研究論文

Thermal Performance of Box Type Solar Cooker: A Study in Japan Climate

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Abstract

In this paper, a box type solar cooker was designed and its thermal performance was tested according to the ASAE International Test Standards procedure and Bureau of Indian Standards (BIS) for testing the thermal performance of box type solar cooker. Thermal performance experiments for the first figure of merit *(F_1)* and the second figure of merit *(F_2)* and cooking power *(P)* were found acceptable and satisfying the ASAE and BIS limits. Experiments were conducted at the Satellite Venture Business Laboratory, Mie University, Tsu City, Mie, Japan (at the Longitude 136°31' & Latitude 34°44' respectively).

Key Words: Solar Cooker, Figure of Merit, Cooking Power, Solar Energy, Performance Test

1. Introduction

Generally solar cookers are thermally rated according to (i) stagnation plate temperature (first figure of merit) and (ii) time required to bring a known amount of water nearly to the boiling point i.e. heat up condition (second figure of merit). Mullick et al.[1] developed a thermal test procedure for box type solar cookers. P.Funk[2, 3] specified a test procedure for evaluation of the thermal performance of a box type solar cooker in terms of effective cooking power, which accounts for the heat gain rates.

This test procedure was developed as American Society of Agricultural Engineers (ASAE) standards for testing the thermal performance of a box type solar cooker. Buddhi et al.[4] has reported the effect of load on the second figure of merit. This paper presents a feasibility study of a box type solar cooker in Japan and reports thermal performance according to ASAE International Standard Procedure & BIS (Bureau of Indian Standards) as a part of Indian Standard IS 13429 procedure[5]. Experiments were conducted for the load of 1.0, 2.0 and 3.0 kg of water respectively. Thermal performance experiments for the first figure of merit *(F_1)* and the second figure of merit *(F_2)* and the cooking power *(P)* were found acceptable and satisfying the ASAE and BIS limits. Experiments were conducted at the Satellite Venture Business Laboratory, Mie University, Tsu City, Mie, Japan (at the Longitude 136°31' & Latitude 34°44').

2. Figure of Merit F_1 and F_2

Figures of merits F_1 and F_2 were determined by conducting the stagnation temperature test (without load) and by sensibly heating a known amount of water respectively.

First Figure of Merit "F_1"

In case of flat plate collectors, to find the heat loss factor U_L, experimentally water is circulated through the tubes at different temperatures and observations are recorded in steady state. In a solar cooker, there is no control over the temperature and the operation is transient. A quasi- steady state is achieved when the stagnation temperature is attended. The energy balance horizontally placed empty solar cooker at stagnation is:

$$\eta_o G_s = U_L (T_p - T_a) \tag{1}$$

The ratio of optical efficiency ($\eta_o = \alpha\tau$) to heat loss factor (U_L) can serve as one figure of merit for thermal performance. The ratio of *(η_o/U_L)* is termed, as First Figure of merit "F_1" The first figure of merit, F_1, is defined as:

$$F_1 = \frac{\alpha\tau}{U_L} = \frac{T_p - T_a}{G_s} \tag{2}$$

Second Figure of Merit "F_2"

Analyzing over an infinitesimal time interval during the sensible heating of water, the time is taken as:

$$d\tau_c = \frac{(MC)_w dT_w}{Q_u}$$

$$= \frac{(MC)_w \cdot dT_w}{AF'(\eta_o G - U_L (T_w - T_a))} \tag{3}$$

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Replacing the ratio η_0/U_L by the factor F_1, equation (3) can be written as:

$$d\tau_c = \frac{(MC)_w dT_w}{AF'\eta_o\left(G-\left(\frac{1}{F_1}\right)(T_w - T_a)\right)} \qquad (4)$$

