

Comparative Study of the Performance of Black-Coated and Reflecting-Surface Solar Box Cookers and a Parabolic Dish Solar Cooker

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ABSTRACT

The thermal performance of a two-compartment solar box cooker and a parabolic dish solar cooker were experimented and compared under same environmental conditions at [name of laboratory/workshop], Bali Town, Taraba State, Nigeria. The identical box compartments (aperture 0.334 m² each) shared one glazing and two booster mirrors; one had black-coated inner surfaces (SC.B) and the other reflecting walls with a black floor (SC.RB). The dish (P.SC) had an aperture of 0.950 m². Stagnation, four-day water-boiling (1 kg of water per pot), heating-and-cooling and single-day rice-cooking tests were carried out. The measured four-day mean maximum water temperatures were 95.1 °C (SC.B), 95.0 °C (SC.RB) and 81.0 °C (P.SC), and the cooling time constants were 182–270 min for the box pots against 50–60 min for the dish pot. Both compartments cooked 1 kg of parboiled rice (maxima 98.3 °C and 97.5 °C), whereas the dish reached only 78.6 °C. The derived first figure of merit was 0.117 (SC.B) and 0.119 (SC.RB) K m² W⁻¹, at the grade A/B boundary. SC.RB heated faster during the first 100 min, but the daily maximum temperatures, useful energies and efficiencies of the compartments did not differ significantly. Referred to the glazed aperture and global irradiance, each compartment was 2.3 times as efficient as the dish (9.7% against 4.2%); allowing for the booster-mirror radiation and for the beam-only acceptance of the dish reduces this ratio to about 1.2. These findings apply only to the prototypes, loads and weather conditions tested.

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INTRODUCTION

Cooking with firewood and other solid fuels remains widespread in Nigeria: over 175 million Nigerians rely on traditional biomass, more than 83% of the population lacked access to clean cooking in 2021, and household air pollution caused more than 128,000 deaths in the country in 2019 (Yetano Roche et al., 2024). Worldwide, about 2.1 billion people cook with polluting fuels and inefficient stoves, and household air pollution is responsible for an estimated 2.9 million deaths a year (WHO, 2025). Solar cooking offers a way to reduce these health burdens, together with local forest degradation and greenhouse gas emissions (Saxena et al., 2022). Solar cookers are broadly classified as box, concentrating and panel types (Aramesh et al., 2019). The solar box cooker uses solar radiation transmitted through a transparent glass cover and absorbed by a dark surface to heat food; it is a simple, low-technology device available in a wide variety of designs, and the way heat is gained, stored and

lost in it determines its performance. The parabolic dish concentrates the direct (beam) component of solar radiation onto a pot at its focus and can reach high temperatures quickly, but it must track the sun and leaves the pot exposed to the surrounding air (Lentswe et al., 2021). Test procedures and equations for assessing the thermal performance of solar cookers have been presented by Mullick et al. (1987, 1991), Shaw (2002) and Kundapur and Sudhir (2009), and a method for measuring cooking efficiency across cooker types has recently been proposed by Bigelow et al. (2024).

The finish of the inner walls is expected to influence the heat transfer in a box cooker in competing ways. A black wall absorbs most of the solar radiation that reaches it; it therefore becomes hot, heats the enclosed air by convection and exchanges long-wave radiation with the pot, but it also increases the conduction loss through the side insulation. A reflecting wall absorbs little and stays cooler, and it redirects part of the incident radiation onto

the black floor and the pot; however, part of the reflected radiation is returned towards the glazing and lost through it, particularly when the sun is low, and the low emittance of a reflecting surface reduces its long-wave exchange with the pot. The net effect therefore depends on the geometry of the compartment, the view factors between the walls and the pot, the angle of incidence of the radiation (and hence the time of day and the booster mirrors) and the irradiance, so it cannot be predicted from the absorptance of the surfaces alone and has to be established experimentally.

Most available solar box cookers have reflecting inner surfaces, and only a few have black-coated inner surfaces, because reflecting surfaces have generally been recommended: Bayabl and Balasuadhakar (2019) found that a box cooker with a reflective (white-coated) interior delivered more useful energy to the pot than an identical cooker with a black-coated interior, and booster mirrors can raise the efficiency of a box cooker substantially (Wassie et al., 2022). The evidence on the inner finish is, however, limited and difficult to generalise. Bayabl and Balasuadhakar (2019) compared two separate cookers in a morning test (10:30–12:50) in which the water reached 75.6 °C with the white interior and 68.6 °C with the black interior, so differences in construction and exposure between the two cookers cannot be excluded. Reported indicators also depend strongly on the design and test conditions: Ademe and Hameer (2018) obtained $F_2 = 0.54$ for a double-glazed box cooker with three reflectors loaded with 1.43 kg of water in an opening of 46 cm × 46 cm (about 7 kg/m²), and Abdulrahim et al. (2021) reported $F_1 = 0.132$ and $F_2 = 0.58$ for a kapok-insulated cooker in Maiduguri, but differences in load per unit aperture, number of reflectors, glazing and irradiance prevent a direct comparison of such values. In Nigeria, box cookers have been evaluated in Maiduguri (Abdulrahim et al., 2021) and in Jalingo, Taraba State (Abutu et al., 2022), and parabolic cookers have been developed for rural communities in Eastern Nigeria (Aririguzo, 2024). However, the two inner finishes have usually been compared in separate cookers, and few studies have compared black-coated and reflecting box-cooker interiors side by side, in identical compartments exposed simultaneously, together with a parabolic dish cooker at the same site. Placing the two finishes in compartments of one enclosure removes the effects of day-to-day weather and of differences in construction, but it introduces others: the compartments share the glazing and the partition, so heat can be exchanged between them, and they occupy different positions relative to the sun and to the booster mirrors. The surface finish therefore cannot be assumed to be the only difference between them, and these effects are considered in the analysis. This work was therefore aimed at comparing the performance of black-coated and reflecting-surface solar box cookers, and of a parabolic

dish solar cooker, under the climatic conditions of Bali Town, Taraba State, Nigeria, with four objectives: (i) to determine the figures of merit of the two compartments by stagnation and water-boiling tests; (ii) to compare the energy and exergy efficiencies and standardised cooking power of the three cookers on a consistent basis; (iii) to compare their heat-loss and heat-retention behaviour by heating-and-cooling tests; and (iv) to assess their practical performance in a controlled rice-cooking test. Bali is located at latitude 7.8587° N, longitude 10.9637° E and altitude 193 m above sea level, and is one of the Local Government Areas in the southern part of Taraba State. It has a tropical climate with a dry season from November to March and a rainy season from about April to October. Daily temperatures range from 32–37 °C in December/January to 37–40 °C in the hottest months of March/April (Elijah & Lamidi, 2023), and annual rainfall is 1,350–1,500 mm (Iganga & Lamidi, 2023); these local studies do not state the period of record [authors: give the period and data source if known]. To place the test conditions in a long-term context, monthly climatological means for the site were taken from the NASA POWER database (NASA Langley Research Center, 2026) for [period]: in the months of the tests (February, April–May and July–August) the mean daily global irradiation is [x–y] kWh m⁻² day⁻¹, the mean daily maximum air temperature [x–y] °C and the mean wind speed [x–y] m s⁻¹. The test days (Table 1) had mean irradiances of 435–941 W/m², mean ambient temperatures of 33.9–41.4 °C and mean wind speeds of 0.62–1.20 m s⁻¹ during the test periods; compared with the long-term means, the water-boiling days of April–July 2023 were [representative / clearer and hotter than average], whereas the heating-and-cooling tests of August were made under the weaker irradiance of the rainy season. The local boiling point of water at this altitude is about 99.3 °C.

MATERIALS AND METHODS

Cooker Design and Instrumentation

The box cooker was built from 2 cm thick plywood, measuring 100 cm × 100 cm × 40 cm externally and 96 cm × 96 cm internally (Figure 1a, b). It was divided centrally into two identical compartments of 0.55 mm aluminium sheet, SC.B and SC.RB, each measuring 88 cm × 38 cm × 34 cm (aperture area $A_{ap} = 0.3344$ m²) and set 2 cm below the rim, with 4 cm of organic-fibre (cotton-wool) insulation around and beneath them. A single 4 mm glass sheet (96 cm × 96 cm) tightly lapped on rubber pad laid on top surface of insulating area to cover both compartments. Two plane mirrors (100 cm × 100 cm × 4 mm) were fixed on the two opposite edges of the rim perpendicular to the partition, so that both compartments received reflected radiation from both mirrors; the mirrors were set at an angle of 119.5° to the glazing and held by stiff wooden supports. This angle

was geometrically calculated using equation (1) rather than optimised experimentally: it is the largest opening angle at which, with the sun overhead in the plane normal to the mirror edges, the ray reflected from the upper edge of a mirror of length $b = 100$ cm just reaches the opposite edge of the glazing of width $a = 96$ cm, which gives $z = 119.5^\circ$ (Figure 1b). A larger angle would let each mirror intercept more radiation but would send part of it beyond the glazing [authors: confirm that this is how the angle was obtained]. The box was fixed in position throughout the tests, with the glazing horizontal and the mirrors on its [north and south / east and west] edges, and was not tracked, because the compartments were set fixed with a stiff wooden support at this inclination to the rim of solar box. Heat exchange between the partition is assumed to be negligible as partition thickness (4 cm) is the same with insulating areas surrounding each compartment [were / were not]; the possible effect of this exchange is considered in the Discussion.

