

Experimental characterization of a panel solar cooker with adjustable geometry for sun tracking

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ABSTRACT

This study experimentally analyzed the performance of a panel solar cooker with a variable geometry for proper sun tracking. Its peculiarity is that, unlike many other panel cookers, the geometry can be adjusted during days, seasons, and at different latitudes to maximize the amount of solar radiation concentrated on the receiver. To study the impact of sun tracking, several tests without and with load (water and glycerin) were performed by adjusting the device geometry considering different time intervals. The tests with water showed that the device usually brought 1 kg of water from 40 to 90 °C in about an hour, proving its good thermal performance. Instead, the tests with load with different sun tracking showed that the performance of the device adjusted every hour was slightly lower than that of the prototype adjusted every 15 min. This proves the device ensures good performance even when oriented every hour. In addition, various receiver configurations were tested, finding that the receivers comprising black pots within different glass bowls ensured rather similar results. In contrast, as expected, the receiver with a plastic enclosure had lower performance but still brought the water temperature from 40 to 90 °C in less than two hours. Finally, the performance parameters of the proposed prototype were compared with those of panel cookers available in the literature. It was found that the parameters of the presented solar cooker are consistent with the values reported in previous studies.

1. Introduction

For years, the exploitation of solar energy for cooking has been considered an efficient way to reduce the environmental and health impacts of the most employed energy sources, such as fossil fuels, electricity, and wood [1–3]. This is especially true for the sunny areas of the world where abundant solar energy is available for several days of the year [4]. The environmental sustainability of solar cooking was recently confirmed by the study of Sanglard et al. [5], where the life cycle assessment (LCA) of a solar cooker, which is a device to directly harvest solar energy for cooking, was compared with the LCA of three conventional cooking devices, i.e., induction hob, electric plate, and gas hob. Their results showed that the solar cooker has a lower ecological footprint than the conventional appliances in all the studied scenarios, despite its environmental performance is affected by the materials used for the construction and the frequency of use. In fact, it was found that the cradle-to-grave climate change impact of worst studied solar cooker was 264 kgCO_{2eq}, while the values for induction hob, electric

plate, and gas hob were 847 kgCO_{2eq}, 1085 kgCO_{2eq}, and 3736 kgCO_{2eq}, respectively.

Although several types of solar cookers have been developed over the years [1,2,6–8], the research of alternative and improved devices is still underway to overcome their main shortcomings and limitations [9–11]. Among the three main types of direct solar cookers in terms of structure [1] (i.e., panel, box, and concentrating), the panel solar cookers are usually less powerful than the others, but are also characterized by simpler design, more flexibility, lower cost, and higher ease of construction and use. For these reasons, numerous designs of panel cookers have been developed and a number of them have been described in the scientific literature [12–14]. Some of the most recent literature works regarding panel solar cookers are described below.

Chepkurui and Biira [15] experimentally studied four prototypes of one of the most well-known panel cookers, called funnel cooker, characterized by different funnel lengths. The results of the tests with water showed that the funnel cooker with the longest funnel length

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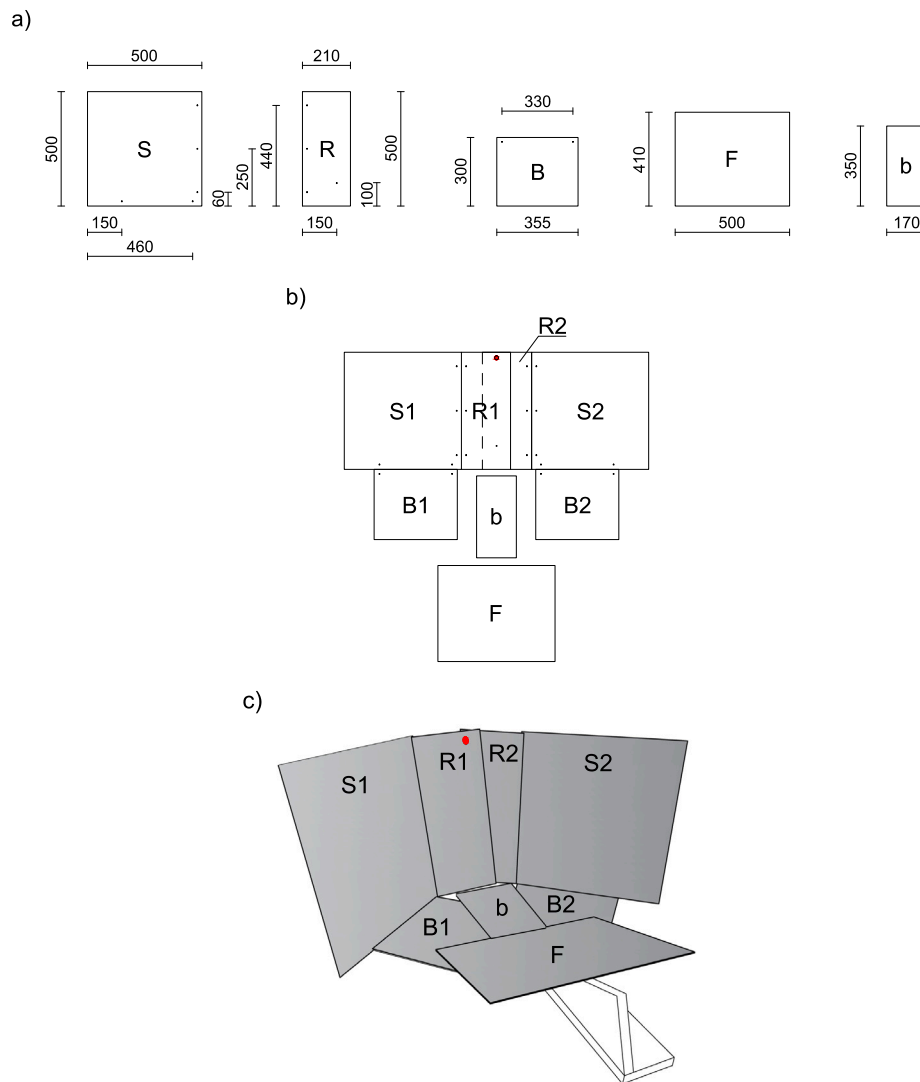


Fig. 1. Components and views of the Kimono solar cooker (dimensions are in mm): (a) reflective panels of the prototype, (b) 2D view, and (c) 3D view of the assembled device. The symbols shown in the figure are described in the main text.

provided the best thermal performance, reaching a maximum temperature of about 93 °C in about 4 h.

A comparison between the experimental performance of a panel cooker, known as Hot Pot, and those of a parabolic cooker, called Sun Chef Cooker, and a box cooker, called Global Sun Oven, was presented by Ebersviller and Jetter [16]. The tests were carried out by following the ASAE S580.1 Standard [17] and using water as testing fluid. It was found that the Hot Pot cooker ensured lower performance than the other two cookers, having a standardized cooking power of 25 W, while the Global Sun Oven and the Sun Chef Cooker had standardized powers of 65 W and 198 W, respectively.

Chauhan et al. [18] designed and experimentally analyzed a funnel-type solar cooker made of cardboard covered by reflective aluminum foils. The prototype was tested with water and glycerin as test loads and different performance parameters were determined. The experimental results showed that the cooker reached a temperature of 125 °C and an efficiency of 0.121. Moreover, a thermal energy storage system containing paraffin wax as phase change material was incorporated in the solar cooker. It was found that the thermal energy storage system ensured a significant improvement in the overall thermal efficiency.

Various studies regarding the experimental performance of a funnel cooker were recently presented by Ruivo and his co-authors [19–23]. The tests were carried out using different working fluids, such as water [19] and glycerin [20,22], and considering the influence of various

aspects, such as the type of cooking pot [19], sun elevation [20], height trivet [21], aperture area [22], and partial load [23]. They also studied the optical performance of the Funnel cooker through ray-tracing simulation [24]. In addition, some of the authors experimentally studied other solar panel cookers, such as different configurations of the Copenhagen [13,25] and the Haines 2 [26].

Aquilanti et al. [14] experimentally compared the performances of four panel cookers, namely Kimono, funnel, Dual Setting Panel Cooker, and Cookit. The prototypes were manufactured using inexpensive materials, i.e., Plexiglas or cardboard sheets covered by a reflective Mylar film. The prototypes were tested in parallel under the same environmental conditions and considering two configurations: one suitable for low-medium sun elevation and one for medium-high sun elevation. The results of the experimental tests without and with load showed that the Kimono and funnel cooker ensured the best performance in all the studied conditions.

Regarding the panel solar cookers, it is worth noting that their performance could be affected by the limited sun tracking that can be applied during use due to their simple design. In fact, unlike the devices with specific zenithal and azimuthal orientation systems [27–30] or with a variable geometry to track the sun [31–33], panel cookers usually have different fixed configurations suitable for specific sun elevations. This implies that they allow only a limited zenithal

sun tracking. An exception is the Kimono solar cooker, developed by one of authors of this work and recently described in Aquilanti et al. [14]. Its design is characterized by a variable geometry that can be adjusted during operation to maximize the amount of solar radiation concentrated on the absorber. However, in the previous work [14], the impact of this important feature on the device's performance was not adequately investigated since the prototype was tested considering only two fixed configurations for low-medium and medium-high sun elevations.

Hence, this study also aims to compensate for this lack of knowledge about the effect of sun tracking on the Kimono solar cooker by presenting the results of tests where its geometry was adjusted during use. In particular, to thoroughly analyze the influence of geometry adjustments on its performance, two identical prototypes made of polished aluminum were tested without and with load (water and glycerin) in parallel by changing their geometry considering different time intervals. These experiments were carried out with the aim to properly understand how often the solar cooker should be oriented for ensuring good performance. Considering that the panel solar cookers can be highly influenced by the used receivers, a further objective of the study was to evaluate the impact of this component on the performance of the studied solar cooker. In this regard, a comparison between the results of tests carried out by using four receivers with different configurations, shapes, and materials is also reported. Finally, the performance parameters of the proposed prototype are compared with those of panel solar cookers available in the literature.

After the Introduction, the main features of the Kimono solar cooker and its optical analysis are reported in Section 2. Section 3 presents the experimental setup and parameters used to characterize the performance of the prototypes. Section 4 shows the results of the experimental tests, dividing them between no-load, water-loaded and glycerin-loaded tests. A comparison with the literature is also reported in the same section. The main conclusions are provided in Section 5.

2. Design, manufacture and optical analysis

The Kimono solar cooker was designed by Matteo Muccioli, one of the authors of this work, and was already described in a previous study [14]. Hence, only the main features regarding the design, manufacture, and working scheme of this solar cooker are reported below. It consists of seven reflective panels made of anodized polished aluminum and one board covered by reflective material that are assembled as shown in Fig. 1. From this figure, it is possible to identify the following main parts of the device:

- Two symmetrical parts (1 and 2 in Fig. 1), each comprising a side panel (S in Fig. 1), a bottom panel (B), and a rear panel (R), which are joined together.
- A front panel (F) placed in front of the others parts on a wooden wedge-shaped support.
- The reflective board (b) placed above the bottom panels. The receiver is placed above this board in order to thermally insulate its base.

