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Experimental characterization and performance comparison of four prototypes of panel solar cooker for low to high sun elevations

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ABSTRACT

Solar panel cookers are affordable and easy-to-manufacture systems to cook food in a sustainable way. In this work, four solar panel cookers were assembled and tested outdoor in parallel to compare their thermal and optical performances under the same environmental conditions. The following four devices, assembled using inexpensive materials, were selected: Kimono, Funnel, Dual Setting Panel Cooker, Cookit. The Kimono cooker is a novel design proposed by one of the authors and was never analyzed before. The four cookers were tested outdoor in three different periods of the year, in the location of Ancona, Italy. Two configurations of the cookers, characterized by different aperture areas, were tested under no load and with the same amount of water (1 kg) in an identical cake pan placed inside a glass bowl used as heat trap. One configuration was more suitable for low-medium sun elevation, while the other one for medium-high sun elevation. It was found that the Kimono and Funnel cookers have the best performance with low-medium and medium-high sun elevations. In the three measurements sets, the average heating time for water to reach the boiling point was 1.74 h for the former cooker and 1.66 h for the latter. The Cookit showed a good performance at medium sun elevations, while the Dual Setting Panel Cooker was never able to reach water boiling point at low-medium sun elevation.

1. Introduction

Solar cookers are considered economical and sustainable solutions to exploit solar energy for cooking purposes in all the sunny areas of the world (Cuce and Cuce, 2013; Kundapur, 2018). This is especially true in developing countries (Narayan and Doytch, 2017; Pillai and Banerjee, 2009; Karekezi and Kithyoma, 2002), where the energy demand for this purpose is usually covered by non-commercial fuels such as firewood, agricultural waste, and cow dung (Pizarro-Loaiza et al., 2021; Tucho and Nonhebel, 2015; Bewket, 2003). Considering that solar energy is abundant in several regions of the world for many days of the year (Barba et al., 2019; Nahar, 2003), it is evident that solar cooking represent a possible environmentally friendly choice to avoid some serious ecological problems. A possible classification of solar cookers comprises the following three main groups: panel cookers, box cookers and parabolic cookers (Cuce and Cuce, 2013; Aramesh et al., 2019; Panwar et al., 2012; Arunachala and Kundapur, 2020). Among these three groups, solar panel cookers are generally more cost-effective and easier to build, presenting the simplest design. The following aspects affect the thermal performance and the cooking time of this type of solar cookers (Ruivo et al., 2021): aperture area; size and properties of the receiver; shape and reflectivity of the reflective panels; transparent cover; cooking vessel; amount and type of food to be cooked; environmental conditions; available solar radiation.

Considering their simplicity and flexibility, several solar panel cooker designs have been developed in the last decades (Cuce and Cuce, 2013; Aramesh et al., 2019; Arunachala and Kundapur, 2020; Thamizharasu et al., 2021). One of the first and well-known solution is the simple and cost-effective configuration known as Cookit (Cookit, 2021), which is based on a design proposed by the French scientist Roger Bernard. Other widespread designs of panel solar cookers are: Hot pot (Hot Pot, 2021), Dual-setting panel cooker (DSPC) (Dual-Setting Panel Cooker, 2021), Copenhagen (Copenhagen, 2021), Fun-panel (Fun-Panel, 2021), and Concrete funnel cooker (Ruivo, 2022), also known as Pucca cooker.

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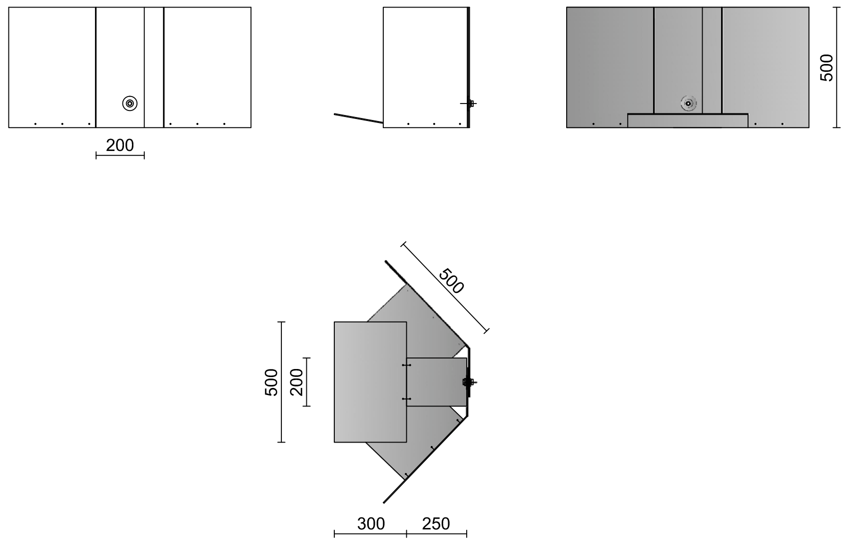