The parabolic dish solar cooker (P.SC) had an aperture diameter of 110 cm (aperture area 0.9503 m^2 , about 2.8

times that of one compartment), a depth of 25 cm and its focal point 36 cm above the base of the dish (Figure 1c). Its shell was formed from 0.55 mm aluminium sheet bolted to a frame of iron bars, and its concave surface was lined with 2 mm plane mirror tiles ($2 \text{ cm} \times 2.5 \text{ cm}$). The pot was suspended at the focus, and the dish was re-aimed manually during the tests (see Experimental Procedures). The ratio of aperture to pot area (geometric concentration ratio) was 7.93 for the dish, against 2.79 for the glazed opening of one compartment. Each compartment, however, also received the radiation reflected onto the glazing by the two booster mirrors, which is not included in its glazed aperture; this is taken into account in the comparison of efficiencies (see Basis of the Energy Comparison).

Identical aluminium pots with a wall thickness of 0.55 mm were used throughout. Each pot had an external diameter and height of 17.55 cm, an internal diameter and height of 17.38 cm and a mass of 216 g, was painted black externally and was closed with its lid.

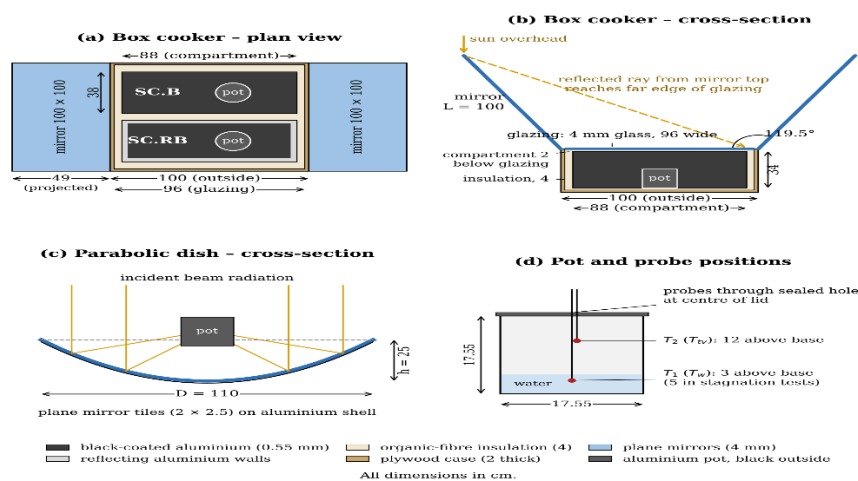


Figure 1: Schematic of the Cookers Tested, with Dimensions in cm: (a) Plan View of the Two-compartment box Cooker (SC.B and SC.RB) Showing the Two Booster Mirrors; (b) Cross-section of the Box Cooker Normal to the Mirror Edges, with the Mirrors at 119.5° to the Glazing and the Reflected Ray that Defines this Angle; (c) Cross-section of the Parabolic Dish Cooker ($D = 110$ cm, $h = 25$ cm) with the Pot at the Focus; (d) pot with the Positions of the Thermocouple Probes

Global solar irradiance was measured with a Kipp and Zonen CC20 pyranometer (ISO 9060:2018 Class C, accuracy $\pm 5\%$) mounted horizontally [beside the cookers at the level of the glazing], wind speed and ambient temperature with a BENETECH GM8901 digital anemometer ($\pm 3\%$), and temperatures with K/J-type thermocouple probes on 5 m leads connected to four-channel digital thermocouple thermometers (TASI TA612 and HT-9815). The positions of the probes in the pots are shown in Figure 1d and described below. The instruments were used with the manufacturers'

calibrations, and the thermocouple probes were not calibrated against one another before the tests. Masses were measured with an Atom-A122 digital balance (resolution 1 g) and time with a digital clock (± 1 min). Combining the thermometer accuracy ($\pm(0.2\%$ of reading $+ 0.7^\circ \text{C}$) with the tolerance of standard thermocouples ($\pm 2.5^\circ \text{C}$) gives an uncertainty of about $\pm 2.7^\circ \text{C}$ in a single temperature and $\pm 3.8^\circ \text{C}$ in the difference between two uncalibrated probes; the corresponding uncertainty in an individual value of F_1 is about ± 0.007 , and that of an energy efficiency about $\pm 6\text{--}8\%$ of its value, mainly

because of the $\pm 5\%$ accuracy of the pyranometer. The uncertainties of the quantities derived by regression are given as 95% confidence intervals (see Statistical Analysis).

Experimental Procedures

All cookers were set up in an open field free from shade, with the box facing the sun and the dish being aimed at the sun at the start and re-aimed at intervals of about [X] min by [method, e.g. adjusting the dish until the shadow

of the pot fell centrally on the reflector]. Readings were taken at 10-minute intervals. The same protocol was followed in every test: the pots, lids and probe positions were identical, the box was not moved, and all the cookers listed for a test in Table 1 were exposed simultaneously, so that cookers are compared only within the same test. The tests, their dates and the weather conditions are summarised in Table 1. Three trial days (18–20 April 2023) preceded the tests and are not reported.

Table 1: Tests Carried Out and Weather Conditions

Test	Date	Cookers and load	Period	Mean I (W/m ²)	Mean T_{amb} (°C)	Mean wind (m/s)
Stagnation Test I	9 Feb 2026	SC.B, SC.RB, P.SC; empty pots	11:30–14:50	508 (130–830)	35.4	0.74
Stagnation Test II	10 Feb 2026	SC.B, SC.RB; empty pots	09:00–13:00	671 (434–838)	34.3	0.68
Water boiling, Day 1	29 Apr 2023	All three; 1 kg water per pot	11:00–15:00	778 (346–1076)	40.1	1.02
Water boiling, Day 2	2 May 2023	All three; 1 kg water per pot	11:00–15:00	941 (540–1194)	41.4	0.62
Water boiling, Day 3	9 May 2023	All three; 1 kg water per pot	10:00–14:00	934 (506–1146)	39.2	1.14
Water boiling, Day 4	27 Jul 2023	All three; 1 kg water per pot	10:00–14:00	779 (246–1346)	34.7	1.20
Heating and cooling A	5 Aug 2026	All three; 1 kg water per pot	09:30–14:00; cooling 14:05–15:35	435 (191–793)	33.9	0.62
Heating and cooling B	7 Aug 2026	All three; 1 kg water per pot	09:30–14:00; cooling 14:05–16:25	483 (162–726)	34.4	0.69
Controlled cooking	11 Feb 2026	All three; 1 kg rice + 1.692 kg water	10:30–14:30	721 (477–1026)	39.6	0.93

Ranges of irradiance in brackets. In the stagnation tests and the heating-and-cooling tests each compartment also carried a second pot on a raised stand or an iron plate, whose results are reported separately; only the pots standing directly on the floor are compared here. The second pots were arranged in the same way in both compartments [authors: confirm], so they did not favour either compartment, but they shaded part of the floor and added load: the values of F_1 therefore refer to compartments carrying two pots, and the compartment efficiencies quoted for the heating-and-cooling tests include both pots. In the water-boiling and cooking tests each compartment carried only one pot.

Stagnation Tests

In the stagnation tests two thermocouple probes, T_1 and T_2 , tied together, were inserted into each empty pot through a hole drilled at the centre of the lid; T_1 was positioned 5 cm and T_2 12 cm above the base of the pot. A 3 g bead was suspended from the tip of each T_1 probe to keep the probes vertical, and each lid was sealed airtight with a thin ring of silicone gum around its rim. The mean of T_1 and T_2 was taken as the pot temperature T_{av} . In each compartment the pot stood

directly on the floor, 10 cm from the centre; in the dish it hung at the focus. Stagnation Test I included all three cookers but started at 11:30 am, later than the 10:00 am start recommended by ASAE S580.1 (ASAE, 2013), because installing the instrumentation took longer than planned, and was interrupted by cloud. Stagnation Test II was carried out on the box cooker only, under steadier irradiance, and provides the quasi-steady values of F_1 . Stagnation was identified operationally as the reading at which T_{av} was highest, provided that the net change in T_{av} between the preceding and the following readings (20 min) was less than 2 °C, i.e. smaller than the uncertainty of a single reading; T_{ps} , T_{as} and H_s are the values recorded at that reading (Mullick et al., 1987).

Water Boiling and Cooling Tests

In each water boiling test one litre ($\equiv 1$ kg) of water was measured into one pot per compartment and into the pot at the focus of the dish. Probe T_1 , designated T_w , was set 3 cm above the base of the pot so that it was fully immersed in the water, and a second probe 12 cm above the base, designated T_{tv} , recorded the vapour space below the lid. The test was repeated on four days between April and July 2023 (Table 1), and the four-day mean water

temperatures were obtained by averaging the four days at equal elapsed times from the start of each test. The indicators were calculated both for each day and for the four-day mean curves; the two are not equivalent, because averaging curves with different timing smooths their peaks, and both are reported. Two further heating tests (A and B) were followed by a cooling period in which the cookers were left in place and the water temperatures were recorded at 5-minute intervals.

Controlled Food Cooking Test

One kilogram of cleaned parboiled rice, washed and drained for five minutes, and 1.692 kg of water (rice-to-water volume ratio 2:3.2) were placed in each of the three pots, and the temperature of the cooking liquid, T_{liq} , was recorded with the probes positioned as in the water boiling test. The pots were weighed before and after the test to obtain the mass of water evaporated. The rice was judged to be completely cooked when [criterion used, e.g. all the grains were soft throughout when pressed between the fingers and no free water remained], assessed [by whom and when]. The water retained by the rice after washing and draining was not measured and is not included in the load [authors: confirm]. The cooking test was carried out once.