The prototype tested in this work was built following a procedure similar to that described in Aquilanti et al. [14]. The seven reflective panels were cut from polished anodized aluminum sheets with a thickness of 0.8 mm and properly drilled. The reflective board (b) was cut from a cardboard sheet and covered with tinfoil. The dimensions of the panels and board are shown in Fig. 1a,b, together with the positions of the holes. Each symmetrical part was assembled by joining the panels with a wire. These two parts were joined together through a fixing system inserted in the holes in the rear panels and three thin cords inserted in specific holes at the top and bottom of the side panels. The fixing system has a knob that allows to adjust the tightening torque required to block the rear panels. The cords have single-point cord locks

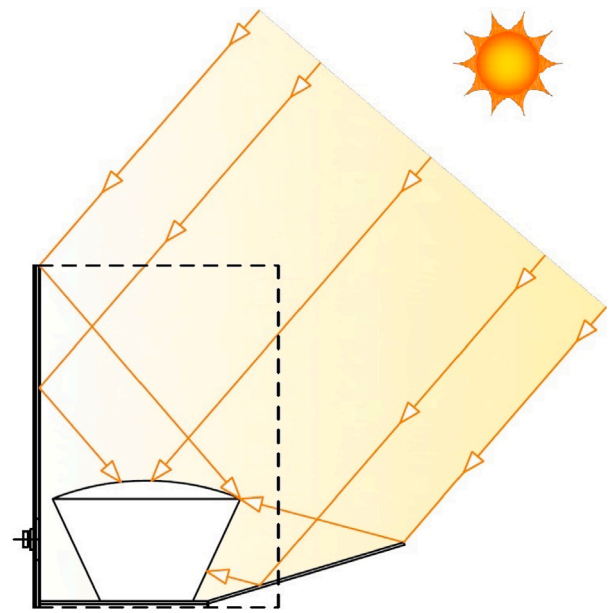


Fig. 2. Kimono working scheme.

at both ends for pulling them taut, increasing the wind resistance of the device.

The working scheme of the Kimono solar cooker is shown in Fig. 2, where it is highlighted how the reflective panels concentrate the solar radiation into the receiver. Given the particular design of the Kimono that allows to modify the tilt angles of the rear, side, and front panels to maximize the solar radiation concentrated into the receiver, the collecting area of the solar cooker change during use. In particular, the rear and side panels can be tilted by reducing the tightening torque through the knob and changing the length of the cords at the top. The tilt angle of the front panel can be changed by moving the wedge-shaped support.

For a proper use of the cooker, it is worth to distinguish between the following three main configurations that should be chosen on the basis of the sun elevations:

- For medium-high sun elevations (between 40° and 80°), the Kimono can be placed in the reference configuration shown in Fig. 3a at the beginning of its use. In this case, the bottom panels are overlapped to form a right angle on the front, while the side and rear panels are perpendicular to the floor. However, as shown in Fig. 3b, the rear and side panels have to be tilted outwards for proper sun tracking during its use by following the procedure described below.
- In the configuration for low sun elevation (lower than 40°), the side and rear panels should be properly tilted inwards on the basis of the sun position. In addition, to increase the collecting area, it is recommended to increase the front angle between the bottom panels by not overlapping them, as shown in Fig. 4.
- In the configuration for very high sun elevation (higher than 70°), the side and rear panels should be strongly tilted outwards to better concentrate the solar radiation towards the receiver. However, since there is a v-shaped empty space in the upper part of the rear panels that reduces the solar cooker collecting area, a modified configuration of the device, known as Kimono Butterfly, was designed to overcome this limitation. As shown in Fig. 5, an additional reflective rear panel is added to the symmetrical parts through the fixing system, while the bottom panels are completely overlapped to ensure higher stability of the device.

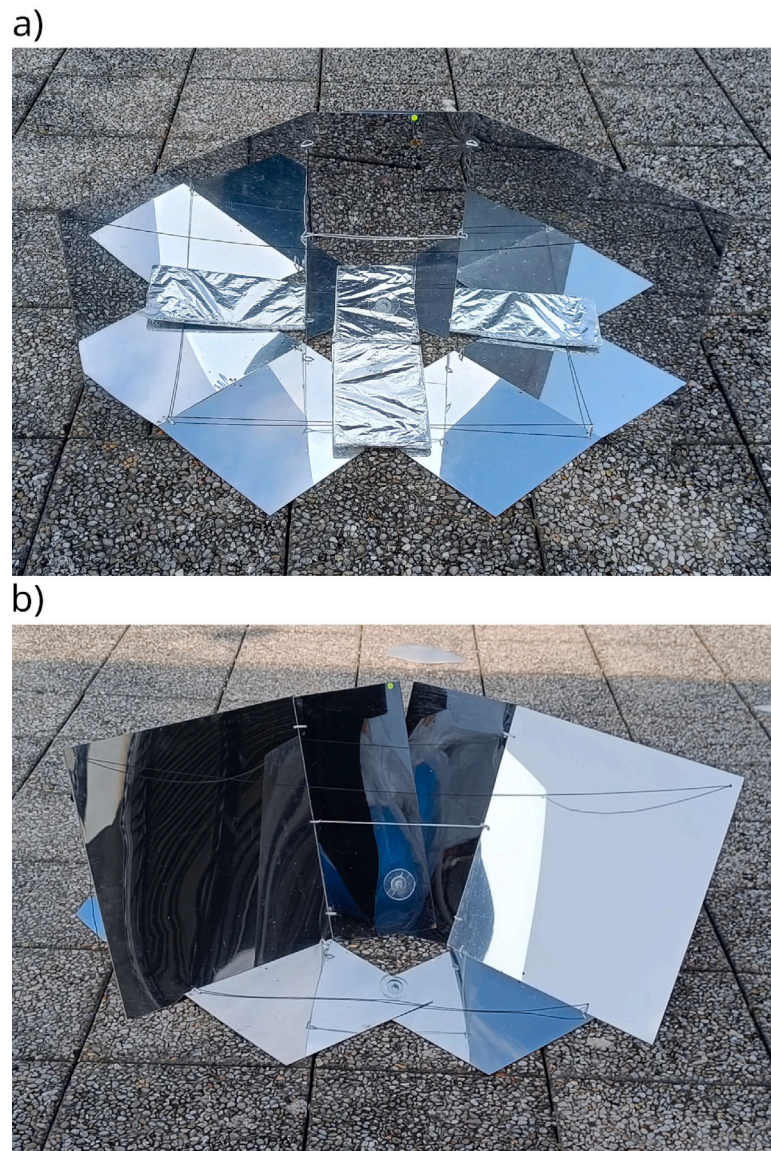


Fig. 3. Configurations of the Kimono for sun elevations between 40° and 70° : (a) Reference configuration; (b) Working configuration.



Fig. 4. Configuration of the Kimono for low sun elevation (lower than 40°).

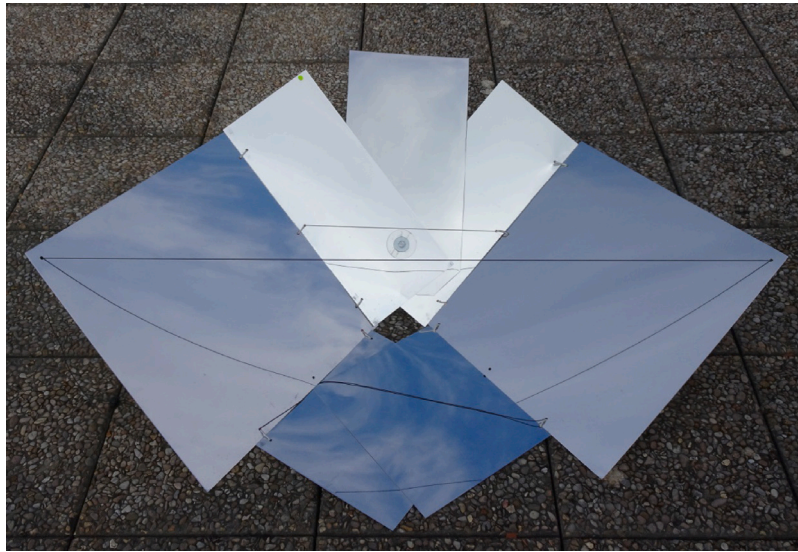


Fig. 5. Kimono Butterfly, i.e., configuration of the Kimono for high sun elevation (higher than 70°).

The procedure to adjust the geometry of the Kimono solar cooker during its use comprises the following steps. Firstly, the device in the reference configuration (shown in Fig. 3a) is placed on a rotating platform to facilitate its manual azimuthal tracking. Then, the receiver is placed on the reflective board and the cooker is rotated to ensure that the rear panels are directed towards the sun direction (azimuthal alignment). At this point, the tilt angles of the rear, side, and front panels are optimized. In particular, the side and rear panels are tilted to concentrate a larger amount of solar radiation towards the receiver. The optimal angle occurs when the shadow of a round sticker placed on the top of one of the rear panels (red point in Fig. 1b,c) falls on the sun-facing edge of the receiver lid. As an alternative to the round sticker, it is possible to check this optimal angle by placing a finger on the top edge of the rear panels. These panels are correctly placed when the shadow of the finger also falls on the sun-facing edge of the receiver lid (Fig. 6a). Instead, to ensure that the solar radiation is properly concentrated on the absorber on the front, the tilt angle of the front panel is changed so that the shadow of the receiver lid falls to half the height of the rear panels (Fig. 6b). Periodically, the platform at the base is rotated for azimuthal tracking. It is also checked that the aforementioned shadows are in correct position, otherwise the angles of the rear, side, and front panels are changed as described above.

3. Experimental setup and test

A description of the tests performed with the Kimono solar cooker is reported in this section, together with details about the test fluids, the equipment used in the outdoor tests, and the analyzed performance parameters.

3.1. Experimental setup

Fig. 7 shows the test bench used for carrying out the outdoor tests. Two identical Kimono prototypes, labeled as K1 and K2, were placed on a cardboard sheet on the ground, side by side, and tested simultaneously under the same outdoor environmental conditions. Four different receivers, comprising different black pots with lid and transparent enclosures, were tested during the experimental campaign. Fig. 8 shows the four receivers analyzed during the tests, while Table 1 shows the specifications for the pots, pot lids, and transparent enclosures. In particular, the selected enclosures are a truncated cone-shaped bowl with a glass lid (used in receiver R1), a hemispherical bowl with a

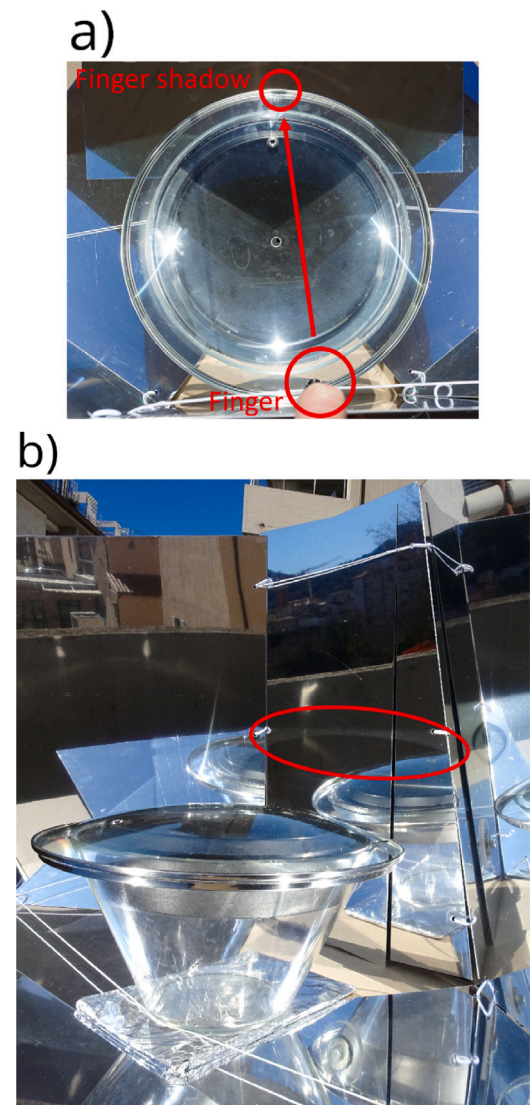


Fig. 6. Check of the rear (a) and front (b) shadows to maximize the solar radiation on the receiver.

