pot}	case H T_{pot}
01	24.5	29.8	28.5	36.5	32.7	42.3	34.8	39.8
10	28.5	33.9	32.5	41.4	36.8	49.7	39.7	47. 2
20	34.5	39.9	38.5	47.4	42.8	55.7	45.7	53.2
30	38.5	44.9	42.5	51.0	46.8	61.8	49.7	57.2
40	42.5	48.9	46.5	55.9	50.8	66.8	53.7	63.2
50	48.5	54.9	52.5	62.7	57.5	69.8	60.4	69.9
60	52.5	59.9	56.8	67.1	61.9	77.5	64.8	74.3
70	57.5	65.6	61.9	72.6	67.4	84.6	70.3	81.3
80	61.5	69.6	65.9	77.9	71.4	89.7	74.9	85.9
90	66.5	75.1	70.6	82.7	76.1	98.6	79.7	90.7
100	72.5	81.6	76.6	88.7	82.1	106.5	85.8	98.6

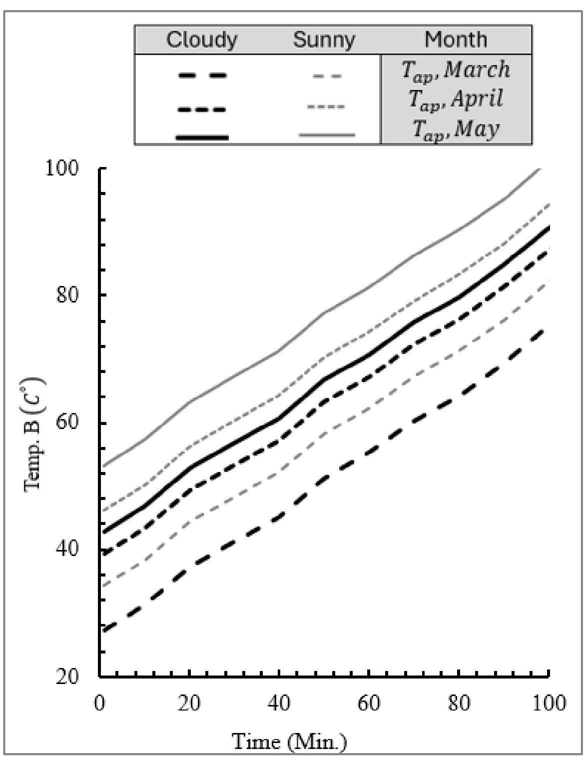

Figure 20. Case B. The association between the Temperature of the absorber plate, ° C, and the time through two hours in different climatic conditions

Table 6. Uncertainty Analysis of the Measured Value [33]

Parameter	Standard value	Uncertainty	Relative error, 10^{-3}
Temperature of external air	14 – 67.43	± 0.41	6.100
Temperature of absorber plate	24 –116. 6	± 0.70	6.053
Temperature of glass cover	10 – 32.95	± 0.21	6.500
Temperature of internal air	16– 55.03	± 0.36	6.470
Temperature wood	10 – 20.50	± 0.15	7.500
The rate of usable heat gain	93– 838.5	± 4.60	5.500
Intensity solar radiation	316 – 906	± 6.11	6.740
Efficiency	19– 86.98	± 0.53	6.120

5. Conclusion

Solar fireplaces are crucial in remote areas with high solar radiation, offering a sustainable and eco-friendly cooking solution without harmful emissions. This study compares different solar box cooker designs to enhance efficiency. Four cases with varying materials and features are tested in Baghdad, Iraq, considering factors like radiation intensity and ambient temperature. Results showed that a box with glass sides performed best, followed by a box coated with aluminum foil. Figure 9 explores the correlation between solar radiation intensity and time, peaking around midday. The intensity increases food maturation in a solar cooker. In Figure 10, temperatures inside and outside the cooker rise with food ripening. Figure 11 shows a rise in temperatures due to a flat mirror reflecting solar rays. Figure 12 demonstrates increased temperatures with black-colored wooden walls. Figure 13 adds a flat mirror to raise temperatures further. Figure 14 replaces wood walls with glass, rising temperatures. Figure 15, with a flat mirror and glass walls, record the highest temperatures. Figure 16 use aluminum foil to boost temperatures. Figure 17 shows foil and mirror temperature. Figure 18 shows the highest cooking pot temperatures in case F. Figure 19 notes the most heat gained by the cooking pot in cases F and H. Figure 19 illustrates the correlation between a cooking pot's heat gain per second and time for eight cases labeled A to H. The graph shows how the heat gain fluctuates over time for each case, indicating variations in the cooking process. This visual representation allows for a clear comparison of the energy transfer rates in the different scenarios. By analyzing the data presented in Fig. 19, individuals can understand the heat transfer efficiency in various cooking situations and make informed decisions about optimizing the cooking process. Ultimately, this graph provides valuable insights into heat transfer dynamics in cooking pots and highlights the importance of monitoring and adjusting heat levels to achieve desired cooking outcomes. Figure 19 illustrates the heat gained by a cooking pot affecting the maturation of rice with mushrooms over two hours. Cases F and H show the highest heat gain due to an increased pot temperature and absorptive surface. Figure 20 demonstrates that cases F and H are the most efficient, with increased heat absorption by the pot, the absorptive surface, and the air inside the box. Optical efficiency, as per equation 9, increases alongside the difference in temperature between the absorptive surface and surrounding air and reduced thermal losses. Figure 21 shows total efficiency depending on food mass, temperature difference, solar radiation, absorptive surface area, ambient temperature, and maturation time. Delta T is crucial in selecting a solar cooker type. Climatic conditions affect surface warming in different scenarios. Figure 22 depicts the relationship between the temperature of the absorber plate and time in various climates, such as sunlit environments leading to faster warming.

This study explores the impact of various weather conditions on the efficiency of solar cookers. Overcast days reduce the amount of solar energy absorbed due to less sunlight. Dusty environments hinder the solar light's ability to reach the absorbing surface, thus decreasing energy collection. High temperatures with strong winds slightly chill the absorbent surface. Factors such as sunlight brightness, clouds, dust, air temperature, and wind influence the solar energy received.

6. Recommendations

Recommendations for developing a box-type solar cooker include improving thermal insulation with materials like polystyrene, using an endothermic substance such as a metal solar panel, covering the top with tempered glass, using heat-reflecting glass, providing ventilation holes for airflow, placing a thermometer inside for temperature control, positioning in a sunny area, enhancing cooking capacity through design changes, and testing modifications for ongoing improvement.

Suggestions provided can enhance the effectiveness and functionality of box-style solar cookers. Modifications can be made based on individual needs. Research in solar energy and sustainability informed the Boxy Solar Cooker standards, focusing on energy efficiency, reduced cooking time, and eco-friendly materials. The cooker is a boxy device using solar energy for heating and cooking, encapsulated in an insulated box to preserve heat. Future enhancements could include the use of magnifying mirrors or solar panels to maximize sunlight collection and focus, along with better insulating materials like double glazing for increased heat retention.

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript".

Author Contribution Statement

Ekram H. Alaskaree designed and fabricated the solar cookers, developed the methodology, carried out the experiments, interpreted the results and drafted the first version of the manuscript. Ahmed Alammar contributed to the writing of the manuscript and revised the first and final draft.

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Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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