Calculation of Optimal Angle Z for the Box Solar Cooker

The optimal angle to which the mirrors will inclined to the rim of the box can be obtained using geometric equation of Solar Oven Design (1st April, 2010). The influence of reflector geometry on the performance of box cookers has been demonstrated experimentally by Coccia *et al.* (2017) and Wassie *et al.* (2022).

$$z = 90^\circ + \left\{ \sin^{-1} \left(\frac{1}{4} \sqrt{\frac{b^2}{a^2} + 8} - \frac{b}{4a} \right) \right\} \quad (1)$$

Where a is the length or width of the glazing glass and b is the length or width of the reflector.

Figures of Merit F_1 and F_2

At quasi-steady stagnation the energy absorbed by the empty pot equals the heat lost, so that:

$$\eta_o H_s = U_L (T_{ps} - T_{as}) \quad (2)$$

Where η_o is the optical efficiency, U_L is the overall heat-loss coefficient, T_{ps} is the pot stagnation temperature, and H_s and T_{as} are the irradiance and ambient temperature at the time stagnation was achieved. Mullick *et al.* (1987) defined the first figure of merit, F_1 , as:

$$F_1 = \frac{\eta_o}{U_L} = \frac{T_{ps} - T_{as}}{H_s} \quad (3)$$

Cookers with $F_1 \geq 0.12 \text{ K m}^2 \text{ W}^{-1}$ are classed as grade A and those below 0.12 as grade B. For sensible water heating, the second figure of merit is given by Mullick *et al.* (1987) as:

$$F_2 = F' \eta_o C_R = \frac{F_1 (mc)_w}{A_{ap} t} \ln \left[\frac{1 - \frac{1}{F_1} \left(\frac{T_{w1} - T_a}{H} \right)}{1 - \frac{1}{F_1} \left(\frac{T_{w2} - T_a}{H} \right)} \right] \quad (4)$$

where A_{ap} is the aperture area, H is the mean irradiance over the heating interval, F' is the heat exchange efficiency factor, C_R is the heat capacity ratio, $(mc)_w = 4186 \text{ J/K}$ is the heat capacity of the 1 kg of water, t is the time taken for the water to heat from $T_{w1} = 60^\circ \text{C}$ to $T_{w2} = 90^\circ \text{C}$ and T_a is the mean ambient temperature over the same interval. The quasi-steady F_1 of each compartment (Stagnation Test II) was used, and where 90°C was not reached the maximum temperature was taken as T_{w2} . A value of $F_2 \geq 0.4$ is recommended for grade A cookers (BIS, 2000).

Energy, Exergy and Cooking Time

The solar energy incident on a cooker over a period was obtained by integrating the measured global irradiance I over its aperture area and time:

$$E_{in} = A_{ap} \int I dt \quad (5)$$

and the useful energy delivered to the load, including the latent heat of any water evaporated, is:

$$E_{out} = (m_w c_w + m_r c_r) (T_f - T_i) + m_{ev} L_w \quad (6)$$

Where m_w and m_r are the masses of water and rice, $c_w = 4186 \text{ J/kg K}$ and $c_r = 1800 \text{ J/kg K}$ are their specific heat capacities, T_i and T_f are the initial and maximum temperatures of the contents, m_{ev} is the mass of water evaporated and $L_w = 2.257 \text{ MJ/kg}$ is its latent heat of vaporisation. The heat taken up by the pot itself (0.194 kJ/K) is not included for any of the cookers. The energy (first-law) efficiency is then:

$$\eta = \frac{E_{out}}{E_{in}} \quad (7)$$

The exergy (second-law) efficiency ψ accounts for the ambient temperature and for the low grade of the heat delivered (Petela, 2003):

$$\psi = \frac{(mc) [(T_f - T_i) - T_a \ln(T_f/T_i)]}{E_{in} \left[1 - \frac{4T_a}{3T_s} + \frac{1}{3} \left(\frac{T_a}{T_s} \right)^4 \right]} \quad (8)$$

With temperatures in kelvin and an apparent sun temperature $T_s = 5777 \text{ K}$. Both efficiencies were evaluated from the start of each test to the time at which the load reached its maximum temperature. Because this interval differs between cookers and days, the efficiencies of the water-boiling tests were also evaluated over a common interval, the first 90 min of the four-day mean curves.

The standard sensible time required to bring a load of total mass M to 100°C and to evaporate the measured mass of water, at a reference irradiance I_{ref} and the measured efficiency η of the cooker, is (ASAE, 2013; Funk, 2000):

$$t = t_1 + t_2 = \frac{Mc(100 - T_i) + m_{ev} L_w}{\eta I_{ref} A_{ap}} \quad (9)$$

Cooking Power and Heat-Loss Parameters

The interval cooking power P_i was calculated for each 10-minute interval ($\Delta t = 600$ s) of the four-day mean heating curves and standardised to an irradiance of 700 W/m² (ASAE, 2013; Funk, 2000):

$$\left. \begin{aligned} P_i &= \frac{m_w c_w \Delta T_w}{\Delta t} \\ P_s &= P_i \frac{700}{I_i} \\ T_d &= T_w - T_a \end{aligned} \right\} \quad (10)$$

Where I_i is the mean irradiance of the interval, and T_w and T_a are the means of the water and ambient temperatures at the start and end of the interval. Only intervals in which the water was at least 5 °C above ambient and 5 °C below the local boiling point, and before the maximum temperature, were used to fit the linear regression:

$$\left. \begin{aligned} P_s &= c + bT_d \\ U_L &= -\frac{b}{A_{ap}} \\ \eta_o &= \frac{c}{700A_{ap}} \end{aligned} \right\} \quad (11)$$

The standardised cooking power at $T_d = 50$ °C was used as the single measure of performance. Because F_1 and F_2 are defined for box cookers, the dish and the box were also compared with the heating-and-cooling method of Mullick et al. (1991). During cooling the excess of the water temperature over ambient decays as:

$$\left. \begin{aligned} T_w - T_a &= (T_{w0} - T_a) e^{-\frac{t}{\tau}} \\ F'U_L &= \frac{(MC)'_w}{A_p \tau} \end{aligned} \right\} \quad (12)$$

Where τ is the time constant, $(MC)'_w = 4380$ J/K is the heat capacity of the water and pot and $A_p = 0.1198$ m² is the heat-transfer area of the pot. The optical efficiency factor $F'\eta_o$ was then obtained from the heating data:

$$\frac{T_{wf} - T_a}{I} = \frac{CF'\eta_o}{F'U_L} (1 - e^{-t/\tau}) + \frac{T_{wi} - T_a}{I} e^{-t/\tau} \quad (13)$$

Where C is the ratio of the aperture to the pot area (7.93 for the dish and 1.40 for a compartment shared by two pots).

Basis of the Energy Comparison

The energy input of Equation (5) refers each cooker to the measured global irradiance on a horizontal surface and to its own aperture. This is the usual practice, but it does not place the box and the dish on an identical basis: each compartment also receives the radiation reflected onto the glazing by the two booster mirrors, which is not counted in its glazed aperture, whereas the dish can concentrate only the beam component of the radiation. The efficiencies were therefore also evaluated on a second basis, which includes the mirror radiation for the box and refers the dish to the beam irradiance. The radiation reflected onto one compartment was estimated for the sun overhead in the plane normal to the mirror edges, for which, by design, all the reflected radiation

falls on the glazing (Figure 1b). The additional effective aperture of one compartment is then:

$$A_m = 2\rho_m \tau_r f_g LW_m |\cos z| \frac{A_{ap}}{A_g} \quad (14)$$

where $\rho_m = 0.85$ is the assumed solar reflectance of the back-silvered mirrors, $\tau_r = 0.91$ is the transmittance of the glazing for the reflected rays (incident at 59°) relative to that at normal incidence, calculated from the Fresnel equations for 4 mm glass, $f_g = 0.94$ is the fraction of the reflected radiation that falls within the glazing, $LW_m = 1$ m² is the area of a mirror, $z = 119.5^\circ$ and $A_g = 0.9216$ m² is the area of the glazing. This gives $A_m = 0.26$ m², so that the energy input to each compartment becomes:

$$E_{in,m} = A_{ap} \int \left(I + \frac{A_m}{A_{ap}} I_b \right) dt \quad (15)$$

Where I_b is the beam irradiance on a horizontal surface? As the sun moves away from the plane normal to the mirror edges, the reflected radiation is displaced across the glazing and partly beyond it, so Equation (14) overestimates the input to the box and therefore gives a lower estimate of its efficiency. For the dish, the input was referred to the direct normal irradiance:

$$E_{in,b} = A_d \int \frac{I_b}{\cos \theta_z} dt \quad (16)$$

Where $A_d = 0.9503$ m² is the aperture of the dish and θ_z is the solar zenith angle. Because the beam irradiance was not measured, I_b was estimated from each measured value of I with the correlation of Erbs et al. (1982) between the diffuse fraction and the clearness index, using the extraterrestrial irradiance and zenith angle calculated for the site, date and time of each reading. The efficiencies obtained in this way are indicative. The same considerations apply to the standardised cooking power per unit aperture and to the optical efficiency factor $F'\eta_o$, which were not recalculated.

Statistical Analysis

Successive 10-minute readings of a heating curve are strongly autocorrelated and cannot be treated as independent observations. The two compartments were therefore compared in two ways. First, each test day was treated as one replicate, and the daily indicators (maximum water temperature, useful energy, energy and exergy efficiency, F_2 and t_{90}) were compared with a two-sided paired t-test ($n = 4$, or $n = 3$ for t_{90}); the mean difference is reported with its 95% confidence interval. Second, paired temperature series were compared with a t-test in which the number of readings n was replaced by the effective sample size $n_{eff} = n(1 - r_1)/(1 + r_1)$, where r_1 is the lag-1 autocorrelation of the differences; this correction is itself approximate for short series (Zwiers, Von and Storch, 1995). The coefficients of Equation (11) and the quantities derived from them are given with 95% confidence intervals based on the t-distribution with $n - 2$ degrees of freedom, and the adequacy of the linear model was checked by testing the

significance of an added quadratic term. Variability between days is expressed as the standard deviation (SD) of the daily values.