Assuming the insolation G and ambient or surrounding air temperature T_a are constant (as would strictly be the case if experiments were performed with the help of solar simulator in an air condition of laboratory), equation (4) can be intergraded over the time period t_1 to t_2, during water temperature rises from Tw_1 to Tw_2

$$(t_2 - t_1) = \frac{-F_1(MC)_w}{AF'\eta_o}\ln\left[\frac{G-\frac{1}{F_1}(T_{w2}-T_a)}{G-\frac{1}{F_1}(T_{w1}-T_a)}\right] \qquad (5)$$

Rewriting the equation (5),

$$F'\eta_o = \frac{F_1(MC)_w}{A(t_2-t_1)}\ln\left[\frac{1-\frac{1}{F_1}\frac{(T_{w1}-T_a)}{G}}{1-\frac{1}{F_1}\frac{(T_{w2}-T_a)}{G}}\right] \qquad (6)$$

The factor $\frac{F_1(MC)_w}{A(t_2-t_1)}\ln\left[\frac{1-\frac{1}{F_1}\frac{(T_{w1}-T_a)}{G}}{1-\frac{1}{F_1}\frac{(T_{w2}-T_a)}{G}}\right]$ is termed as "F_2".

$$F_2 = F'\eta_o = \frac{F_1(MC)_w}{A(t_2-t_1)}\ln\left[\frac{1-\frac{1}{F_1}\frac{(T_{w1}-T_a)}{G}}{1-\frac{1}{F_1}\frac{(T_{w2}-T_a)}{G}}\right] \qquad (7)$$

First figure of merit "F_1" tells about the ratio of the optical efficiency ($\alpha\tau$) and heat loss *(U_L)* factor in the box type solar cooker. Second figure of merit "F_2" tells about the product of the heat exchange efficiency factor *(F')* and optical efficiency ($\eta_o=\alpha\tau$). For the solar cooker, a high optical efficiency ($\eta_o=\alpha\tau$) and high heat exchange efficiency factor (F') with low heat loss factor (U_L) are desirable. Bureau of Indian Standards (BIS) has suggested the lower limit of F_1 and F_2 are 0.12 and 0.40 for the load of 8 kg/m^2 of the aperture area. These lower limits were proposed in Indian Standards IS 13429 procedure[6).

3. Calculating Cooking Power

The cooking power, *P (W)*, of solar cooker is defined as:

$$P = (T_f - T_i)\frac{(MC)_w}{600} \qquad (8)$$

To calculate it, the change in water temperature for each ten-minute interval was multiplied by the mass, M_w (kg), and specific heat capacity, C_w (J/kgK), of the water in the cooking vessel. This product was divided by the 600 seconds contained in a ten-minute interval.

Cooking power for each time interval was transferred to a standardized cooking power, P_s, by multiplying the cooking power, P_i, from equation (8) multiplied by the standard insolation, 700 (W/m^2), and dividing by the average insolation, I_i, recorded during the corresponding interval.

$$P_s = P_i\left(\frac{700}{I_i}\right) \qquad (9)$$

where P_s is the standardized cooking power.

The average insolation, average ambient air temperature and average water temperature were found for each interval.

The temperature difference, T_d, was obtained by subtracting the ambient temperature from the water temperature of cooking vessel for each time interval.

$$T_d = T_w - T_a \qquad (10)$$

4. Design And Thermal Performance Test

A double glazed box type solar cooker with reflector was designed and fabricated at the Workshop of Mie University. The dimensions of the outer box were 710x710x300 mm^3 and the inner box were 500x500 mm^2 at the top and 480x480 mm^2 at the bottom (absorbing tray) with 190 mm height. The space between the outer box and inner box was filled with glass wool insulation. The box type solar cooker is made of 1 mm thick galvanized aluminum sheet. The two ordinary clear window glasses with spacing of 5 mm covers the top aperture of the cooker and was used for trapping the heat using the green house effect and minimizing the rate of heat loss through the top of the solar cooker. A silicone sealant (CEMEDINE 8060, Japan) was filled on the edges of the frame to prevent any heat leakage. A reflector with the dimensions of 520x520 mm^2 was used for reflecting the solar radiation onto the absorbing plate of the solar cooker. The absorbing plate was painted with black board paint. The thermal performance tests for F_1 and F_2 were conducted as per BIS and cooking power evaluation by International Standards in the months of April & May 2002.