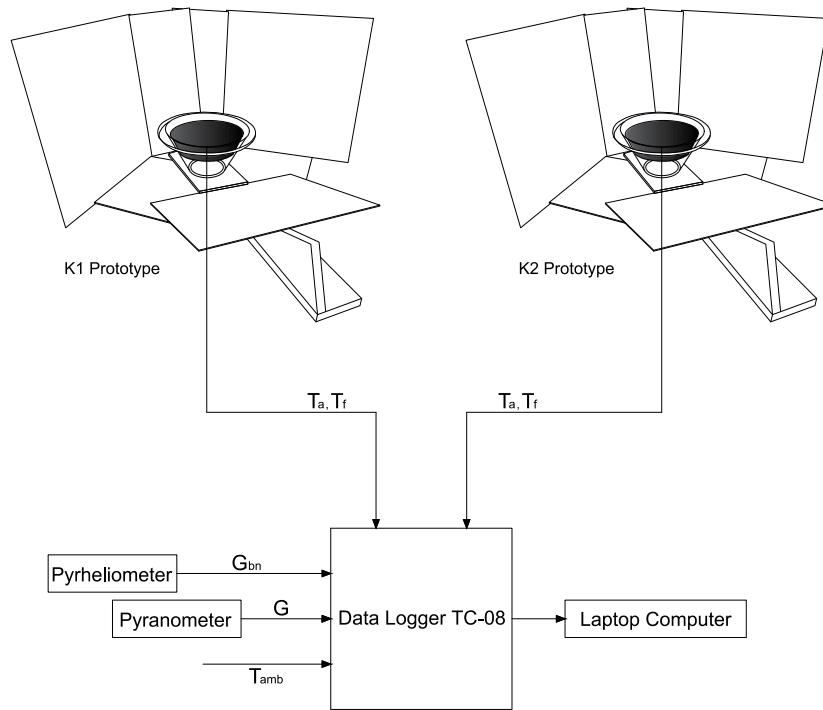


Fig. 7. Experimental setup. T_a : absorber temperature; T_f : testing fluid temperature; T_{amb} : ambient temperature; G_{bn} : direct normal irradiance; G : global horizontal irradiance.

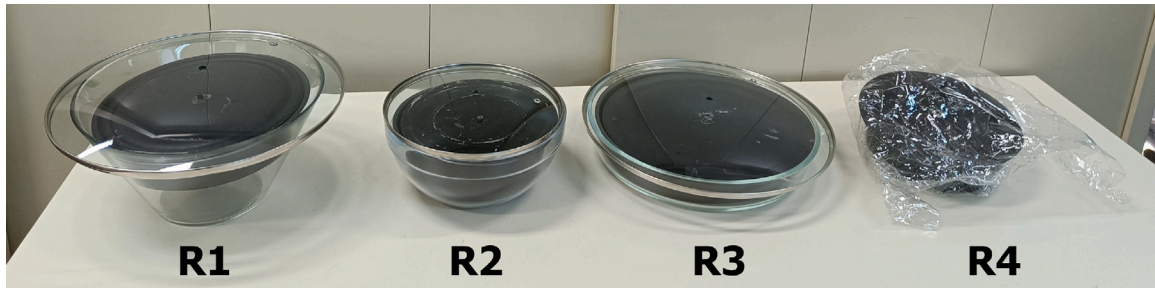


Fig. 8. Receivers used during the experimental campaign.

glass lid (used in R2), a round baking dish with a glass lid (used in R3), and a plastic bag (used in R4). Water and glycerin were used as test fluids. Water was chosen because it is the most widespread fluid to characterize the solar cookers' performance. Glycerin was selected since it is a well known and widely used fluid for properly testing solar cookers at temperatures higher than the water boiling point [34,35].

The following physical quantities were recorded in all the tests: ambient temperature (T_{amb}), direct normal solar irradiance (G_{bn}), and global horizontal solar irradiance (G). Instead, the temperature of the absorbers of the two receivers (T_a) was measured in no-load tests, while the temperature of the fluids inside the pots (T_f) in the load tests.

The sensors and instruments used during the tests to record the measured properties were:

- T-type thermocouples with an uncertainty of $\pm 1^\circ\text{C}$ to record T_a , T_f , and T_{amb} .
- An Eppley NIP (normal incidence pyrheliometer) with linearity $\pm 0.5\%$ in the range 0 to 1400 W/m^2 and with a 1-second response to measure G_{bn} .
- A CMP3 pyranometer (KIPP & ZONEN) with linearity $< 2\%$ from 0 to 1000 W/m^2 positioned horizontally to measure G .

The signals from the thermocouples, pyrheliometer, and pyranometer were recorded by a Pico Technology TC-08 datalogger and sent to a laptop as shown in Fig. 7. As detailed in previous works [14,19,33],

the global normal solar irradiance (G_n) was calculated from G_{bn} and G by using a procedure based on the Liu Jordan isotropic sky model [36] and considering an albedo of 0.2.

3.2. Experimental tests and parameters

The experimental campaign was carried out in May, June, and July 2023 on the DIISM building roof of the Marche Polytechnic University, Italy (latitude 43.5871° N , longitude 13.5149° E). The two Kimono prototypes were tested in parallel under the same external conditions. The devices were placed on cardboard sheets on the ground near the rooftop parapets, avoiding shaded areas and making sure they were sheltered from the wind.

During the tests, the operator adjusted the orientation and geometry of both devices for maximizing the solar radiation concentrated towards the receiver by following the procedure described in Section 2. Any change in the configuration of the cookers was recorded by the operator in terms of the tilt angles of the side and front panels. Considering that the aperture area of prototypes (i.e., the projected area on a plane perpendicular to the direction of the sun's rays) changed during the tests due to changes in their geometry, this area was calculated a posteriori by taking into account the sun elevation and the specific configuration of the reflective panels for each test. A dynamic 3D model was used for this purpose. However, to simplify the analysis

Table 1
Specifications of the four receivers used in the tests.

	Quantity	R1	R2	R3	R4
<i>Black pot with lid</i>					
Pot	Material	Enameled steel	Enameled steel	Enameled steel	Enameled steel
	Diameter, $\varnothing$ (cm)	$\varnothing_{upper} = 22.0$ $\varnothing_{lower} = 19.5$	$\varnothing_{upper} = 19.8$ $\varnothing_{lower} = 17.0$	$\varnothing_{upper} = 28.0$ $\varnothing_{lower} = 26.5$	$\varnothing_{upper} = 19.8$ $\varnothing_{lower} = 17.0$
	Height (cm)	5.0	6.0	6.0	6.0
	Volume (dm ³)	1.7	1.6	3.5	1.6
	Mass (kg)	0.268	0.124	0.196	0.124
Lid	Material	Enameled steel	Enameled steel	Enameled steel	Enameled steel
	Diameter, $\varnothing_{out}$ (cm)	23.0	20.4	29.0	20.4
	Thickness (mm)	0.2	0.2	0.2	0.2
	Mass (kg)	0.140	0.048	0.264	0.048
<i>Transparent enclosure</i>					
Base	Material	Glass	Glass	Glass	PETE
	Diameter, $\varnothing$ (cm)	$\varnothing_{upper} = 26.8$ $\varnothing_{lower} = 13.0$	$\varnothing_{upper} = 22.3$ $\varnothing_{lower} = 11.5$	$\varnothing_{upper} = 30.5$ $\varnothing_{lower} = 28.0$	–
	Height (cm)	14.5	10.5	6.0	55 × 60 ^a
	Volume (dm ³)	4.7	2.4	4.0	–
	Thickness (mm)	0.3	0.3	0.2	–
Lid	Material	Glass ^b	Glass ^b	Glass ^b	–
	Diameter, $\varnothing_{out}$ (cm)	33.0	23.0	34.0	–
	Thickness (mm)	0.2	0.2	0.2	–
	Mass (kg)	0.872	0.432	1.020	–

^a Length × width.

^b Tempered glass with stainless steel edge.

of the results, the values of the aperture area used to calculate the performance parameters and reported below were determined using the average sun elevation and tilt angles for each test, as suggested by the Standard ASAE S580.1 [17,37].

With the aim of accurately characterizing the device both thermally and optically, understanding the impact of the sun tracking and the receiver on its performance, an exhaustive experimental campaign was performed. In detail, several tests with the truncated cone-shaped receiver (R1 in Table 1) were repeated with and without a metallic lid and were divided between no-load and load tests. In this last case, the receiver was loaded with a mass of 1 kg of water or glycerin. Moreover, to analyze the influence of the sun tracking, various load tests were performed by adjusting the orientation of one prototype every 15 min, and the orientation of the other every 60 min. Finally, to identifying the influence of the receiver on the system, four different receivers (R1, R2, R3, and R4 described in Fig. 8 and Table 1) were tested with water and glycerin.

To thoroughly analyze the thermal and optical behaviors of the Kimono cooker, some of the main parameters proposed in the literature to characterize solar cookers were determined. For the no-load tests, the first figure of merit (F_1) described by Mullick et al. [38] was obtained. For the tests with load, the following parameters were calculated:

- heating time interval (Δt_h);
- overall thermal efficiency (η_{av}) based on definition proposed by Khalifa et al. [39];
- cooker opto-thermal ratio (COR) proposed by Lahkar et al. [40] and widely used to characterize the solar cookers tested with water and glycerin [32,34,35];
- standardized cooking power (P^*) derived by following the procedure recently proposed by Ruivo et al. [41].

Details about the parameters are reported in Appendix, together with the procedures applied to determine their values. However, it is worth noting that, in addition to the main procedure proposed by Lahkar et al. [40], the COR can be determined from the coefficients of standardized cooking power linear regression. In fact, in a manner similar to what Ruivo et al. [42] described in their work, it can be demonstrated that the coefficients a_0 and a_1 of the thermal efficiency linear regression

(Eq. (A.4)) can be derived from the coefficients a_0^* and a_1^* of the standardized cooking power linear regression (Eq. (A.6)) as follows:

$$a_0 = \frac{a_0^*}{A_a G_n^*} \quad (1)$$

$$a_1 = \frac{a_1^*}{A_a} \quad (2)$$

where A_a is the aperture area of the solar cooker and G_n^* is the reference solar irradiance ($G_n^* = 700 \text{ W/m}^2$). These expressions can be mathematically determined by obtaining Eq. (A.4) starting from Eq. (A.6). Consequently, the values of COR can be determined from the following expression:

$$COR = \frac{\alpha_0}{\alpha_1} = \frac{a_0^*}{a_1^* G_n^*} \quad (3)$$

4. Experimental results

In this section, the results obtained from the tests without and with load (water and glycerin) are reported. Finally, the results of the load tests carried out by using different receivers are compared and discussed.