RESULTS AND DISCUSSION

Stagnation Tests

Table 2 presents the average stagnation temperature T_{av} (mean of T_1 and T_2), ambient temperature T_{amb} , global

irradiance I and wind speed recorded during Stagnation Test I for the black-coated compartment (SC.B), the reflecting compartment (SC.RB) and the parabolic dish cooker (P.SC); the temperatures of both stagnation tests are plotted in Figure 2; Table 3 presents the average stagnation temperatures during Stagnation Test II for SC.B and SC.RB and the figures of merit are summarised in Table 4.

Table 2: Stagnation Test I: Average Stagnation Temperature T_{av} , Ambient Temperature, Irradiance and Wind Speed for SC.B, SC.RB and P.SC

Local Time	T_{av} SC.B (°C)	T_{av} SC.RB (°C)	T_{av} P.SC (°C)	T_{amb} (°C)	Rad. I (W/m ²)	Wind speed (m/s)
11.30	34.45	35.05	48.50	35.4	621	1.01
11.40	76.90	80.30	51.35	36.1	604	0.04
11.50	97.90	101.55	57.60	36.4	782	0.81
12.00	106.35	110.70	56.75	37.5	716	1.06
12.10	115.65	122.20	56.25	36.1	830	0.00
12.20	95.75	97.80	49.75	37.2	516	1.17
12.40	87.00	89.30	50.90	37.7	621	1.17
12.50	96.75	101.25	47.45	34.5	439	0.00
13.00	85.35	87.80	50.30	34.2	552	1.22
13.10	98.05	107.75	43.55	36.5	632	1.25
13.20	99.70	109.30	47.80	36.1	582	1.04
13.30	83.25	88.55	44.20	36.0	579	1.07
13.40	91.15	98.50	46.35	34.1	552	1.12
13.50	93.75	101.30	38.75	35.2	532	1.19
14.00	91.85	80.25	42.45	35.0	514	1.01
14.10	78.10	76.25	40.05	34.5	327	0.00
14.20	78.95	74.85	43.05	34.1	130	0.44
14.30	75.05	69.35	42.25	34.0	234	1.06
14.40	69.05	69.20	43.40	34.1	206	0.00
14.50	68.35	66.55	41.25	33.5	184	0.22
Average	86.17	88.39	47.10	35.41	507.65	0.74

Table 3: Stagnation Test II: Mean Stagnation Temperatures of Empty Pots In SC.B and SC.RB

Local time	SC.B (°C)	SC.RB (°C)	T_{amb} (°C)	I (W m ⁻²)	v (m s ⁻¹)
9.00	28.75	29.75	34.7	434	0.36
9.10	46.70	48.25	35.0	440	0.04
9.20	63.9	74.75	34.1	640	0.45
9.30	69.75	78.55	34.6	833	1.12
9.40	75.70	86.05	35.0	838	1.42
9.50	78.65	89.45	36.1	758	0.00
10.00	84.70	98.15	35.0	693	1.64
10.10	90.80	106.55	33.0	686	0.44
10.20	98.30	115.90	31.0	669	1.44
10.30	103.3	120.15	31.2	654	1.20
10.40	108.05	124.1	31.7	646	0.00
10.50	112.95	126.3	31.8	640	0.00
11.00	116.75	127.50	33.4	626	1.10
11.10	121.20	129.55	34.2	602	1.21
11.20	124.25	130.40	34.1	597	1.01
11.30	125.60	130.75	34.0	600	0.30
11.40	129.35	131.10	35.0	810	0.44
11.50	124.55	129.15	34.8	735	0.00

Local time	SC.B (°C)	SC.RB (°C)	T_{amb} (°C)	I (W m ⁻²)	v (m s ⁻¹)
12.00	127.35	127.60	34.9	724	0.45
12.10	125.20	124.85	35.5	719	0.22
12.20	124.65	123.75	35.5	803	1.45
12.30	122.10	121.15	35.4	639	0.00
12.40	122.75	121.0	34.8	784	0.44
12.50	119.90	117.50	35.6	601	1.27
13.00	119.50	117.75	36.0	597	0.99
Mean			34.3	670.7	0.680

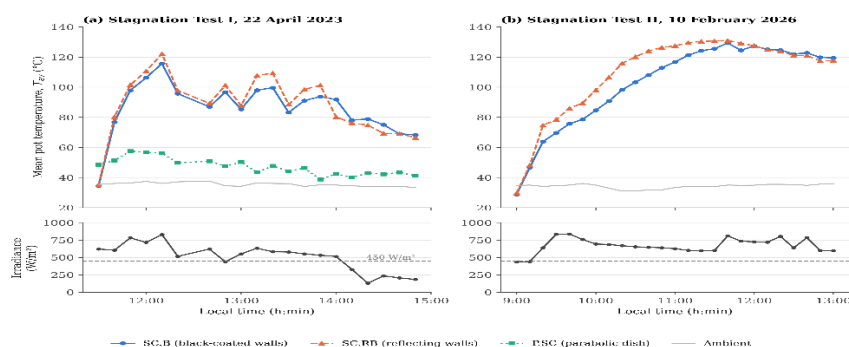


Figure 2: Variation of the Average pot Temperature with Local Time for the Pots Standing on the Floor of SC.B and SC.RB and at the Focus of P.SC: (a) Stagnation Test I under Intermittent Cloud; (b) Stagnation Test II (Box Cooker only) under Steadier Irradiance. The lower Panels show the Global Irradiance, with the 450 W/m² Minimum of ASAE S580.1 Marked

In Stagnation Test I the average wind speed was 0.74 m s⁻¹ (maximum 1.25 m s⁻¹), so convective losses due to wind were not a dominant factor, but the sky was intermittently cloudy: the irradiance varied between 130 and 830 W/m² (mean 507.65 W/m²), it changed by more than 100 W/m² between successive readings on nine occasions, six readings fell below the minimum of 450 W/m² set by ASAE S580.1, and the ambient temperature exceeded the 35 °C upper limit of the standard in 11 of the 20 readings. Such reductions are typical of the wet season in Nigeria's savannah, when absorption, scattering and reflection by clouds reduce the solar radiation reaching the surface (Ladan et al., 2024). The pot temperatures therefore rose and fell with the irradiance (Figure 2a) instead of settling at a steady value. SC.RB reached 122.20 °C at 12:10 and SC.B 115.65 °C at the same time, giving indicative values of $F_1 = 0.104$ and 0.096 (Table 3); because the temperatures fell by more than 10 K within the following 10 min, these readings do not satisfy the stagnation criterion and are not used to grade the cooker. SC.RB recorded the higher temperature in 15 of the 20 readings (on average 2.2 °C higher) and exceeded 100 °C after 20 min, against 30 min for SC.B, whereas from 14:00 onwards, when the irradiance fell to about 500 W/m² and below, SC.B was equal or warmer.

From Table.3, Stagnation Test II was carried out under steadier and stronger irradiance (434–838 W/m², mean

671 W/m²), and the pots approached quasi-steady temperatures between 11:30 and 12:40 (Figure 2b), which makes this test the appropriate basis for F_1 . The pots reached 129.35 °C (SC.B) and 131.10 °C (SC.RB) at 11:40, where the stagnation criterion was satisfied, giving $F_1 = 0.1165$ and 0.1186. The irradiance was, however, not constant around this time: it rose from about 600 W/m² between 11:10 and 11:30 to 810 W/m² at 11:40 (Figure 2b), so the pot temperatures at stagnation had been reached under a lower irradiance than H_S . When T_{av} , T_{amb} and I are averaged over the 40 min centred on stagnation (11:20–12:00), F_1 becomes about 0.13 (SC.B) and 0.14 (SC.RB) [authors: verify these two values, and that the criterion is met at 11:40, from the raw data], so the values in Table 3 are conservative. Both values in Table 3 lie within about 3% of the value of 0.12 that separates grade A from grade B, and within the uncertainty of that boundary, so the compartments are best described as lying at or slightly above the boundary between the two grades. They are close to the lower end of the range of 0.12–0.16 reported by Mullick et al. (1987) for box cookers and comparable with the 0.132 of a kapok-insulated cooker in Maiduguri (Abdulrahim et al., 2021). The pot in SC.RB again crossed 100 °C earlier (after 62 min against 83 min), but after noon the two compartments converged and the pot in SC.B finished slightly warmer. A possible explanation, which the present measurements do not test directly, is that

reflecting walls redirect radiation onto the black floor and pot and so give a faster response when direct radiation is strong, consistent with Bayabl and Balasuadhakar (2019), whereas black walls absorb radiation and re-radiate part of it to the pot, which may help to sustain its temperature as the irradiance falls. Wall temperatures and radiative fluxes were not measured, however, and the different positions of the two compartments relative to the booster mirrors could produce a similar pattern (see Black-Coated against Reflecting Inner Walls).