Type "T" calibrated thermocouples were used to measure the temperatures for the absorbing plate, water and ambient air respectively. The accuracy of the thermocouple was ± 0.2°C. Thermocouple was welded at the center of the absorbing plate to measure its temperature. For the water temperature inside the cooking pot, thermocouple was inserted through the cooking pot lid. For the ambient air temperature, thermocouple was kept in the shadow with well contact in the air. All thermocouples were connected with a data logger (Solac III , MP-090, Japan) to record the temperature with the interval of 15 seconds. Solar radiation was measured with a Pyranometer (EKO, MS-801). Thermocouple positions in solar cooker are shown in Fig.1 (a). The cooker direction was adjusted to the sun direction with a 30 min. interval. The designed cooker is given schematically in Figure 1(a) and a photograph is shown in Figure 1(b).

4.1 Stagnation Temperature Test

To determine the first figure of merit F_1, solar cooker without reflector was exposed to the solar radiation at about 10 A.M. Global solar radiation on horizontal surface, plate temperature and ambient temperature were recorded at a interval of 15 second simultaneously till the stagnation condition was reached.

4.2 Heat up Condition Test

To determine the second figure of merit F_2, the solar cooker without reflector was loaded with a known amount of water at 50±5°C temperature. Solar radiation, ambient air temperature and water temperature were recorded at a interval of 15 second till the water temperature exceeded 95 °C. To calculate F_2, initial and final water temperatures were chosen between 60 to 65 and 90 to 95 °C respectively.

4.3 Cooking Power Test

Cooking power, P, and standardized cooking power, P_s, was calculated by the equations (8 &9). The Standardized cooking power, P_s, was plotted against the temperature difference, T_d, for each time interval. Temperature difference, T_d, was calculated by the equation (10). A linear regression of the plotted points was used to find the relationship between cooking power and temperature difference in terms of intercept, W, and slope, W/°C. We evaluated the thermal performance of the box type solar cooker according to the international standards of American Society of Agricultural Engineers (ASAE), and in this standard we have to use linear fit. Furthermore, this evaluation is in safer side. The Figures 5, 6 and 7 shows that the experimental cooking power P_s (W) has higher value than the cooking power predicted by linear regression equation.

The coefficient of determination, R^2, or proportion of variation in cooking power that can be attributed to the relationship found by regression should be better than 0.75 according to P. Funk[2, 3] The value for standardized cooking power, P_s, was calculated for a temperature difference, T_d, of 50 °C using the above determined relationship.

5. Results And Discussion

Solar cooker performance experiments were conducted in April and May 2002. Temperature for absorbing plate, ambient air temperature, water temperature and solar radiation were measured during the experiments.