4.1. Tests without load

Six tests without load were carried out under different environmental conditions. In detail, the two identical Kimono prototypes (K1 and K2) were tested in parallel by making orientation and geometry adjustments every 15 min to track the sun. The receiver used in both devices in all the tests was the truncated cone-shaped receiver (R1 in Table 1). In the first three tests shown in Table 2 (tests 1–3), the receivers were tested without a metal lid on the pot, while in tests 4–6 they were evaluated with a black metal lid. Table 2 shows the global and direct normal solar irradiances (G_n and G_{bn}) and the ambient temperature (T_{amb}) associated with the maximum temperature reached by bottom surface of the pot ($T_{a,max}$) for all the tests. The average sun elevation for the test location during the test time ($H_{sun,av}$) and the aperture area of the two prototypes ($A_{a,av}$) are also reported in Table 2, together with the calculated values of F_1 .

Table 2

Summary of tests without load. During the tests, the two devices were tested in parallel with receiver R1 and a sun tracking of 15 min.

Quantity	Test 1		Test 2		Test 3		Test 4		Test 5		Test 6	
Date	05/05/2023		22/05/2023		23/05/2023		07/06/2023		08/06/2023		20/07/2023	
Type of cooker	K1	K2	K1	K2	K1	K2	K1	K2	K1	K2	K1	K2
Metal lid	–	–	–	–	–	–	✓	✓	✓	✓	✓	✓
$H_{\text{sun,av}}$ (°)	59	59	58	58	59	59	62	62	61	61	63	63
$A_{\text{a,av}}$ (m ²)	0.521	0.511	0.509	0.515	0.510	0.512	0.519	0.508	0.527	0.512	0.521	0.513
G_{n} (W/m ²)	1044.76	1037.96	895.96	897.20	951.93	953.36	931.12	931.12	965.21	965.23	859.00	860.01
G_{bn} (W/m ²)	914.76	908.81	774.65	775.72	805.88	807.09	814.41	814.41	841.50	841.52	760.67	761.56
T_{amb} (°C)	22.97	22.50	23.62	22.85	25.07	25.33	27.27	27.27	26.00	26.36	31.53	31.84
$T_{\text{a,max}}$ (°C)	188.42	185.67	179.94	180.08	179.64	179.15	159.20	156.42	161.49	161.20	153.31	154.07
F_1 (°C/(W/m ²))	0.158	0.157	0.174	0.175	0.162	0.161	0.142	0.139	0.140	0.140	0.142	0.142

Table 3

Summary of the tests with water: the two devices were tested in parallel with receiver R1 with 1 kg of water and a sun tracking of 15 min. Testing parameters are referred to a time interval during which water temperature rose from 40 to 90 °C.

Quantity	Test 7		Test 8		Test 9		Test 10		Test 11		Test 12	
Date	24/05/2023		24/05/2023		12/06/2023		12/06/2023		26/06/2023		10/07/2023	
Type of cooker	K1	K2	K1	K2	K1	K2	K1	K2	K1	K2	K1	K2
Metal lid	–	–	–	–	✓	✓	✓	✓	✓	✓	✓	✓
Time when $T_f=40$ °C	10:41:36	10:40:56	14:41:38	14:42:44	10:35:38	10:36:33	12:21:31	12:19:54	10:49:22	10:50:17	14:07:21	14:07:46
$H_{\text{sun,av}}$ (°)	58	58	54	54	58	58	69	69	59	59	63	63
$A_{\text{a,av}}$ (m ²)	0.556	0.545	0.551	0.570	0.527	0.515	0.525	0.525	0.537	0.516	0.461	0.488
$G_{\text{n,av}}$ (W/m ²)	1006.90	1006.70	885.25	883.00	989.95	991.19	977.38	977.27	1014.37	1014.70	915.04	915.02
$G_{\text{bn,av}}$ (W/m ²)	810.78	810.62	822.30	820.21	835.46	836.51	867.36	867.25	851.09	851.37	828.39	828.38
$T_{\text{amb,av}}$ (°C)	25.50	25.48	28.05	28.10	24.76	24.77	25.75	25.74	26.56	26.57	36.18	36.18
Δt_h (min)	75.52	75.97	65.28	74.10	55.92	60.75	73.33	73.82	58.95	58.58	54.83	54.90
η_{av}	–	–	–	–	0.12	0.11	0.09	0.09	0.11	0.11	0.15	0.14
α_0	–	–	–	–	0.233	0.185	0.185	0.161	0.180	0.170	0.219	0.182
α_1 (W/m ² °C)	–	–	–	–	2.475	1.662	2.057	1.496	1.765	1.394	1.804	1.117
COR (Eq. (A.5)) (°C/(W/m ²))	–	–	–	–	0.094	0.111	0.090	0.108	0.102	0.122	0.121	0.163
R^2	–	–	–	–	0.939	0.941	0.948	0.901	0.937	0.943	0.940	0.866
α_0^* (W)	–	–	–	–	74.91	66.65	65.02	60.74	67.21	61.61	71.46	59.19
α_1^* (W/°C)	–	–	–	–	0.972	0.856	0.993	0.863	0.924	0.730	0.874	0.448
P_{50}^* (W)	–	–	–	–	26.3	23.9	15.4	17.6	21.0	25.1	27.8	36.8
COR (Eq. (3)) (°C/(W/m ²))	–	–	–	–	0.110	0.111	0.094	0.101	0.104	0.121	0.117	0.189
R^2 (P_1)	–	–	–	–	0.915	0.948	0.852	0.956	0.991	0.984	0.983	0.862

Table 4

Summary of the tests with water carried out with different sun tracking: the two devices were tested in parallel with receiver R1 with 1 kg of water. Testing parameters are referred to a time interval during which water temperature rose from 40 to 90 °C.

Quantity	Test 13		Test 14		Test 15		Test 16		Test 17		Test 18	
Date	25/05/2023		25/05/2023		21/06/2023		21/06/2023		26/06/2023		26/06/2023	
Type of cooker	K1	K2	K1	K2	K1	K2	K1	K2	K1	K2	K1	K2
Metal lid	–	–	–	–	✓	✓	✓	✓	✓	✓	✓	✓
Sun tracking (min)	60	15	15	60	60	15	60	15	60	15	60	15
Time when $T_f=40$ °C	10:11:59	10:12:17	13:08:00	13:08:30	11:31:12	11:32:08	13:22:04	13:22:33	12:18:36	12:18:47	14:33:54	14:35:48
$H_{\text{sun,av}}$ (°)	58	58	63	63	65	65	67	67	69	69	59	59
$A_{\text{a,av}}$ (m ²)	0.515	0.513	0.573	0.534	0.555	0.536	0.537	0.542	0.526	0.559	0.550	0.541
$G_{\text{n,av}}$ (W/m ²)	989.20	971.70	933.70	930.38	942.54	948.52	898.14	899.05	994.81	995.37	903.80	903.89
$G_{\text{bn,av}}$ (W/m ²)	791.40	777.39	819.19	816.28	602.88	606.71	667.69	668.37	864.47	864.96	849.82	849.90
$T_{\text{amb,av}}$ (°C)	23.49	22.97	24.50	24.50	31.36	31.34	32.65	32.49	28.89	28.74	29.50	29.48
Δt_h (min)	138.12	92.07	84.27	130.40	67.35	69.27	76.33	64.98	76.40	66.02	64.00	61.23
η_{av}	–	–	–	–	0.10	0.10	0.09	0.11	0.09	0.09	0.11	0.12
α_0	–	–	–	–	0.152	0.165	0.146	0.158	0.140	0.156	0.168	0.156
α_1 (W/m ² °C)	–	–	–	–	1.350	1.786	1.265	1.213	1.360	1.536	1.376	0.947
COR (Eq. (A.5)) (°C/(W/m ²))	–	–	–	–	0.113	0.092	0.115	0.130	0.103	0.102	0.122	0.165
R^2	–	–	–	–	0.940	0.991	0.899	0.876	0.883	0.960	0.868	0.883
α_0^* (W)	–	–	–	–	59.13	61.74	56.53	59.09	52.06	60.66	62.70	59.00
α_1^* (W/°C)	–	–	–	–	0.748	0.949	0.772	0.623	0.734	0.837	0.766	0.512
P_{50}^* (W)	–	–	–	–	21.73	14.29	17.93	27.94	15.36	18.81	24.40	33.40
COR (Eq. (3)) (°C/(W/m ²))	–	–	–	–	0.113	0.093	0.105	0.136	0.101	0.104	0.117	0.165
R^2 (P_2)	–	–	–	–	0.955	0.995	0.948	0.906	0.919	0.972	0.856	0.954

It can be seen from Table 2 that similar values of $T_{\text{a,max}}$ and F_1 were obtained for the two prototypes K1 and K2 for the tests performed in the same conditions. Furthermore, it should be noted that, as expected, $T_{\text{a,max}}$ and F_1 are higher in the tests where the receiver was not equipped with a lid (tests 1–3 of Table 2). In detail, the average $T_{\text{a,max}}$ are 182.67 °C for K1 and 181.63 °C for K2 in tests 1–3, while they are 158.00 °C and 157.23 °C for K1 and K2, respectively, in tests 4–6. Instead, the average values of F_1 are as follows: 0.165 °C/(W/m²) for

K1 and 0.164 °C/(W/m²) for K2 in the first three tests of Table 2 and 0.141 °C/(W/m²) for K1 and 0.140 °C/(W/m²) for K2 in tests 4–6.

4.2. Tests with water

Twelve tests were carried out using the receiver R1 loaded with 1 kg of water under different conditions. In detail, six tests were performed by arranging the two prototypes K1 and K2 in parallel and adjusting their orientation and geometry every 15 min. Their results are reported

in Table 3. In particular, tests 7 and 8 of Table 3 were conducted without a black metal lid on the pot, while the others with a black metal lid (tests 9–12 of Table 3). The remaining six tests reported in Table 4 were carried out by testing the two prototypes with different sun tracking: one was adjusted every 15 min and the other every 60 min. Whenever the second prototype was adjusted, it was also rotated about 15° clockwise from the sun direction to ensure a good azimuthal orientation for all the 60 min. The receiver without a black metal lid was used in tests 13 and 14, while the receiver with a metal lid was used in tests 15–18 of Table 4.

The results reported in Tables 3 and 4 show that, under the same conditions (presence or absence of a metal lid and sun tracking every 15 min or every 60 min), the two prototypes K1 and K2 ensured very similar and repeatable performance even on different days. In general, they were able to bring the water from 40 °C to 90 °C in about an hour, with some exceptions. However, the results provided by the solar cooker tested with the receiver without a metal lid were worse than that of the receiver with the metal lid, regardless of sun tracking. In particular, for the tests with sun tracking every 15 min, the heating time interval (Δt_h) for the cooker without a metal lid was about 19% longer than that of the prototype tested with the lid. This difference was even greater for the tests with sun tracking every 60 min (about 47%). A possible explanation of the limited performance of the device tested without the metal lid and loaded with water could be the condensation formation on the glass lid which caused a significant decrease in the optical efficiency of the system. In fact, the formation of a liquid film on the glass lid, which reduced the solar radiation absorbed by the water in the pot, was noted at temperatures above 60 °C due to water evaporation. Since the results of the tests with water carried out without a metal lid were highly affected by the condensation issue, it was not possible to properly analyze the thermal and optical behaviors of the device; consequently, the related performance parameters are not reported in Tables 3 and 4.