The parabolic cooker performed far below the box cooker in Stagnation Test I. Its pot temperature was already 48.50 °C at the start of the readings, probably because the pot had been exposed at the focus while the instruments were being set up, and it reached a maximum of only 57.60 °C at 11:50 ($F_1 = 0.027$). This is lower than the water temperatures that the same dish attained under load, which suggests that an empty pot at the focus of an

unglazed concentrator stores little of the absorbed energy and loses it rapidly by convection and radiation, and that the small focal spot may have drifted off the pot between manual re-orientations; neither the heat loss of the receiver nor the position of the focal spot was measured directly. Theu and Kimambo (2023) similarly found that wind significantly increases heat loss from the receiver of a parabolic dish cooker, that manual tracking every 15–20 min was difficult and subjective, and that intermittent radiation on partly cloudy days reduced the rate of heat accumulation. The stagnation procedure of Equation (2) was developed for box-type cookers; concentrating cookers are more appropriately characterised by the heating-and-cooling procedure of Mullick et al. (1991), so the F_1 value for P.SC is given for comparison only, and the dish is characterised below by $F'U_L$ and $F'\eta_o$.

Table 4: First Figure Of Merit F_1 from the Stagnation Tests

Test	Cooker	T_{ps} (°C)	T_{as} (°C)	H_s (W/m ²)	Time	F_1 (K m ² W ⁻¹)	Grade
I (intermittent cloud)	SC.B	115.65	36.1	830	12:10	0.096	B (indicative)
I (intermittent cloud)	SC.RB	122.20	36.1	830	12:10	0.104	B (indicative)
I (intermittent cloud)	P.SC	57.60	36.4	782	11:50	0.027	not applicable
II (quasi-steady)	SC.B	129.35	35.0	810	11:40	0.1165	A/B boundary
II (quasi-steady)	SC.RB	131.10	35.0	810	11:40	0.1186	A/B boundary

Grade A: $F_1 \geq 0.12$; grade B: $F_1 < 0.12$ (Mullick et al., 1987). Uncertainty of each F_1 about ± 0.007 . The Test I values were read at the peak temperatures under intermittent cloud and do not satisfy the stagnation criterion; the grades shown for them are indicative only.

Water Boiling Tests

The water temperatures recorded on the four test days are shown in Figure 3, the four-day mean values in Table 4 and Figure 4, and the main indicators for each day in Table 5.

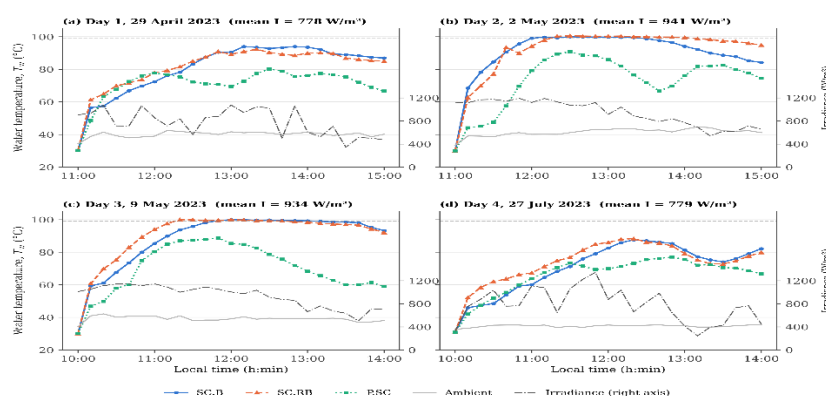


Figure 3: Variation of the Water Temperature in SC.B, SC.RB and P.SC (1 kg of Water Per Pot) with Local Time on the Four Water Boiling Test Days, with the Ambient Temperature and the Global Irradiance (Right Axis). The Dashed Line Marks the Local Boiling Point (99.3 °C)

Day 2 had the clearest sky (mean irradiance 941 W/m²). On that day SC.B and SC.RB raised the water from 30 °C to 90 °C in 39 min and 38 min and brought it to the boil (100.0 °C and 100.6 °C) within 90 min, while the dish reached 90 °C only after 84 min and a maximum of 90.8

°C. On Day 3 both compartments again brought the water to the boil, SC.RB after 51 min to 90 °C and SC.B after 70 min, whereas the dish reached 88.7 °C. On Days 1 and 4, which had intermittent cloud (mean irradiance 778 and 779 W/m²), the compartments attained 92.3–94.0 °C and

87.6–88.4 °C, against 80.2 °C and 77.0 °C for the dish. SC.RB was warmer than SC.B during the first hour on Days 1, 3 and 4, whereas on Day 2 SC.B was warmer during the first 30 min (Figure 3). The water in the dish pot generally rose quickly in the first 10–20 min but then stagnated or fell, apparently when the focal spot drifted or the irradiance dropped, which is consistent with its low thermal inertia and high heat loss; on Day 2, for example, it fell from 90.8 °C to 66.7 °C between 12:30 and 13:40

while the irradiance was still 790–1118 W/m². Averaged over the four days, the maximum water temperatures of the four-day mean curves were 95.08 °C (SC.B), 95.02 °C (SC.RB) and 80.95 °C (P.SC), and the compartments reached 90 °C after 99 min and 86 min, while the mean water temperature in the dish never reached 90 °C (Table 4, Figure 4). The means ($\pm$ SD) of the daily maxima were 95.4 ± 5.9 °C, 95.3 ± 6.0 °C and 84.2 ± 6.6 °C (Table 5).

Table 5: Four-Day Mean Water Temperatures of SC.B, SC.RB and P.SC (1 Kg of Water per Pot)

Elapsed time (min)	T_w SC.B (°C)	T_w SC.RB (°C)	T_w P.SC (°C)	T_{amb} (°C)	Rad. I (W/m ²)	Wind speed (m/s)
0	30.32	30.32	30.32	33.68	840.5	1.25
10	57.45	59.23	48.10	38.10	965.5	1.26
20	60.78	65.47	50.90	39.45	1058.5	1.11
30	65.78	71.85	56.25	38.28	1017.5	0.83
40	71.20	77.95	61.40	38.58	940.0	0.81
50	76.15	79.80	70.10	38.92	1035.5	0.75
60	79.25	83.36	75.28	38.97	1083.0	0.85
70	82.60	86.55	78.75	38.73	1019.5	0.96
80	84.90	89.18	80.60	38.68	905.0	1.06
90	87.55	90.58	80.95	39.25	937.0	0.88
100	90.35	92.20	79.83	38.55	1060.5	0.57
110	92.20	93.93	79.28	38.88	1073.5	1.24
120	93.23	93.98	77.65	39.65	968.0	0.92
130	94.85	94.78	77.70	39.58	999.5	1.17
140	95.08	95.02	77.45	40.13	907.8	0.80
150	94.63	93.95	76.58	39.65	903.5	0.85
160	94.18	93.48	74.38	39.35	788.5	0.78
170	93.83	92.73	73.55	39.40	852.0	1.36
180	92.08	91.78	74.05	39.30	614.0	0.93
190	90.18	90.47	74.22	39.30	667.0	0.99
200	88.32	89.53	73.48	39.37	580.0	1.08
210	87.58	88.53	72.15	39.53	503.5	0.59
220	86.88	88.65	70.55	39.53	592.8	1.29
230	86.75	88.30	69.20	38.32	674.5	1.21
240	86.68	87.98	66.75	38.77	621.5	1.25
Maximum	95.08	95.02	80.95	—	—	—
Mean	—	—	—	38.88	864.3	0.99

Elapsed time is measured from the start of each test (10:00 or 11:00). The last two rows give the maximum

water temperatures and the mean ambient temperature, irradiance and wind speed.

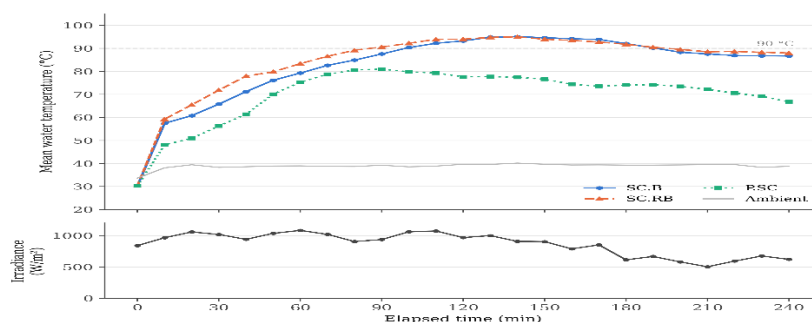


Figure 4: Four-day Mean Water Temperature of SC.B, SC.RB and P.SC against Elapsed Time, with the Ambient Temperature and the Mean Global Irradiance

Table 6: Water Boiling Tests: Heating Milestones, Figures Of Merit and Efficiencies