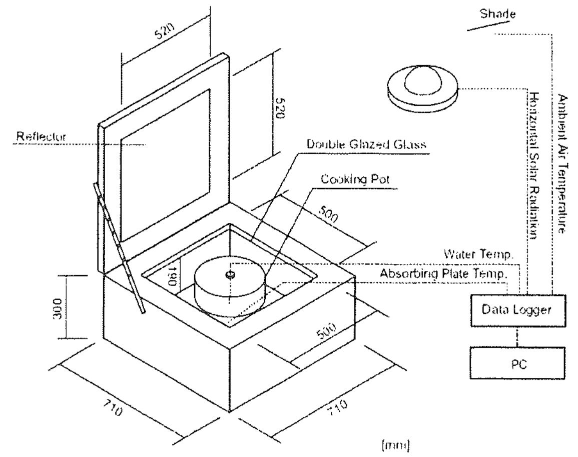

Fig. 1 (a): Schematic Diagram of Box Type Solar Cooker

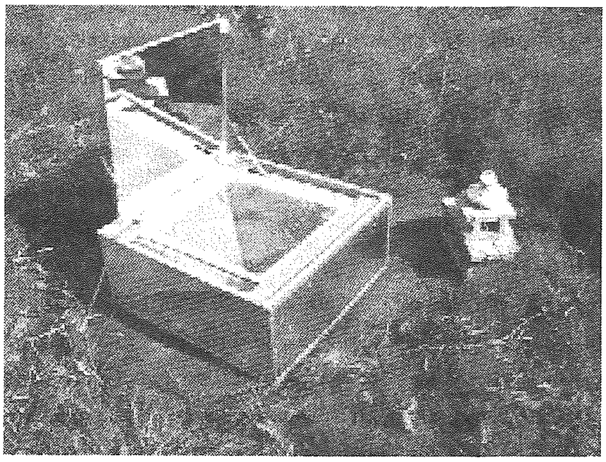

Fig 1(b): A photograph of the box type solar cooker

The figures of merits ($F_1$and F_2) were calculated for the present box type solar cooker. For the first figure of merit F_1, experiment was conducted on 19th March 2002. Solar cooker was exposed at 10 A.M. without reflector. Stagnation condition was achieved at 12:55 P.M. Solar radiation, ambient air temperature and absorbing plate temperature were measured for 15-second interval. At the stagnation condition, average values for the consecutive three-stagnation temperature of absorbing plate, average value for three consecutive ambient air temperature and average value for three consecutive solar radiations were 115.2 °C, 20.5 °C and 763 W/m^2 respectively. The first figure of merit F_1 was calculated using equation (2) as per the stagnation thermal performance test. F_1 for the present box type solar cooker was found 0.124 and acceptable as per the suggested value by Mullick et al.[1].

To determine the second figure of merit F_2, experiments were conducted with 1.0, 2.0 and 3.0 kg load of water respectively. F_2 was calculated by using equation (7) for each load of water.

Experiments were conducted in April – May 2002. Solar cooker was exposed at 10 A.M. with the different load of water and without reflector. Quantity of loaded water, Tw_1, Tw_2, (t_2-t_1), *and* G during the time (t_2-t_1) and the calculated value for the second figure of merit F_2 were tabulated in Table 1. Experiments for second figure of merit F_2 were conducted as per the heat up condition test. From the Table1, it was observed that the value of F_2 may depends on the quantity of water loaded in the solar cooker, but its reason is not clear at the present study.

Cooking power experiments were conducted in April 2002. Experiments were conducted for the load of 1.0 kg, 2.0 kg and 3.0 kg of water on 15th April 2002, 26th April 2002 and 13th May respectively. Solar cooker was exposed at 10 A.M. with the different load of water and closed at 3 P.M. for each experiments. Maximum temperature of absorbing plate and water for the load of 1.0 kg, 2.0 kg and 3.0 kg were 100 °C, 100.5 °C, 100.7 °C, 102 °C and 100.5°C, 102.1°C respectively. Solar radiation on the horizontal surface and ambient air temperature were also measured for each experiments. The temperature profiles of the absorbing plate temperature, loaded water temperature and solar radiation on horizontal surface on the day of 15th April 2002, 26th April 2002 and 13th May are plotted in Figures 2, 3 and 4 respectively. From the Figures, any one can see the water temperature was reached 100°C in Japan spring climate conditions. Water temperature slightly exceeds 100°C in Figures 2, 3 and 4 due to the higher pressure than 760 mmHg in the cooking pot because the cooking pot was covered with a lid and kept inside the inner box of the solar cooker and transparent double glazed glass with 5 mm gap between them covers the inner box of the cooker. At this temperature (100°C), the cooker is able to cook the food. During the cooking experiments, when water temperature of solar cooker is over 100°C, vapors deposition and condensation was observed on the interior surface. A same phenomenon has reported by Malik and Hussen[7]. This is because the opening of the solar cooker was provided through the sliding of the double glazed glass. This can be overcome by sealing the double glazed glass permanently and having the cooker opening from either wall.