The results reported in Table 4 also indicate that the performance of the solar cooker adjusted every 60 min was generally lower than that of the prototype with sun tracking of 15 min. However, this performance drop was limited and more evident for the tests with a receiver without a metal lid, again due to condensation issue. Instead, the values of parameters obtained for the tests with the metal lid are quite similar, proving that the Kimono solar cooker ensures good performance even when it is properly oriented every hour.

It is worth noting from the tables that the values of COR calculated using Eqs. (3) and (A.5) are close for all the tests, having a relative deviation of about 5%. This outcome proves the accuracy of both approaches in the description of the solar cooker performance, since they are based on reliable theoretical basis.

For the tests with water, the average standardized power (P^*) for the four tested conditions (i.e., absence and presence of a black metal lid and sun tracking every 15 min and every 60 min) was also calculated by applying the procedure described in Appendix. Fig. 9 shows the results of these calculations, together with the linear regressions and the coefficients of determination R^2 . Moreover, the trends of P^* reported in this figure are summarized in Fig. 10

It is evident from Figs. 9 and 10 that:

- For the tests with a metal lid, the coefficients of the linear regression (lines b and d) are comparable to that of the single tests reported in Tables 3 and 4. Also the values of P_{50}^* for lines b and d (which are 22.45 W and 19.79 W, respectively) agree with the values of each test. This further confirm the repeatable performance of the device under study.
- For the tests without a metal lid (lines a and c), the values of P^* at low temperature differences are greater than that for the tests with a metallic lid (lines b and d). This behavior agrees with the results of the tests without load where higher $T_{a,max}$ were achieved in the tests without the metal lid. However, the lines a and c

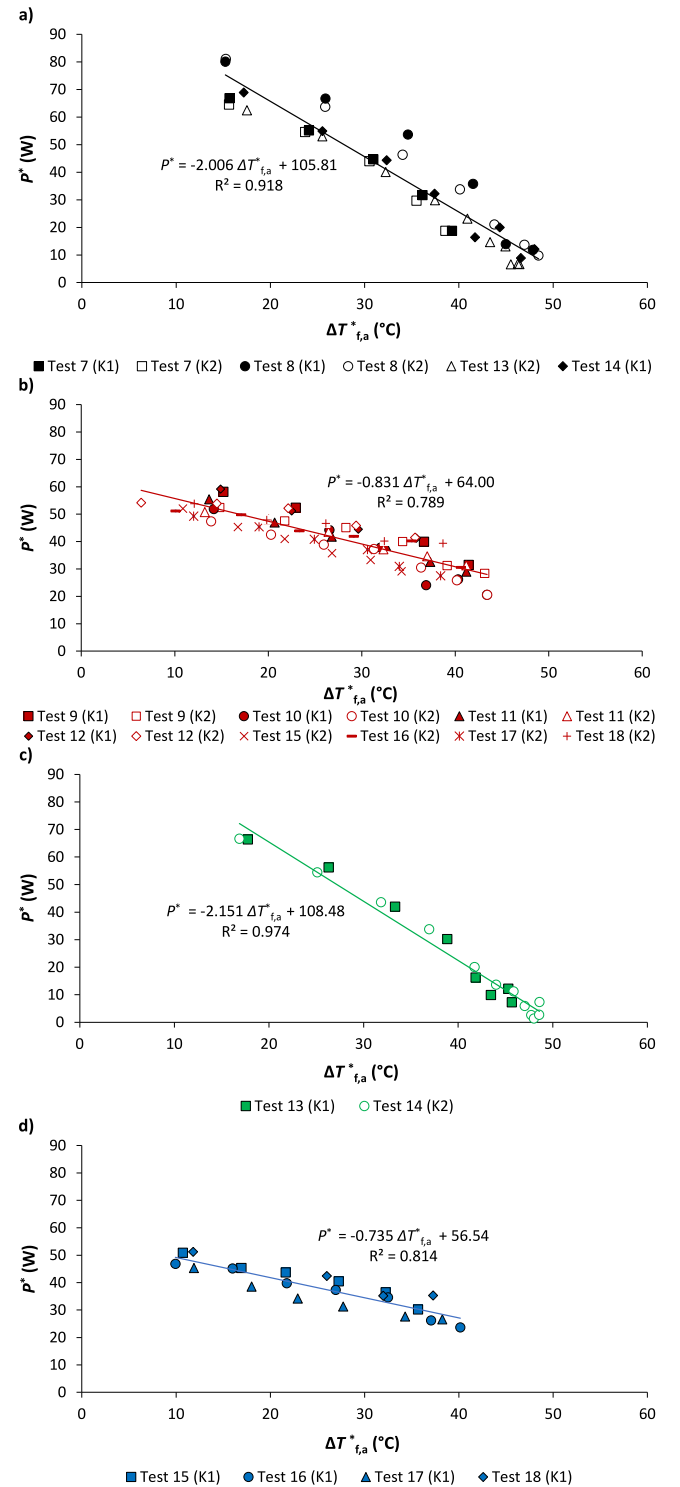


Fig. 9. Average standardized power (P^*) as a function of the standardized temperature difference (ΔT^*) for the tests with water (Tables 3 and 4): (a) tests without a black lid and sun tracking of 15 min; (b) tests with a black lid and sun tracking of 15 min; (c) tests without a black lid and sun tracking of 60 min; (d) tests with a black lid and sun tracking of 60 min.

have a steeper decrease at high temperature difference due to the condensation formation that reduces the optical efficiency of the device. Consequently, the values of P_{50}^* and COR derived from lines a ($P_{50}^* = 5.51$ W and COR (Eq. (3)) = 0.075 °C/(W/m²)) and c ($P_{50}^* = 0.93$ W and COR (Eq. (3)) = 0.072 °C/(W/m²))

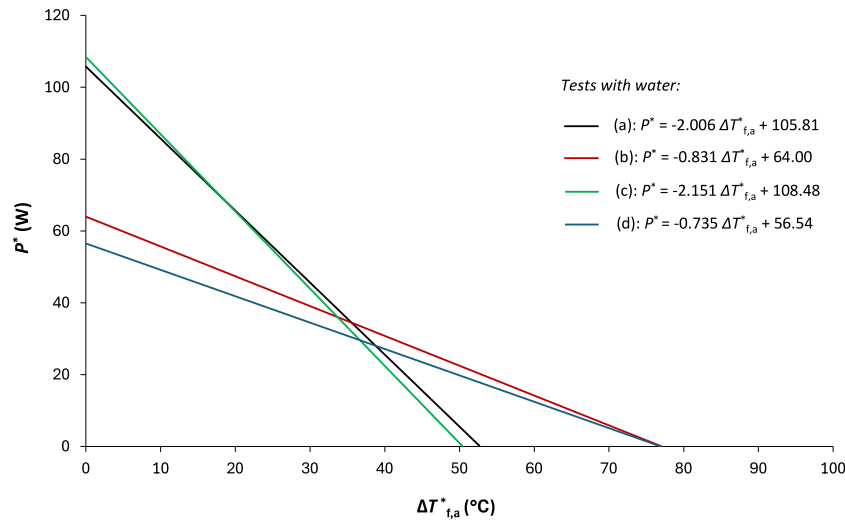


Fig. 10. Summary of the linear regression curves of the average standardized power (P^*) for the tests with water (Fig. 9): (a) tests without a black lid and sun tracking of 15 min; (b) tests with a black lid and sun tracking of 15 min; (c) tests without a black lid and sun tracking of 60 min; (d) tests with a black lid and sun tracking of 60 min.

Table 5

Summary of the tests with glycerin: the two devices were tested in parallel with receiver R1 with 1 kg of glycerin and a sun tracking of 15 min. Testing parameters are referred to a time interval during which glycerin temperature rose from 50 to 120 °C.

Quantity	Test 19		Test 20		Test 21		Test 22		Test 23	
Date	29/06/2023		05/07/2023		29/06/2023		03/07/2023		19/07/2023	
Type of cooker	K1		K2		K1		K2		K1	
Metal lid	—		—		✓		✓		✓	
Time when $T_f=50$ °C	10:20:06	10:21:32	13:11:20	13:11:30	12:46:05	12:43:49	10:26:19	10:27:04	10:27:26	10:29:05
$H_{\text{sun,av}}$ (°)	57	57	67	67	65	65	62	62	55	55
$A_{\text{a,av}}$ (m ²)	0.505	0.497	0.554	0.530	0.556	0.532	0.610	0.590	0.532	0.525
$G_{\text{n,av}}$ (W/m ²)	1004.89	1006.16	957.81	957.80	987.10	987.88	978.94	980.78	914.35	923.07
$G_{\text{bn,av}}$ (W/m ²)	880.12	881.24	839.81	839.80	918.43	919.16	825.83	827.38	630.64	636.66
$T_{\text{amb,av}}$ (°C)	25.42	25.43	28.19	28.20	26.73	26.89	30.10	30.22	31.65	31.68
Δt_h (min)	43.65	45.00	60.93	60.22	86.97	99.77	95.25	101.42	81.70	90.07
η_{av}	0.15	0.15	0.10	0.11	0.07	0.06	0.06	0.06	0.08	0.08
α_0	0.298	0.260	0.220	0.260	0.130	0.150	0.179	0.175	0.200	0.195
α_1 (W/m ² °C)	2.264	1.718	1.790	2.276	0.972	1.290	1.784	1.758	1.743	1.781
COR (Eq. (A.5)) (°C/(W/m ²))	0.132	0.151	0.123	0.114	0.134	0.116	0.100	0.100	0.115	0.109
R^2	0.996	0.857	0.990	0.997	0.900	0.916	0.969	0.937	0.987	0.980
a_0^* (W)	94.84	84.73	85.99	98.12	62.68	54.22	75.46	72.02	74.31	67.63
a_1^* (W/°C)	0.937	0.736	0.987	1.212	0.750	0.683	1.066	1.035	0.927	0.859
P_{50}^* (W)	47.99	47.93	36.64	37.52	25.18	20.07	22.16	20.27	27.96	24.68
COR (Eq. (3)) (°C/(W/m ²))	0.145	0.164	0.124	0.116	0.120	0.113	0.101	0.099	0.115	0.112
R^2 (P_i)	0.989	0.992	0.994	0.998	0.865	0.977	0.983	0.967	0.993	0.986

are significantly lower than that of lines b ($P_{50}^* = 22.45$ W and COR (Eq. (3)) = 0.110 °C/(W/m²)) and d ($P_{50}^* = 19.79$ W and COR (Eq. (3)) = 0.110 °C/(W/m²)). This outcome confirms that the results of the tests without a lid were highly affected by the condensation and do not accurately describe the thermal and optical behaviors of the solar cooker.

- Fig. 10 also confirms that the performance of the prototype adjusted every 60 min (lines c and d) was only slightly lower compared to that ensured by the device adjusted every 15 min (curves a and b, respectively).