Test	Cooker	t_{90} (min)	$T_{w,max}$ (°C)	Q_u (kJ)	η (%)	ψ (%)	F_2
Day 1 (778 W/m ²)	SC.B	108	94.00	266.6	11.85	0.81	0.145
	SC.RB	107	92.30	259.5	10.59	0.70	0.120
	P.SC	n.r.	80.20	208.9	2.77	0.13	–
Day 2 (941 W/m ²)	SC.B	39	100.00	293.0	14.14	1.11	0.245
	SC.RB	38	100.60	295.5	14.26	1.13	0.264
	P.SC	84	90.80	254.5	4.32	0.28	–
Day 3 (934 W/m ²)	SC.B	70	100.00	292.6	11.20	0.87	0.139
	SC.RB	51	100.00	292.6	16.54	1.26	0.187
	P.SC	n.r.	88.70	245.3	3.59	0.22	–
Day 4 (779 W/m ²)	SC.B	n.r.	87.60	237.3	9.04	0.70	0.111*
	SC.RB	n.r.	88.40	240.7	9.17	0.72	0.083*
	P.SC	n.r.	77.00	193.0	2.18	0.13	–
Mean $\pm$ SD of daily values	SC.B	72 $\pm$ 35	95.4 $\pm$ 5.9	272 $\pm$ 26	11.6 $\pm$ 2.1	0.87 $\pm$ 0.17	0.160 $\pm$ 0.059
	SC.RB	65 $\pm$ 37	95.3 $\pm$ 6.0	272 $\pm$ 27	12.6 $\pm$ 3.4	0.95 $\pm$ 0.29	0.163 $\pm$ 0.080
	P.SC	n.r.	84.2 $\pm$ 6.6	225 $\pm$ 29	3.2 $\pm$ 0.9	0.19 $\pm$ 0.07	–
Four-day mean curve (864 W/m ²)	SC.B	99	95.08	271.1	9.69 [5.93]	0.72 [0.44]	0.113 (0.160)
	SC.RB	86	95.02	270.8	9.69 [5.92]	0.72 [0.44]	0.123 (0.163)
	P.SC	n.r.	80.95	211.9	4.17 [4.79]	0.23 [0.26]	–
Four-day mean curve, first 90 min	SC.B	–	87.55 ^b	239.6	13.40 [8.19]	0.86 [0.53]	–
	SC.RB	–	90.58 ^b	252.2	14.11 [8.62]	0.97 [0.59]	–
	P.SC	–	80.95 ^b	211.9	4.17 [4.79]	0.23 [0.26]	–

t_{90} = elapsed time to reach 90 °C (linear interpolation); n.r. = not reached. Q_u , η and ψ are evaluated from the start of the test to the maximum water temperature, except in the rows for the first 90 min. 90 °C * = not reached; maximum temperature used as T_{w2} . Values of F_2 in brackets are the means of the four daily values. F_2 is not defined for the concentrating dish. Mean $\pm$ SD of daily values: mean and standard deviation of the four daily values (for t_{90} , of the three days on which 90 °C was reached). Values of η and ψ in square brackets are on the mirror-inclusive and beam-referred basis (Equations 14 and 15). ^b Water temperature at 90 min.

The useful energy delivered to the 1 kg of water up to its maximum temperature was 266.6–293.0 kJ in SC.B, 259.5–295.5 kJ in SC.RB and 193.0–254.5 kJ in P.SC, and 271.1, 270.8 and 211.9 kJ for the four-day mean curves (Table 5). The energy efficiencies ranged from 9.0% to 14.1% for SC.B, from 9.2% to 16.5% for SC.RB and from 2.2% to 4.3% for P.SC; the four-day mean curves give 9.69% for both compartments (12.6% and 14.1% if only the heating phase up to 90 °C is considered) and 4.17% for the dish, and the means ($\pm$ SD) of the daily values were 11.6 $\pm$ 2.1%, 12.6 $\pm$ 3.4% and 3.2 $\pm$ 0.9%. Referred to their glazed or reflector apertures and to the global irradiance, the compartments therefore converted the incident solar energy 2.3 times more effectively than the dish, and 3.2 (SC.B) and 3.4 (SC.RB) times over the common first 90 min. The exergy efficiencies, 0.70–1.11% (SC.B), 0.70–1.26% (SC.RB) and 0.13–0.28% (P.SC), are an order of magnitude smaller than the energy efficiencies because the useful output is low-grade heat below 100 °C whereas solar radiation carries an exergy of about 93% of its energy; the compartments were 3.1 times more effective than the dish on this measure. These ratios, however, depend on the basis of the comparison. When the radiation reflected onto the glazing by the booster mirrors is added to the input of each compartment (Equation 15) and the dish is referred to the beam

irradiance (Equation 16), the energy efficiencies of the four-day mean curves become 5.9% (SC.B and SC.RB) and 4.8% (P.SC), a ratio of about 1.2 (1.7–1.8 over the first 90 min), and the exergy efficiencies 0.44% and 0.26%, a ratio of 1.7 (Table 5). Because the mirror term is an upper estimate, the true ratios lie between these limits: the compartments were the more efficient converters on every basis, but the ratios should not be read as an intrinsic ranking of the two cooker technologies. Comparisons with other studies are also limited by differences in design and test conditions: Ademe and Hameer (2018) reported a maximum of 99.1 °C after 2 h 40 min for a double-glazed box cooker with three reflectors and 1.43 kg of water, Das et al. (2019) a maximum water temperature of 95.1 °C with a paraboloid dish cooker, and Mekonnen et al. (2020) about 90 °C within 90 minutes with an SK14 parabolic cooker, whereas in this work both compartments, each with 1 kg of water and two booster mirrors, boiled the water within 90 min on a clear day and the locally built dish, re-aimed manually and with an unshielded pot, attained 90.8 °C in the same time.

The second figure of merit (Equation 3), evaluated between 60 °C and 90 °C, ranged from 0.111 to 0.245 for SC.B and from 0.083 to 0.264 for SC.RB, with daily means ($\pm$ SD) of 0.160 $\pm$ 0.059 and 0.163 $\pm$ 0.080; the

four-day mean curves give 0.113 and 0.123. The highest values were obtained on the clearest day. All values fall short of the minimum of 0.4 recommended for grade A cookers. F_2 depends strongly on the ratio of the heat capacity of the load to the aperture area and increases with the load (Mullick et al., 1996); the standard procedures prescribe about 7–8 kg of water per m^2 of aperture, whereas the present tests used 1 kg in 0.3344 m^2 (about 3 kg/m^2). Values of $F_2 = 0.533$ for a box cooker with mirror reflectors (Wassie et al., 2022) and 0.58 for a kapok-insulated box cooker (Abdulrahim et al., 2021) have been reported under clear skies, but differences in load and conditions make a direct comparison difficult; the low F_2 found here is consistent with the light load rather than indicating a poor cooker. This interpretation is supported by the heating-and-cooling tests, in which two pots of 1 kg each per compartment raised the compartment efficiency from about 10% to 15.8–23.5%, although those tests were made on different days and under weaker irradiance.

The standard sensible time required to bring 1 kg of water to the boil (Equation 8), computed at the four-day mean irradiance (864 W/m^2) with the efficiency of each cooker during its heating phase and including the measured evaporation (19–28 g), was 162 min for SC.B, 138 min for SC.RB and 163 min for P.SC. The value for the dish assumes that its mean efficiency is maintained up to boiling; in practice its losses rose steeply with temperature and it did not boil the water on average, so its effective time is longer.

Cooking Power and Heat-Loss Parameters

The standardised cooking powers (Equation 9) of the four-day mean heating curves are plotted against the temperature difference in Figure 5, and the regression parameters, with their 95% confidence intervals, are given in Table 6. Within the valid range the regressions

were $P_s = 33.70 - 0.449T_d$ ($R^2 = 0.56$, $p = 0.008$) for SC.B, $P_s = 55.03 - 0.911T_d$ ($R^2 = 0.80$, $p < 0.001$) for SC.RB and $P_s = 31.67 - 0.416T_d$ ($R^2 = 0.16$, $p = 0.32$) for P.SC. Only the regression of SC.RB satisfies the criterion $R^2 \geq 0.75$ of the standard, and that of the dish is not statistically significant, probably because its heating rate was governed by the fluctuating alignment of the focal spot rather than by the temperature difference. The linear model is the one prescribed by ASAE S580.1, which keeps the results comparable with other studies; it was adequate for SC.RB (added quadratic term $p = 0.58$), but for SC.B the quadratic term was significant ($p = 0.04$), showing curvature as the light load approached its plateau, so the U_L and η_o derived from its slope and intercept are approximate, and no conclusion is drawn from the non-significant fit for the dish. The standardised cooking power at $T_d = 50 \text{ K}$ was $11.3 \pm 4.4 \text{ W}$ (SC.B), $9.5 \pm 4.0 \text{ W}$ (SC.RB) and $10.9 \pm 23.1 \text{ W}$ (P.SC), or 33.7, 28.4 and 11.4 W per m^2 of aperture. These values are lower than the 36–51 W reported by Ademe and Hameer (2018) for a box cooker with three reflectors and about 7 kg/m^2 of water, partly because the light load allowed the water to approach its plateau temperature within the regression range; per unit aperture, the compartments delivered 2.5–3.0 times the standardised power of the dish, although the confidence interval of the dish value is very wide and the ratio depends on the energy basis, as discussed above. The higher intercept and steeper slope of SC.RB ($U_L = 2.72$ against $1.34 \text{ W m}^{-2} \text{ K}^{-1}$) suggest a compartment that gains heat faster at low temperature but loses a larger fraction of it as the temperature rises, which would agree with its faster early heating and with the identical final temperatures of the two compartments. The 95% confidence intervals of U_L overlap, however (Table 6), and the cooling tests gave similar heat-loss factors for the two compartments, so this difference is not conclusive.