Figure 4 shows the temperature variation up to 6 P.M. while the cooker was closed after 3:30 P.M due to low solar radiation. Water temperature was observed 60 °C at 6 P.M. So, if once food was cooked then we can get warm food in evening time too.

The standardized cooking power was calculated for the load of 1.0, 2.0 and 3.0 kg of water from the equations (8-10) and plotted against the temperature difference for each time interval.

Table 1.: Variations of the second figure of merit 'F_2' with quantity of loaded water.

M_w* (kg)	T_{W1} (°C)	T_{W2} (°C)	$(t_2 - t_1)$ (s)	T_a (°C)	G (W/m²)	F_2
1.0	60.5	94.5	6645	26.6	764	0.257
2.0	60.5	94.5	9260	20.1	856	0.322
3.0	60.6	94.5	10665	24.2	881	0.558

*This is the loaded mass of the water. The mass of the water was not measured at the end of the experiments.

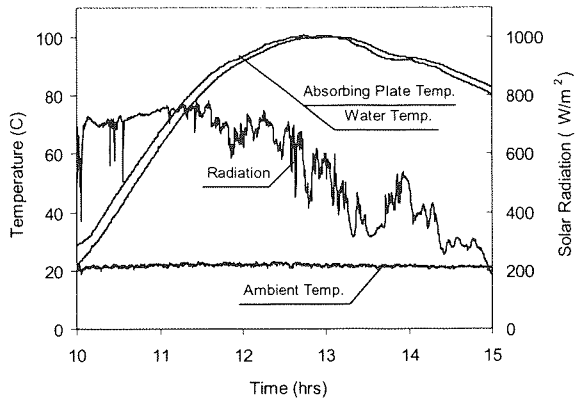

Fig.2: Variations in Temperatures for Box Type Solar Cooker (Water=1.0kg, 15 April, 2002)

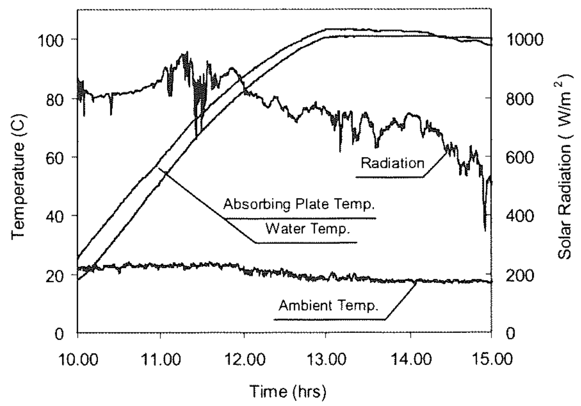

Fig. 3: Variations in Temperatures for Box Type Solar Cooker (Water = 2.0 kg, 26 April, 2002)

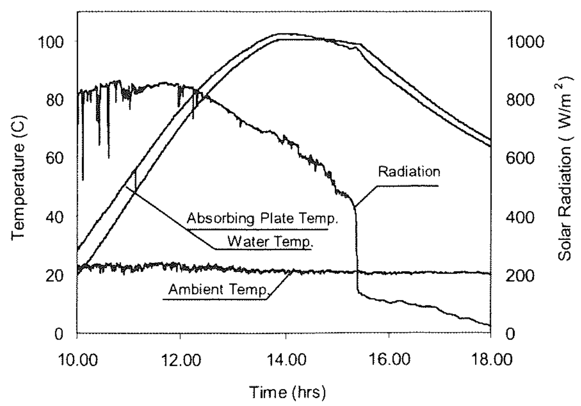

Fig. 4: Variations in Temperatures for Box Type Solar Cooker (Water=3.0kg, 13 May, 2002)

Table 2: Variation of Cooking Power Regression Equation (Intercept & Slope) and Cooking Power at 50 °C.