4.3. Tests with glycerin

Nine tests were carried out by using the receiver R1 loaded with 1 kg of glycerin under different conditions. In detail, the first five tests reported in Table 5 were performed by placing the two devices K1 and K2 in parallel and adjusting their orientation every 15 min. The receiver without a metal lid was used in tests 19 and 20, while the receiver with a metal lid was tested in the remaining three tests (21–23 of Table 5). The four tests reported in Table 6 were carried out by testing the two prototypes with different sun tracking: one was adjusted

every 15 min (as in the tests of Table 5) and the other every 60 min. As in the tests with water, the second prototype was rotated about 15° clockwise from the sun direction whenever it was adjusted. In tests 24 and 25 of Table 6, the receiver without a metal lid was used. Instead, the receiver R1 with a metal lid was used in tests 26 and 27 of Table 6. The quantities reported in Tables 5 and 6 for the glycerin tests are the same as those measured and calculated for the tests with water. However, the reported testing parameters were calculated in the time interval during which glycerin temperature rose from 50 to 120 °C.

The results of Tables 5 and 6 show that the two prototypes have a comparable behavior when tested under the same conditions, as already pointed out for the tests with water. Moreover, they confirm that the prototype with sun tracking of 60 min provided slightly lower performance than that of the solar cooker adjusted every 15 min. However, this difference was very limited: Δt_h of the solar cooker adjusted every 60 min increased by about 8% for the tests without a metal lid and 10% for that with a metal lid. As for the tests with water, similar values of COR were provided by Eqs. (A.5) and (3).

Instead, in contrast to the tests with water, the prototype with a receiver without a metal lid ensured better results than the device tested with a black lid. In fact, for the tests with sun tracking of 15 min, the average Δt_h of the device without a metal lid (60.65 min) was about

Table 6

Summary of the tests with glycerin carried out with different sun tracking: the two devices were tested in parallel with receiver R1 with 1 kg of glycerin. Testing parameters are referred to a time interval during which glycerin temperature rose from 50 to 120 °C.

Quantity	Test 24		Test 25		Test 26		Test 27	
Date	06/07/2023		19/07/2023		06/07/2023		07/07/2023	
Type of cooker	K1	K2	K1	K2	K1	K2	K1	K2
Metal lid	–	–	–	–	✓	✓	✓	✓
Sun tracking (min)	60	15	60	15	60	15	60	15
Time when $T_f=50$ °C	12:59:13	13:00:08	12:33:50	12:33:42	10:23:34	10:20:24	12:39:32	12:37:32
$H_{\text{sun,av}}$ (°)	67	67	67	67	56	56	66	66
$A_{\text{a,av}}$ (m ²)	0.553	0.540	0.522	0.518	0.496	0.499	0.447	0.479
$G_{\text{a,av}}$ (W/m ²)	888.72	889.37	928.79	927.75	975.50	967.32	972.66	973.29
$G_{\text{bn,av}}$ (W/m ²)	807.92	808.51	678.12	677.36	788.53	781.92	854.56	855.12
$T_{\text{amb,av}}$ (°C)	29.64	29.63	33.85	33.83	27.95	27.94	26.18	26.10
Δt_h (min)	96.23	90.23	70.92	63.87	84.87	78.63	139.42	124.45
η_{av}	0.07	0.08	0.10	0.11	0.08	0.09	0.05	0.06
α_0	0.235	0.216	0.255	0.269	0.168	0.177	0.168	0.151
α_1 (W/m ² °C)	2.128	1.863	2.398	2.450	1.349	1.403	1.655	1.328
COR (Eq. (A.5)) (°C/(W/m ²))	0.110	0.116	0.106	0.110	0.125	0.126	0.102	0.114
R^2	0.976	0.972	0.995	0.989	0.826	0.887	0.836	0.958
a_0^* (W)	90.92	82.27	93.52	84.10	56.79	62.48	54.07	51.71
a_1^* (W/°C)	1.175	1.020	1.263	1.010	0.641	0.688	0.789	0.663
P_{50}^* (W)	32.17	31.27	30.37	33.60	24.74	28.08	14.62	18.56
COR (Eq. (3)) (°C/(W/m ²))	0.111	0.115	0.106	0.119	0.127	0.130	0.100	0.111
R^2 (P_s)	0.986	0.986	0.999	0.951	0.795	0.826	0.900	0.979

Table 7

Summary of the water load tests carried out by using different receivers. The two devices were tested in parallel with sun tracking of 15 min. The receivers comprised pots with a metal lid loaded with 1 kg of water. Testing parameters are referred to a time interval during which water temperature rose from 40 to 90 °C.

Quantity	Test 28		Test 29		Test 30		Test 31		Test 32		Test 33	
Date	10/07/2023		10/07/2023		14/07/2023		14/07/2023		17/07/2023		17/07/2023	
Type of cooker	K1	K2	K1	K2	K1	K2	K1	K2	K1	K2	K1	K2
Type of receiver	R2	R1	R1	R2	R3	R1	R1	R3	R1	R4	R4	R1
Time when $T_f=40$ °C	10:56:59	10:55:33	12:32:45	12:29:17	13:04:41	13:06:16	14:42:47	14:40:47	12:12:03	12:10:12	14:09:47	14:13:05
$H_{\text{sun,av}}$ (°)	59	59	68	68	67	67	57	57	67	67	60	60
$A_{\text{a,av}}$ (m ²)	0.557	0.523	0.528	0.517	0.508	0.456	0.450	0.479	0.505	0.481	0.491	0.518
$G_{\text{a,av}}$ (W/m ²)	988.38	985.15	973.87	973.81	941.94	941.89	827.48	826.71	947.92	948.17	864.83	868.77
$G_{\text{bn,av}}$ (W/m ²)	790.83	788.25	822.84	822.79	789.67	789.64	780.37	779.64	742.62	742.81	727.27	730.58
$T_{\text{amb,av}}$ (°C)	32.04	31.98	33.80	33.71	31.94	31.89	33.10	33.05	34.42	34.43	35.84	35.55
Δt_h (min)	64.30	51.95	56.25	59.37	71.17	56.58	56.38	62.07	77.85	92.32	78.72	53.72
η_{av}	0.10	0.13	0.12	0.12	0.10	0.14	0.17	0.14	0.09	0.08	0.10	0.14
α_0	0.140	0.181	0.184	0.177	0.178	0.198	0.253	0.211	0.158	0.141	0.181	0.186
α_1 (W/m ² °C)	1.117	1.425	1.797	1.750	1.937	1.436	1.889	1.633	1.727	1.584	2.059	1.114
COR (Eq. (A.5)) (°C/(W/m ²))	0.124	0.127	0.102	0.101	0.092	0.138	0.134	0.129	0.091	0.089	0.088	0.167
R^2	0.979	0.891	0.984	0.974	0.975	0.973	0.856	0.938	0.853	0.944	0.908	0.907
a_0^* (W)	53.65	66.00	68.43	63.04	63.44	62.50	79.57	87.83	54.81	47.32	70.02	64.00
a_1^* (W/°C)	0.608	0.729	0.977	0.849	1.002	0.624	0.824	1.234	0.819	0.754	1.228	0.463
P_{50}^* (W)	23.25	29.55	19.58	20.59	13.34	31.30	38.37	26.13	13.86	9.62	8.62	40.85
COR (Eq. (3)) (°C/(W/m ²))	0.126	0.129	0.100	0.106	0.090	0.143	0.138	0.102	0.096	0.090	0.081	0.197
R^2 (P_s)	0.985	0.966	0.989	0.992	0.984	0.994	0.905	0.963	0.872	0.955	0.909	0.921

56% lower than that of the cooker with the lid (94.78 min), while it was about 34% lower for the tests with sun tracking of 60 minutes: 83.58 min for the former and 112.15 for the latter. In accordance with this, the values of the calculated parameters are generally higher for the prototype tested without the black lid. The better performance provided by this device configuration could be due to the fact that, unlike the water load tests, glycerin condensation on the glass lid was extremely limited and almost all the solar radiation was directly absorbed by the fluid.

Also for the tests with glycerin, the average P^* for the four tested conditions was determined as shown in Fig. 11. A summary of these trends of P^* as a function of $\Delta T_{f,\text{amb}}^*$ are shown in Fig. 12, together with the water trends reported in Figs. 9 and 10. It is evident from Figs. 11 and 12 that:

- The values of P^* for the glycerin load tests without a metal lid are always higher than those of the tests without a metal lid. This outcome is consistent with the results obtained in the no-load tests. However, as shown above, it does not match the behavior of the tests with water.
- The results of the tests with glycerin confirm that the performance of the prototype aligned every 60 min only slightly decreased compared to that with sun tracking of 15 min.

Table 8

Average values of Δt_h , η_{av} , COR , and P_{50}^* for the tests with water performed with different receivers (Table 7).

	Tests 28 and 29		Tests 30 and 31		Tests 32 and 33	
	R1	R2	R1	R3	R1	R4
$\Delta t_{h,\text{av}}$ (min)	54.10	61.84	56.48	66.62	65.79	85.52
η_{av}	0.13	0.11	0.16	0.12	0.12	0.09
COR_{av} (°C/(W/m ²))	0.115	0.113	0.136	0.111	0.129	0.089
$P_{50,\text{av}}^*$ (W)	24.57	21.92	34.84	19.72	27.36	9.12

- An almost perfect match between the P^* trends of the glycerin load tests with a metal lid (Figs. 11b and d) and those of the water load tests with a metal lid (Figs. 9b and d) is evident in Fig. 12. In particular, the values of P_{50}^* and COR (Eq. (3)) derived from the linear regressions for the tests with a black lid and sun tracking of 15 min are: 22.45 W and 0.110 °C/(W/m²) for water load tests (water (b) of Fig. 12) and 22.79 W and 0.110 °C/(W/m²) for glycerin load tests (glycerin (b)). Their values for the tests with sun tracking of 60 min are as follows: $P_{50}^* = 19.79$ W and COR (Eq. (3)) = 0.109 °C/(W/m²) for water load tests (water (d)) and $P_{50}^* = 18.94$ W and COR (Eq. (3)) = 0.107 °C/(W/m²) for glycerin

load tests (glycerin (d)). These results show that, in this case, not only the COR is independent from the fluid used in the tests, as already stated by Sagade et al. [34], but also the behaviors of P^* are very similar for both fluids.

- In contrast, as shown in Fig. 12, the linear regressions for the water load tests without a metal lid (Figs. 9a and c) are different than those of the corresponding tests with glycerin (Figs. 9a and c). This outcome is due to the fact that the tests with water were negatively affected by the condensation issue, as explained above.

4.4. Comparison between the receivers

In this section, the influence of the receiver on the performance of the solar cooker is analyzed. In this regard, the two prototypes were tested in parallel by using the four receivers described in Table 1 and Fig. 8 of Section 3 as follows: in each test, one prototype was tested with receiver R1 (taken as reference), while the other with one of the other three receivers (R2, R3 or R4). During the tests, the devices' orientation was adjusted every 15 min and pots with a metal lid loaded with 1 kg of fluid were used. Table 7 shows the results of the tests with water carried out using the four receivers. The average values of the parameters for the solar cooker tested with the different receivers are reported in Table 8.