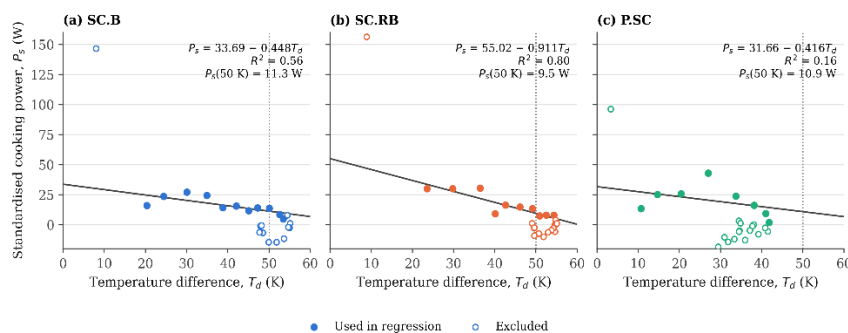


Figure 5: Standardised Cooking Power against Temperature Difference with Linear Regression for (a) SC.B, (b) SC.RB and (c) P.SC, from the Four-day Mean Heating Curves. Open Symbols are Intervals Excluded by the Standard; the Dotted Line Marks $T_d = 50 \text{ K}$

Table 7: Cooking-Power Regression and Heat-Loss Parameters

Parameter	SC.B	SC.RB	P.SC
Intercept a (W); slope b (W/K)	33.70 $\pm$ 12.43; -0.449 $\pm$ 0.301	55.03 $\pm$ 15.46; -0.911 $\pm$ 0.345	31.67 $\pm$ 29.01; -0.416 $\pm$ 0.948†
R^2 (n); p -value	0.56 (11); 0.008	0.80 (11); < 0.001	0.16 (8); 0.32†
P_s at $T_d = 50$ K (W)	11.27 $\pm$ 4.44	9.48 $\pm$ 4.04	10.86 $\pm$ 23.08†
P_s (50 K) per m ² of aperture (W/m ²)	33.7 $\pm$ 13.3	28.4 $\pm$ 12.1	11.4 $\pm$ 24.3†
$U_L = -b/A_{ap}$ (W m ⁻² K ⁻¹); $\eta_o = a/(700A_{ap})$	1.34 $\pm$ 0.90; 0.144 $\pm$ 0.053	2.72 $\pm$ 1.03; 0.235 $\pm$ 0.066	0.44 $\pm$ 1.00†; 0.048 $\pm$ 0.044†
Cooling time constant τ , tests A; B (min)	270; 208	251; 182	60; 50
Heat-loss factor $F'U_L$, tests A; B (W m ⁻² K ⁻¹)	2.26; 2.94	2.43; 3.36	10.10; 12.22
Optical efficiency factor $F'\eta_o$, tests A; B	0.299; 0.384	0.245; 0.420	0.051; 0.057

Values after $\pm$ are 95% confidence half-widths of the regression estimates. †Regression not statistically significant ($p > 0.05$); values indicative only. τ , $F'U_L$ and $F'\eta_o$ refer to the pots standing on the floor of each compartment and to the pot at the focus of the dish (Equations 11 and 12); with only two cooling tests, the difference between tests A and B indicates their uncertainty.

The cooling tests provide a characterisation that applies equally to both types of cooker. The cooling curves followed the exponential decay of Equation (12) closely ($R^2 = 0.95$ – 0.98 for the box pots and 0.75 – 0.96 for the dish); the lower R^2 of the dish shows that its cooling was less regular, so its time constants are less reliable. The pots in the box had time constants of 182–270 min and heat-loss factors of 2.3 – 3.4 W m⁻² K⁻¹, whereas the pot at the focus of the dish had time constants of only 50–60 min and heat-loss factors of 10.1 – 12.2 W m⁻² K⁻¹ (Table 7): this directly measured difference shows that the closed, insulated box retains heat three to five times longer, which helps it to continue cooking through passing clouds. Because the box pots were hotter than the dish pot during cooling and radiative losses rise more than linearly with temperature, this comparison, if anything, understates the advantage of the box. The optical efficiency factors of the box pots were 0.25 – 0.42 , whereas that of the dish was only 0.05 – 0.06 , which indicates that only a small fraction of the radiation

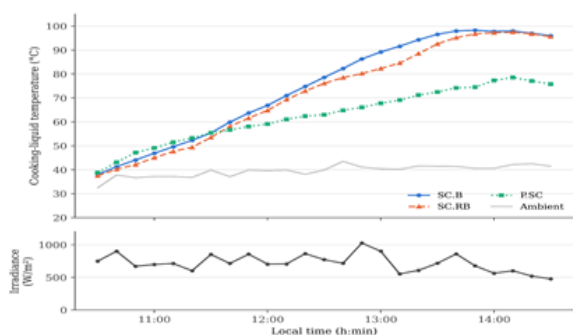
intercepted by its aperture reached the pot as absorbed heat. Part of this difference arises from the energy basis, since $F'\eta_o$ of the dish is referred to the global rather than the beam irradiance, which was probably largely diffuse under the weak irradiance of these tests, while that of the box includes the radiation reflected by its booster mirrors. Possible further causes, which were not measured separately, are slope errors of the hand-moulded reflector and its small mirror facets, a focal spot that did not coincide with the pot and drifted between manual re-orientations, and the unshielded pot (Lentswe et al., 2021; Theu & Kimambo, 2023). In the same tests, carried out under weak irradiance (435 and 483 W/m²), the water in the box pots reached 73.1 – 83.3 °C and 98.2 – 99.8 °C, against only 54.0 °C and 57.6 °C in the dish, and each compartment, with two pots, delivered 3.8 – 5.0 times as much useful energy as the dish. Together, the low $F'\eta_o$ and the high $F'U_L$ are consistent with the dish, despite its larger aperture, being out-performed by each compartment of the box.

Controlled Food Cooking Test

Table 8: Controlled Cooking Test (9 February 2026): Temperature of the Cooking Liquid (T_{liq}), Ambient Temperature (T_{amb}), Irradiance and Wind Speed for SC.B, SC.RB and P.SC

Local Time	T_{liq} SC.B (°C)	T_{liq} SC.RB (°C)	T_{liq} P.SC (°C)	T_{amb} (°C)	Rad. I (W/m ²)	Wind speed (m/s)
10.30	38.0	37.5	38.8	32.5	750	0.00
10.40	41.3	40.2	43.1	37.8	901	0.40
10.50	44.1	42.2	47.2	36.7	670	1.24
11.00	46.9	45.0	49.1	37.2	699	1.50
11.10	49.6	47.7	51.5	37.2	713	1.14
11.20	52.3	49.4	53.3	36.8	602	0.00
11.30	55.4	53.5	55.4	39.9	852	0.43
11.40	59.9	58.1	56.6	37.1	714	0.00
11.50	63.7	61.6	58.1	39.9	856	1.66
12.00	66.9	64.8	59.1	39.6	704	1.36
12.10	71.0	69.3	61.1	39.9	706	2.04
12.20	74.8	72.9	62.4	38.1	864	1.90
12.30	78.6	76.1	63.0	39.9	772	0.00
12.40	82.3	78.5	64.8	43.5	716	1.11

Local Time	T_{1liq} SC.B (°C)	T_{1liq} SC.RB (°C)	T_{1liq} P.SC (°C)	T_{amb} (°C)	Rad. I (W/m ²)	Wind speed (m/s)
12.50	86.3	80.2	66.1	41.1	1026	1.51
13.00	89.2	82.3	67.8	40.4	902	1.27
13.10	91.6	84.6	69.1	40.2	553	0.99
13.20	94.3	88.5	71.2	41.6	608	1.51
13.30	96.6	92.6	72.5	41.5	716	1.25
13.40	98.0	95.2	74.2	41.4	860	1.25
13.50	98.3	96.8	74.5	40.6	677	0.31
14.00	97.8	97.3	77.3	40.6	564	1.29
14.10	98.0	97.5	78.6	42.2	601	0.00
14.20	97.0	96.8	77.1	42.5	520	0.41
14.30	96.0	95.6	75.8	41.5	477	0.77
Average				39.6	720.9	0.93



(a) Variation of the Cooking-liquid Temperature T_{1liq} with Local Time for SC.B, SC.RB and P.SC During the Controlled Cooking Test, with the Ambient Temperature and the Global Irradiance; (b) Rice Cooked in the Box Solar Cooker.

In the controlled cooking test (Table 8, Figure 6a; mean irradiance 720.9 W/m²) SC.B attained a maximum liquid temperature of 98.3 °C at 13:50 (200 min after the start) and SC.RB 97.5 °C at 14:10 (220 min); the contents passed 90 °C after about 153 min in SC.B and 174 min in SC.RB. P.SC reached a maximum of only 78.6 °C, at 14:10. The temperatures in the two compartments followed almost the same curve, with SC.B leading by up to 7 °C around 13:00 before the two converged. The rice in both compartments was completely cooked according to the criterion given in the Methods (Figure 6b), whereas the rice in the dish remained under-cooked, as the liquid never exceeded 78.6 °C.

Only 36.4 g (SC.B), 38.2 g (SC.RB) and 23.5 g (P.SC) of water were lost from the 2.692 kg charge, about 1.4% in the box pots, far less than the 25% of the cooking water commonly lost by evaporation in conventional open cooking (Mahavar et al., 2013); the closed pot in a glazed box therefore conserves water. Including the latent heat of the evaporated water (Equation 5), the useful energy delivered was 617.8 kJ (SC.B), 619.2 kJ (SC.RB) and 406.6 kJ (P.SC), with energy efficiencies of 20.3%, 18.9% and 4.4% and exergy efficiencies of 1.57%, 1.40% and 0.23%; on the mirror-inclusive and beam-referred basis (Equations 14 and 15) the energy efficiencies were

14.0%, 13.1% and 6.8%. The box-cooker efficiencies agree with the mean cooking efficiency of 18.9% measured for solar box ovens by Bigelow et al. (2024), whereas the value for P.SC is far below the 35.2% they report for parabolic reflectors, probably reflecting the open pot and intermittent tracking used here. The standard sensible times for cooking 1 kg of rice (Equation 8) were 180 min (SC.B), 196 min (SC.RB) and 278 min (P.SC); the two compartments are within 10% of each other. The successful cooking of the rice in both compartments shows that the box cooker was adequate for this load on this day; because the test was made once, it does not by itself rank the configurations thermodynamically.