Date	M_w (kg)	Cooking Power Regression Equation		Cooking Power (W) at 50°C
		Intercept (W)	Slope (W/°C)	
15 April , 2002	1.0	57	- 0.594	28
26 April, 2002	2.0	71	- 0.905	57
13 May, 2002	3.0	76	- 0.606	62

Table 3: Thermal Efficiency for the box type solar cooker on different day

Date	M_w (kg)	T_{wmax} (°C)	T_{avg} (°C)	ΔT(°C) $= T_{wmax} - T_{avg}$	Δt (s)	I_{avg} (W/m^2)	Thermal Efficiency η (%)
15th April, 2002	1.0	100	26.6	73.4	9990	750.0	16.4
26th May, 2002	2.0	100.7	20.1	80.6	11745	812.8	28.2
13th May, 2002	3.0	100.5	24.2	76.3	14790	790.4	32.7

The variations in standardized cooking power and temperature difference for the load of 1.0 kg, 2.0. kg and 3.0 kg were shown in Figures 5, 6 and 7 respectively. These Figures have shown the standardized cooking power as a function of temperature difference on different day and load of water. A linear regression of the plotted points was used to find the relationship between the cooking power and the temperature difference in terms of intercept, W, and the slope, W/ °C.

The coefficient of determination, R^2, or proportions of variation in cooking power for different loads (1.0, 2.0 and 3.0 kg) were found 0.86, 0.82 and 0.88 and satisfying the ASAE International Test Standards. According to the ASAE International Test Standards, the coefficient of determination, R^2, should be better than 0.75[3]. The regression equation coefficients and the cooking power at 50 °C were presented in Table 2. Cooking power results were found within the range of the ASAE International Test Procedure.

The thermal efficiency of the solar cooker is obtained from the following relation

$$\eta = \frac{M_w C_w \Delta T}{I_{avg} A_c \Delta t} \qquad (11)$$

where I_{avg} does not include the reflected solar radiation by the reflector but the thermal efficiency (η) includes this effect. Thermal efficiencies were calculated using the above relation for the load of 1.0 kg, 2.0 kg and 3.0 kg of water and tabulated in Table 3. From Table 3, it was observed that considerable difference in thermal efficiency was noticed only for the 1 kg and 3 kg cases. Box type solar cooker has shown high efficiency for the load of 3 kg. Thermal efficiency of the cooker was found 32.7 % for the load of 3 kg. However, thermal efficiencies for 2 kg and 3 kg show similar values.

Thermal efficiency of the solar cooker depends on many factors like solar radiation, wind velocity, mass of the loaded water, time taken to boil the water, control of the reflector etc. So, lots of experiments will be needed to fully understand their effects on thermal efficiency.

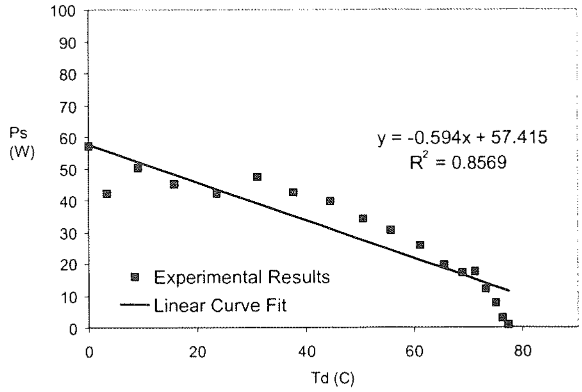

Fig. 5: Standardized Cooking Power (Ps) against the Temperature Difference (Td) (Water=1.0kg, 15 April, 2002)