From these tables, it is evident that the first three receivers (R1, R2, and R3) ensured rather similar results. Instead, as expected, the prototype tested with the plastic bag (R4) was characterized by lower performance, but it was still able to rise the water temperature from 40 to 90 °C in less than two hours. However, in all the tests, the device with the receiver R1 performed better than the others. In particular, it can be noted that, with respect to R1:

- $\Delta t_{h,av}$ increased by about 14% for R2, 18% for R3, and 30% for R4.
- η_{av} decreased by about 15% for R2, 25% for R3, and 25% for R4.
- COR calculated from Eq. (A.5) decreased by about 2% for R2, 18% for R3 and 31% for R4.
- P_{50}^* decreased by about 11% for R2, 43% for R3 and 67% for R4.

Also the results of the tests with glycerin carried out by using the prototypes with receivers R1 and R3 confirmed these outcomes. In fact, it was found that $\Delta t_{h,av}$ increased by about 11% for R3 with respect to R1, η_{av} decreased by about 10%, COR (Eq. (A.5)) decreased by about 6%, and P_{50}^* decreased by about 6%.

Finally, it is worth to point out that the analysis reported in this section only shows that the receiver R1 seems the better configuration for the Kimono solar cooker among the four studied receivers, but it does not prove that this receiver is the best in general. In fact, considering the huge number of configurations, shapes, and materials that can be used, it could be possible to identify alternative options that ensure better performance. Consequently, additional studies are necessary to find the best receiver for the solar cooker under analysis.

4.5. Comparison with the literature

Table 9 compares the values of the COR collected from experimental studies about panel solar cookers available in the literature with the average ones for the presented prototype. Details about the experimental tests used to derive the selected parameters are also reported. It is worth noting that only the COR was selected in the comparison since no values or not reliable data were found for the other parameters used to analyze the load tests. In fact, the parameters reported in the works that did not provide reliable information about the procedure and tests used for their calculation were neglected. It is important noting

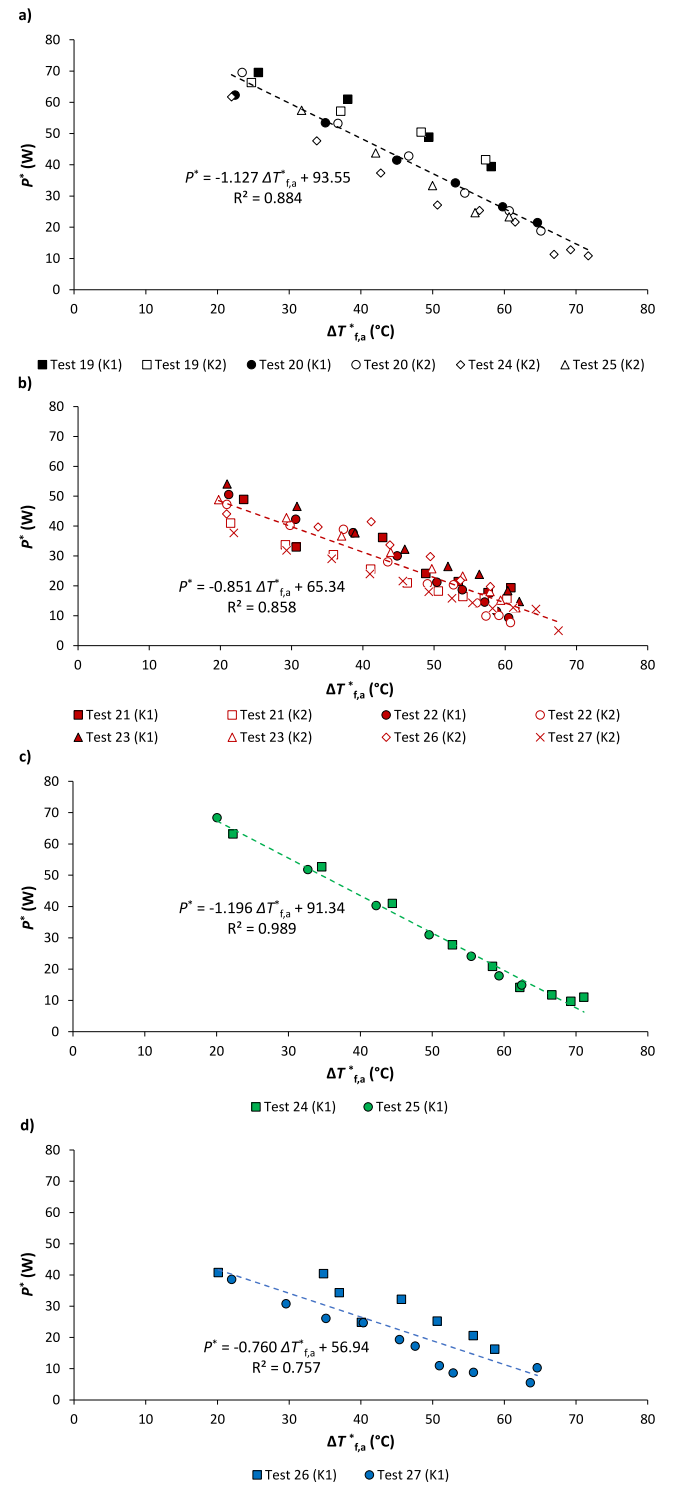


Fig. 11. Average standardized power (P^*) as a function of the standardized temperature difference (ΔT^*) for the tests with glycerin (Tables 5 and 6): (a) tests without a metallic lid and sun tracking of 15 min; (b) tests with a metallic lid and sun tracking of 15 min; (c) tests without a metallic lid and sun tracking of 60 min; (d) tests with a metallic lid and sun tracking of 60 min.

that it is not a trivial task to carry out a comparison between solar cookers since the differences in the prototypes and experimental tests presented in the various studies. Moreover, the experimental studies do not always follow the same testing procedure and do not present all the performance parameters. In this regard, despite only works about

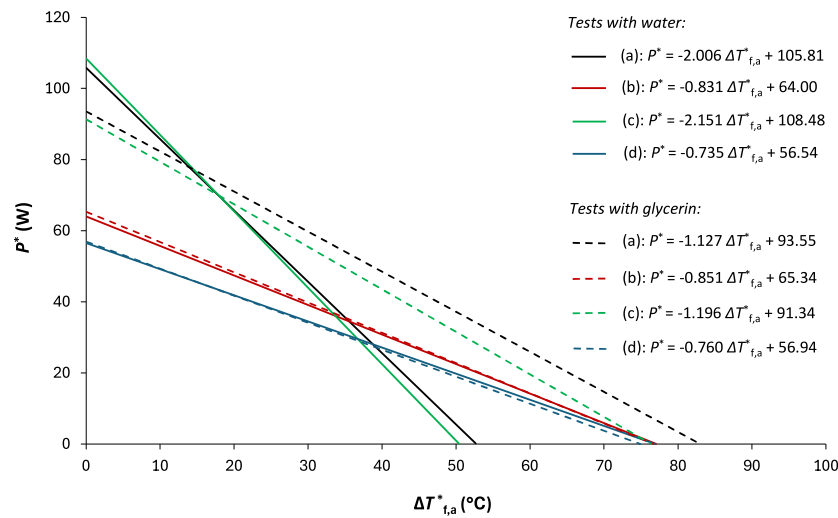


Fig. 12. Summary of the linear regression curves of the average standardized power (P^*) for the tests with glycerin (Fig. 11) and water (Fig. 9): (a) tests without a metallic lid and sun tracking of 15 min; (b) tests with a metallic lid and sun tracking of 15 min; (c) tests without a metallic lid and sun tracking of 60 min; (d) tests with a metallic lid and sun tracking of 60 min.

Table 9
Comparison with the literature.

Quantity	This work			Aquilanti et al. [14]				Apaolaza-Pagoaga et al. [20]		Ruivo et al. [42]
Test location	Ancona, Italy			Ancona, Italy				Malaga, Spain		Malaga, Spain
Test period	June and July 2023			July and August 2021				October–December 2020		11 November 2020
Type of cooker	Kimono			Kimono	Funnel	DSPC	Cookit	Funnel		Funnel
Type of receiver	Black enameled steel pot with a glass enclosure			Black stainless-steel cake pan with a glass enclosure				Black enameled steel pot without a glass enclosure	Black enameled steel pot with a glass enclosure	Black enameled steel pot with a glass enclosure
Lid	Black enameled steel		No	No				Transparent glass		Transparent glass
Testing fluid	Water	Glycerin	Glycerin	Water	Water	Water	Water	Glycerin	Glycerin	Glycerin
m_f (kg)	1	1	1	1	1	1	1	1.736	1.736	1.736
$A_{a,av}$ (m ²)	0.523	0.540	0.524	0.540	0.420	0.440	0.323	0.500 ^a	0.500 ^a	0.500 ^a
$G_{a,av}$ (W/m ²)	961.81	964.09	957.3	935.43	935.43	935.43	935.43	916.13	916.13	913.00
$T_{amb,av}$ (°C)	29.05	28.91	28.45	28.75	28.75	28.75	28.75	21.09	21.09	22.70
α_0	0.179	0.170	0.254	0.172	0.265	0.201	0.290	0.299	0.301	0.464
α_1 (W/m ² °C)	1.604	1.507	2.06	2.135	2.636	2.634	3.719	2.73	1.925	2.920
COR (Eq. (A.5)) (°C/(W/m ²))	0.117	0.114	0.124	0.081	0.101	0.076	0.078	0.110	0.157	0.159

^a Maximum solar collecting area.

panel cookers were considered in this analysis, they are characterized by different characteristics of the prototype (e.g., design, aperture area, and material), receivers, testing fluids and procedures.

From Table 9, it is evident that only a limited number of works reporting the COR for panel solar cookers were found. In general, it can be stated that the values of the Kimono analyzed here is consistent with those available in the literature. In particular, the studied solar cooker ensured higher COR for the tests with water with respect to the values of the four panel cookers presented by [14]. The lower performance of these prototypes could be due to the fact that they were made of low quality materials, such as cardboard and reflective Mylar film. Instead, for the tests with glycerin, the COR values of the proposed solar cooker generally agree with the ones reported for the funnel cooker by [20,42]. It is worth noting that this solar cooker provided higher values than those of the Kimono solar cooker when it was tested using a receiver comprising a black enameled steel pot with a glass enclosure and a transparent glass lid. However, it is not easy to directly state that this funnel cooker has better thermal performance

that the proposed prototype. In fact, this outcome can be influenced by the different receivers used in the tests. The receivers used in [20,42] could ensure higher performance than that of the studied receivers since they present an enclosure with a double glass.

5. Conclusions

A panel solar cooker with a variable geometry for proper sun tracking, called Kimono solar cooker, was experimentally characterized under different environmental conditions in Ancona, Italy. To evaluate the influence of the sun tracking and receiver on the cooker performance, two identical prototypes were tested without and with load by changing their geometry considering different time intervals and using various receiver configurations. The experimental results were used to determine some of the main performance parameters of solar cookers available in the literature. In details, water and glycerin were used as test fluids. In some tests, the orientation of one prototype was adjusted every 15 min, while the orientation of the other every 60 min. The

following four different receiver configurations were analyzed: a black pot with a truncated cone-shaped bowl with a glass lid (R1), a black pot with a hemispherical bowl with a glass lid (R2), a black pot with a round baking dish with a glass lid (R3), and a black pot with a plastic bag (R4). Moreover, a black pot lid was used in some tests.