Black-Coated against Reflecting Inner Walls

Because the two compartments were identical apart from the finish of their inner walls and were exposed simultaneously, the comparison removes the effect of day-to-day weather, but it does not remove the effects of compartment position, of heat exchange between the compartments or of probe offsets. The paired comparison of the water temperatures recorded simultaneously in SC.B and SC.RB during the four water boiling tests is summarised in Table 8. Over the 100 paired readings

SC.RB was on average $1.80\text{ }^{\circ}\text{C}$ warmer than SC.B (standard deviation of the differences $4.56\text{ }^{\circ}\text{C}$). Successive readings are, however, strongly autocorrelated (the lag-1 autocorrelation of the differences of the four-day mean curve is 0.84), so the naive paired t-test ($p = 0.00015$) greatly overstates the evidence; with the effective sample size, the mean difference of the four-day mean curve ($-1.87\text{ }^{\circ}\text{C}$) is not statistically significant ($p \approx 0.4$). Treating each test day as one replicate, none of the daily indicators differed significantly between the compartments: the mean differences (SC.B – SC.RB, $\pm 95\%$ confidence interval) were $0.08 \pm 1.81\text{ }^{\circ}\text{C}$ in maximum water temperature ($p = 0.90$), $0.3 \pm 7.6\text{ kJ}$ in useful energy ($p = 0.91$), -1.1 ± 4.6 percentage points in energy efficiency ($p = 0.51$) and

-0.004 ± 0.058 in F_2 ($p = 0.86$). The only consistent difference was in the early heating phase: over the first 100 min of the four-day mean curve SC.RB was $3.65\text{ }^{\circ}\text{C}$ warmer ($p \approx 0.02$ after the correction for autocorrelation), whereas thereafter the difference was only $0.47\text{ }^{\circ}\text{C}$, and SC.RB was warmer during the first hour on three of the four days. This early difference is, however, comparable to the $\pm 3.8\text{ }^{\circ}\text{C}$ uncertainty between two uncalibrated probes, and it could also arise from the different positions of the compartments, which were not interchanged. In the cooking test the order was reversed, SC.B being on average $2.55\text{ }^{\circ}\text{C}$ warmer ($p \approx 0.3$). The peak temperatures, useful energies and energy efficiencies of the four-day mean curves are practically identical, and the figures of merit differ only slightly.

Table 9: Statistical Comparison of SC.B (Black Walls) and SC.RB (Reflecting Walls)

Comparison	n	SC.B	SC.RB	Difference (SC.B – SC.RB)	t	p
Paired water temperatures, four test days ($^{\circ}\text{C}$) ^a	100	82.55	84.36	-1.80	-3.95	0.00015
Four-day mean curve ($^{\circ}\text{C}$) ^b	25 (2.2)	82.51	84.38	-1.87	-1.27	0.40
Four-day mean curve, first 100 min ($^{\circ}\text{C}$) ^b	11 (4.5)	–	–	-3.65	-3.97	0.02
Four-day mean curve, after 100 min ($^{\circ}\text{C}$) ^b	14 (2.4)	–	–	-0.47	-0.75	0.56
Cooking test, liquid temperature ($^{\circ}\text{C}$) ^b	25 (2.1)	74.72	72.17	+2.55	1.83	0.31
Maximum water temperature, daily values ($^{\circ}\text{C}$) ^c	4	95.40	95.33	$+0.08 \pm 1.81$	0.13	0.90
Useful energy, daily values (kJ) ^c	4	272.4	272.1	$+0.3 \pm 7.6$	0.13	0.91
Energy efficiency, daily values (%) ^c	4	11.56	12.64	-1.08 ± 4.63	-0.74	0.51
Exergy efficiency, daily values (%) ^c	4	0.87	0.95	-0.08 ± 0.34	-0.74	0.51
F_2 , daily values ^c	4	0.160	0.163	-0.004 ± 0.058	-0.19	0.86
t_{90} , daily values (min) ^c	3	72.3	65.3	$+7.0 \pm 25.8$	1.17	0.36
Maximum water temperature, four-day mean curve ($^{\circ}\text{C}$)	–	95.08	95.02	+0.06	–	–
Useful energy, four-day mean curve (kJ)	–	271.1	270.8	+0.3	–	–
F_1 (Stagnation Test II)	–	0.1165	0.1186	-0.0021	–	–
F_2 (four-day mean curve)	–	0.113	0.123	-0.010	–	–
Useful energy, cooking 1 kg rice (kJ)	–	617.8	619.2	-1.4	–	–

^a Paired t-test (two-sided) treating the 100 readings as independent; because successive readings are autocorrelated, this p-value overstates the strength of the evidence and is shown for comparison only. ^b Paired t-test with the effective sample size n_{eff} (in brackets). ^c Paired t-test with each test day as one replicate; differences $\pm 95\%$ confidence half-widths.

A possible explanation is that reflecting walls redirect radiation onto the black floor and the pot and so accelerate the initial heating, whereas black walls absorb radiation and re-emit part of it to the pot and to the vapour space but lose part of it through the side insulation; the two effects may largely compensate. Neither the wall temperatures nor the radiative fluxes were measured, however, so this explanation remains tentative, and two other effects could produce, or mask, differences of the size observed. First, away from solar noon the radiation reflected by the booster mirrors is displaced across the glazing in the direction away from the sun, so that one compartment can receive more reflected radiation in the

morning and the other in the afternoon; since the compartments were not interchanged, such a position effect cannot be separated from the effect of the finish. Second, heat exchanged between the compartments through the partition and below the shared glazing would reduce any difference between them, so the measured differences may be smaller than those between two separate cookers. The result differs from that of Bayabl and Balasuadhakar (2019), who found a clear advantage for a reflective interior when two separate cookers were compared; when the two finishes are applied to identical compartments of the same cooker exposed simultaneously, the advantage of the reflecting walls is limited to faster heating in the first hour or so. These results therefore do not show a clear advantage of reflecting inner walls under the conditions tested; whether this holds after the compartment positions are interchanged and the probes are inter-calibrated remains to be established.

Limitations of the Study

Several limitations should be borne in mind when interpreting these results. First, each stagnation test was carried out on a single day; Stagnation Test I took place under intermittent cloud and outside the irradiance and ambient-temperature limits of ASAE S580.1 (450–1100 W/m² and 20–35 °C), so its figures of merit are indicative only, and Stagnation Test II, which gives the quasi-steady F_1 , did not include the dish and was made under an irradiance that rose by about a third shortly before stagnation. Second, the ambient temperature exceeded 35 °C during most of the water boiling tests and the irradiance occasionally exceeded 1100 W/m², and the load of about 3 kg/m² of aperture was well below the 7–8 kg/m² of the standard procedures, so F_2 and the standardised cooking power are not suitable for formal grading. Third, on the usual basis the efficiencies of the box compartments are based on the glazed aperture only and exclude the additional radiation reflected by the booster mirrors, which overstates them relative to the dish, whereas the dish efficiency is based on global rather than beam irradiance, which understates it; the corrected basis used here relies on an assumed mirror reflectance and on modelled rather than measured beam irradiance, and its mirror term is an upper estimate. Fourth, the dish was operated with an open pot and manual tracking while the box compartments were glazed and fixed, so the comparison reflects the cookers as built and operated rather than their optimum designs. Fifth, the two compartments shared a common glazing sheet and partition, so heat could be exchanged between them, their positions were not interchanged and the probes were not calibrated against each other, so differences between the compartments smaller than about 4 °C cannot be attributed with confidence to the inner finish. Sixth, successive readings are serially correlated, and with only four water-boiling days the power to detect small differences between the compartments is low. Finally, in the stagnation and heating-and-cooling tests each compartment also carried a second pot on a raised support, only two cooling tests were made, and the controlled cooking test was carried out once, with a judgement of doneness rather than an instrumental endpoint.

CONCLUSION

Within the limits of the prototypes, loads, operating procedures and weather conditions tested at Bali, the following conclusions can be drawn. The most robust findings concern the box against the dish and rest on direct measurements. In four water boiling tests both box compartments brought 1 kg of water to the boil within 90 min on a clear day and reached four-day mean maxima of 95.1 °C and 95.0 °C, against 81.0 °C for the dish; both compartments cooked 1 kg of parboiled rice completely with only 1.4% loss of water, whereas the dish left the

rice under-cooked; and the pots in the box cooled three to five times more slowly than the pot at the focus of the dish (time constants 182–270 min against 50–60 min). On this evidence, the box-type cooker was the more suitable of the tested prototypes for household cooking under the conditions of Bali. The energy and exergy efficiencies of the compartments (9.7% and 0.72% for the four-day mean curves, referred to the glazed aperture) were 2.3 and 3.1 times those of the dish, but these ratios fall to about 1.2 and 1.7 when the booster-mirror radiation and the beam-only acceptance of the dish are taken into account, so they do not represent an intrinsic ranking of the two technologies. The comparison of the inner finishes is tentative. Under quasi-steady stagnation the first figures of merit of SC.B (black-coated walls) and SC.RB (reflecting walls with a black floor) were 0.1165 and 0.1186, at or slightly above the boundary between grades A and B, and their daily maximum temperatures, useful energies, efficiencies and F_2 did not differ significantly. SC.RB heated faster in the first 100 min (on average 3.7 °C warmer), but this difference is comparable to the uncertainty between two uncalibrated probes and could also reflect the positions of the compartments, so the present results do not show a clear advantage of either finish. The figures of merit should be confirmed at the standard load of 7–8 kg of water per m² of aperture and over several seasons; the comparison of the finishes should be repeated with interchanged compartment positions, inter-calibrated probes, repeated cooking trials and consistent energy accounting with measured beam irradiance; and the dish would require a more accurate reflector, reliable tracking and an enclosed pot to realise its potential.

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