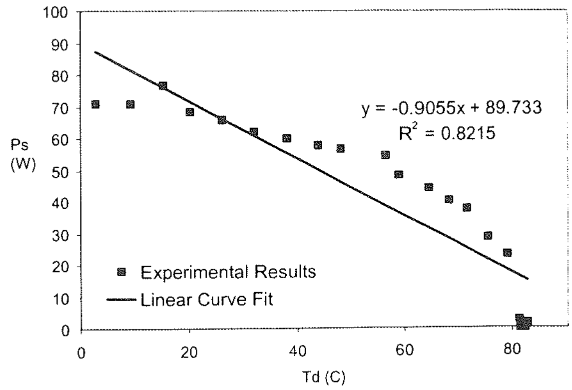

Fig. 6: Standardized Cooking Power (Ps) against the Temperature Difference (Td) (Water = 2.0 kg, 26 April, 2002)

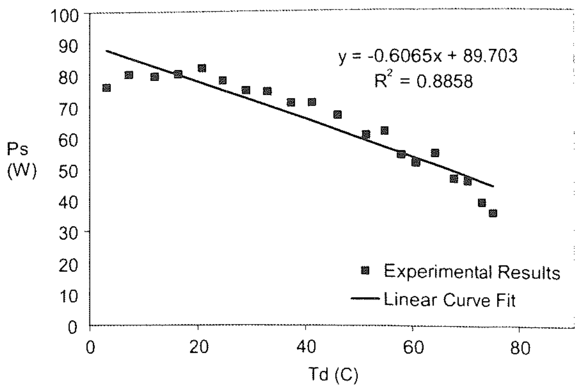

Fig. 7: Standardized Cooking Power (Ps) against the Temperature Difference (Td) (Water=3.0kg, 13 April, 2002)

The Present box type solar cooker has shown the best performance and highest efficiency for the maximum load.

6. Conclusion

The experimental results show that figures of merits (F_1 & F_2) and cooking power satisfied the BIS and ASAE International Standards for thermal performance testing of the box type solar cooker. F_1, F_2 and cooking power were found acceptable and satisfying the standards (ASAE & BIS) limits. The thermal efficiency of the box type solar cooker was 32.7% for the water load of 3.0 kg. The present box type solar cooker has shown the best performance and highest efficiency for the maximum load. Box type solar cooker was found feasible in Japan for the spring months. Solar cooking promotes the use of renewable solar energy and represents the simplest application of solar thermal energy and has a potential to reduce conventional fuels and CO_2 pollution.

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Nomenclature

A	Aperture area of the cooker of cover plate (m^2)
C_w	Specific heat of the water (J/kg°C)
F_1	First figure of merit from stagnation test (m^{2o} C/W)
F_2	Second figure of merit
F'	Heat exchange efficiency factor
G	Average global solar radiation over time period $t_2 - t_1$ (W/m^2)
G_S	Global solar radiation during steady state (W/m^2)
I_i	Average interval solar radiation (W/m^2)
I_{avg}	Average solar radiation between the period $(t_2 - t_1)$
M_w	Mass of water (kg)
P	Cooking Power (W)
P_i	Interval Cooking Power (W)
P_s	Standardized Cooking Power (W)
Q_u	Rate of useful heat gain by water (W)
T_a	Average air temperature over time period $t_2 - t_1$ (°C)
T_d	Temperature Difference (°C)
T_f	Water temperature at the end of the 10-minute interval
T_i	Water temperature at the beginning of the 10-minute interval
T_P	Plate temperature at stagnation (°C)
T_w	Water Temperature (°C)
T_{w1}	Lower value of water temperature for evaluating the F_2 (°C)
T_{W2}	Upper value of water temperature for evaluating the F_2 (°C)
T_{wmax}	Maximum water temperature (°C)
ΔT	Temperature difference of T_{wmax} and T_a
$(t_2 - t_1)$	Time taken for heating from Tw_1 to T_{W2} (seconds)
Δt	$(t_2 - t_1)$ (seconds)
U_L	Heat loss coefficient of the cooker ($W/m^{2o}C$)
α	Absorbitivity of cooking tray
τ	Transmittivity of glass
η	Thermal efficiency
η_o	Optical Efficiency

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