The tests without load carried out with receiver R1 showed that the performance of the two prototypes was very similar. However, the solar cooker with the receiver without a black lid provided better results than those with the receiver with a lid. In fact, the former reached an average maximum temperature ($T_{a,max}$) and F_1 of 182.15 °C and 0.165 °C/(W/m²), respectively, while the latter provided $T_{a,max}$ = 157.62 °C and F_1 = 0.141 °C/(W/m²) as an average.

From the results of the tests with water carried out also using receiver R1, the following remarks can be made:

- Also in this case, both prototypes provided very similar results.
- The studied cooker was able to bring 1 kg of water from 40 to 90 °C in about an hour, proving its good performance.
- The device adjusted every 60 min provided only slightly lower results than the one adjusted every 15 min. This is evident from the average standardized cooking power (P_{50}^*) obtained in the tests with a black lid, that is 19.79 W for the former and 22.45 W for the latter. Consequently, it was shown that the Kimono solar cooker ensures good performance even when it is properly oriented every hour.
- The cooker tested with a receiver without a metal lid ensured much lower performance than that with a metal lid. In fact, the following average P_{50}^* for the device adjusted every 15 min were found: 5.51 W for the tests without a metal lid and 22.45 W for the tests with a metal lid. This result could be due to the condensation formation on the glass lid which caused a significant decrease in the optical efficiency of the first configuration.

The results of the tests with glycerin confirmed that the solar cooker had good thermal performance, even when its geometry is adjusted every hour. It was able to bring 1 kg of fluid from 50 to 120 °C in less than 2 h in almost all the cases. Instead, unlike the tests with water, the prototype tested without a metal lid provided better results than that with a black lid, since glycerin condensation on the glass lid was limited. In particular, the following average P_{50}^* for the device adjusted every 15 min were found: 37.20 W for the tests without a metal lid and 22.79 W for the tests with a metal lid. As a consequence, since the water condensation issue could highly affect the performance of panel solar cookers, specific studies about this topic should be carried out to properly evaluate its influence on different receiver configurations.

The comparison between the results obtained by using the four receivers showed that the receivers R1, R2, and R3 ensured rather similar results, while the receiver with a plastic bag (R4) was characterized by lower performance. Anyway, it was still able to rise the water temperature from 40 to 90 °C in less than two hours. However, the device with the receiver R1 provided better results than the others. Despite these results showed that the receiver R1 seems the better configuration for the Kimono solar cooker, it is worth to point out that they do not prove that it is the best in general. In fact, considering the huge number of configurations, shapes, and materials that can be used, additional studies are necessary to find the best receiver for the solar cooker under analysis.

From the comparison with the parameters collected from the literature for panel solar cookers, it was found that the performance of the proposed solar cooker was consistent with those of available prototypes.

Finally, it is important to point out that the solar cooker analyzed in this study was well described by performance parameters that are determined by considering a linear trend of the efficiency and power with respect to the difference between fluid temperature and ambient temperature. Moreover, it was found that the values of COR for the load tests derived by considering two different procedures, one based

on the thermal efficiency as suggested by Lahkar et al. [40] and another based on the standardized cooking power (P^*) proposed by Ruivo et al. [41], were very similar. This outcome proves the accuracy of both approaches in the description of the studied solar cooker performance. Therefore, given the reliability and accuracy of both parameters, the values of COR and P_{50}^* can be selected as the two independent parameters needed for a complete characterization of solar cookers well described by a linear behavior, ensuring an accurate comparison between devices with different designs. In fact, these two parameters allow to unequivocally define the two points, i.e., $P^*(\Delta T_{f,amb}^* = 50^\circ\text{C}) = P_{50}^*$ and $P^*(\Delta T_{f,amb}^* = COR \cdot G_n^*) = 0$ W, needed for determining their linear behavior of the standardized power as a function of the difference between the load and ambient temperatures.

CRediT authorship contribution statement

Sebastiano Tomassetti: Writing – original draft, Validation, Methodology, Investigation. **Alessia Aquilanti:** Writing – original draft, Visualization, Formal analysis. **Pio Francesco Muciaccia:** Writing – original draft, Investigation, Formal analysis. **Matteo Muccioli:** Writing – review & editing, Conceptualization. **Giovanni Di Nicola:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix. Experimental parameters

The parameters used to characterize the solar cooker under study are described in this section, together with their calculation procedures. For the tests without load, the first figure of merit (F_1) proposed by Mullick et al. [38] was determined. It has the following form:

$$F_1 = \frac{T_{a,max} - T_{amb}}{G_n} \quad (\text{A.1})$$

where $T_{a,max}$ is the absorber maximum temperature, T_{amb} is the ambient temperature recorded at $T_{a,max}$, and G_n is the global normal irradiance recorded at $T_{a,max}$.

The simplest parameter used to analyze the performance of the solar cooker tested with load is the heating time interval, defined as:

$$\Delta t_h = t(T_2) - t(T_1) \quad (\text{A.2})$$

where $t(T_1)$ and $t(T_2)$ are the starting and ending time of the heating phase, respectively. As suggested by Funk [37], the following reference temperatures were considered for the tests with water: $T_1 = 40^\circ\text{C}$ and $T_2 = 90^\circ\text{C}$. Instead, $T_1 = 50^\circ\text{C}$ and $T_2 = 120^\circ\text{C}$ were used for the tests with glycerin. Also the parameters indicated hereafter were calculated in these temperature ranges.

The overall thermal efficiency of the solar cooker was calculated for the load tests as follows:

$$\eta_{av} = \frac{m_f c_f (T_2 - T_1)}{G_{n,av} A_a \Delta t_h} \quad (\text{A.3})$$

where m_f is the mass of the test fluid, c_f is the specific heat of the test fluid, $G_{n,av}$ is the average global normal irradiance measured at Δt_h , and A_a is the aperture area of the solar cooker. Eq. (A.3) is based on the expression for the overall thermal efficiency proposed by Khalifa et al. [39], which comprises the direct normal solar irradiance (G_{bn}) instead of G_n .

As suggested by Lahkar et al. [40], the opto-thermal ratio of the cooker (COR) was determined through a procedure based on the Hottel–Whillier–Bliss equation for solar cookers, which is:

$$\eta = F' \eta_0 - \left(\frac{F' U_1}{C} \right) \frac{T_f - T_{amb}}{G_n} = \alpha_0 - \alpha_1 \chi \quad (\text{A.4})$$

where η is the thermal efficiency, F' is the heat exchange efficiency factor, η_0 is the optical efficiency, U_1 is the heat loss factor, C is the geometrical concentration ratio, T_f is the fluid temperature, and $\chi = (T_f - T_{amb})/G_n$. The coefficients $\alpha_0 = F'\eta_0$ and $\alpha_1 = (F'U_1)/C$ are the intercept value of the thermal efficiency linear regression and the opposite value of its slope, respectively. The COR has the following expression:

$$COR = \frac{\eta_0 C}{U_1} = \frac{\alpha_0}{\alpha_1} \quad (A.5)$$

The values of α_0 and α_1 to derive the COR parameter were calculated from the measurements as follows:

- The experimental data recorded in the time interval to cover the aforementioned temperature ranges were divided into sub-intervals of 5 min.
- The values of $G_{n,av}$, $T_{amb,av}$, $T_{f,av}$, η , and χ were determined for each 5 min sub-interval.
- From the plot of (η, χ) points for all the sub-intervals, the coefficients of the thermal efficiency linear regression and the corresponding coefficient of determination R^2 were determined.

Finally, the standardized cooking power (P^*) was determined by following the procedure recently proposed by Ruivo et al. [41], which is based on the Hottel-Whillier-Bliss equation. In this case, P^* can be written as:

$$P^* = a_0^* - a_1^* \Delta T_{f,amb}^* \quad (A.6)$$

where the coefficients a_0^* and a_1^* are the intercept value of the standardized cooking power linear regression and the opposite value of its slope, respectively. $\Delta T_{f,amb}^*$ corresponds to the difference between the fluid and ambient temperatures associated to the fluid heating process under the reference solar irradiance ($G_n^* = 700 \text{ W/m}^2$), defined as:

$$\Delta T_{f,amb}^* = (T_f - T_{amb}) \frac{G_n}{G_n^*} \quad (A.7)$$

The values of a_0^* and a_1^* were determined from the measurements using the following procedure:

- The experimental data recorded in the time interval to cover the aforementioned temperature ranges were divided into sub-intervals of 10 min.
- The values of $G_{n,av}$, $T_{amb,av}$, $T_{f,av}$, P_{av}^* , and $\Delta T_{f,amb}^*$ were determined for each sub-interval. In particular, P_{av}^* is defined as:

$$P_{av}^* = \frac{m_f c_f \Delta T_f}{\Delta t} \frac{G_n}{G_{n,av}} \quad (A.8)$$

where ΔT_f is the variation of the fluid temperature in the considered sub-interval and the time interval Δt is equal to 600 s.

- From the plot of $(P_{av}^*, \Delta T_{f,amb}^*)$ points for all the sub-intervals, the coefficients of the standardized cooking power linear regression and the corresponding coefficient of determination R^2 were determined.

The standardized power at a temperature difference of 50°C between fluid and air (P_{50}^*) was calculated from Eq. (A.6) with $\Delta T_{f,a}^* = 50^\circ\text{C}$.

Nomenclature

Latin symbols

A Area (m^2)

a_0^* Intercept of the standardized cooking power linear regression

a_1^* Opposite value of the slope of the standardized cooking power linear regression

C Geometrical concentration ratio

COR Cooker opto-thermal ratio ($^\circ\text{C}/(\text{W}/\text{m}^2)$)

c Specific heat ($\text{J}/(\text{kg } ^\circ\text{C})$)

F_1 First figure of merit ($^\circ\text{C}/(\text{W}/\text{m}^2)$)

F' Heat exchange efficiency factor

$F'U_1$ Heat loss factor ($\text{W}/\text{m}^2 \text{ } ^\circ\text{C}$)

G Global horizontal irradiance (W/m^2)

G_{bn} Direct normal irradiance (W/m^2)

G_n Global normal irradiance (W/m^2)

G_n^* Reference solar irradiance ($700 \text{ W}/\text{m}^2$)

H_{sun} Sun elevation ($^\circ$)

m Mass (kg)

P^* Standardized cooking power (W)

P_{50}^* Standardized cooking power at a temperature difference of 50°C (W)

T Temperature ($^\circ\text{C}$)

t Time (s)

Greek symbols

α_0 Intercept of the thermal efficiency linear regression

α_1 opposite value of the slope of the thermal efficiency linear regression

Δ Delta difference

$\Delta T_{f,amb}^*$ Difference between the fluid and ambient temperatures associated to the fluid heating process under G_n^* ($^\circ\text{C}$)

η Thermal efficiency

η_0 Optical efficiency

χ Specific temperature difference ($^\circ\text{C}/(\text{W}/\text{m}^2)$)

Subscripts

a Absorber, aperture

amb Ambient

av Average

f Fluid

h Heating

max Maximum

Acronyms

DIISM Department of Industrial Engineering and Mathematical Sciences

DSPC Dual Setting Panel Cooker

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