Fig. 1. Kimono solar cooker views (dimensions in mm).

Table 1 summarizes some of the main experimental works related to solar panel cookers available in the literature. It should be noted that Ruivo and his co-authors not only carried out experimental works (Ruivo et al., 2021; Apaolaza-Pagoaga et al., 2021a,b, 2022b,a; Ruivo et al., 2022a), but also other analyses on solar panel cookers (Ruivo et al., 2022c; Carrillo-Andrés et al., 2022; Ruivo et al., 2022b).

In order to investigate in detail the performance of solar panel cookers, in this paper four devices were assembled and experimentally tested outdoor. Tests were carried out both under no-load conditions and using water as test fluid. The performance of the cookers at different sun elevation angles were investigated, using suitable configurations. Another novelty of this study lies in the proposal of a new original design, the Kimono solar oven, whose performance was not reported in the literature. Moreover, the DSPC was never analyzed in the scientific literature. The paper is organized as follows. Section 2 provides the details of the design, construction and materials for each solar panel cooker tested, together with their working configurations. Section 3 describes the test rig and the parameters considered to evaluate the performance of the cookers. Section 4 reports the experimental results of the work. Finally, Section 5 reports the main conclusions of the work.

2. Design, manufacture and materials

In this section, the construction details of the four panel solar cooker prototypes, namely the Kimono solar cooker, the Funnel solar cooker, the Dual-setting panel cooker (DSPC) and the Cookit, along with the materials chosen for their construction, are provided.

2.1. Kimono solar cooker

The Kimono solar cooker, shown in Figs. 1 and 2a,b, was constructed by following the design specification provided by one of the authors of this work, Matteo Muccioli, who is the designer of this device (Kimono Solar Cooker, 2021). Starting from a Plexiglas sheet with a thickness of 3 mm, two side panels (500×500 mm each), two bottom panels (300×350 mm each), a front panel (250×200 mm) and two rear panels (500×200 mm each) were cut and drilled. A Mylar film, chosen as reflective material, was fixed to the seven panels using double-sided adhesive tape, obtaining a smooth and uniform surface. This reflective material has been applied in the other prototypes using the same procedure. Then, one side panel, one bottom panel and one rear panel were joined together with a wire, creating one part. A symmetrical part was obtained by assembling together the three remaining panels. The two parts were joined together by two holes, one in each rear panel, specifically designed for this purpose. A knob was inserted to adjust the tightening torque and to be able to change the panels alignment in order to adjust the solar collecting area during usage. Finally, the front panel was placed in front of the two parts and its tilt angle was adjusted according to the position of the sun.

The Kimono solar cooker can assume the following two main configurations to better concentrate the solar radiation towards the receiver according to the sun elevation: one for low-medium sun elevation and one for medium-high sun elevation, shown in Fig. 2a and b, respectively. In the former, the two rear panels are perfectly overlapped and perpendicular to the bottom panels. Instead, the rear panels of the latter configuration are tilted back to increase the solar collecting area when the solar elevation is medium-high. In this latter configuration, the tilt angle of the rear panels is not fixed but can be adjusted according to the elevation of the sun.

2.2. Funnel solar cooker

The dimensions of the Funnel solar cooker studied in this work and shown in Fig. 2c,d were defined by Müller (2022). This Funnel solar cooker was derived from the portable version designed by Ruivo Celestino Solar Funnel Cooker (2022). The maximum aperture area of the device investigated in this work is 16% smaller than that of the Funnel solar cooker tested by Ruivo et al. (2021). Starting with two sheets of cardboard, each measuring 500×800 mm, the folds and cuts necessary for the construction were made. The construction of the prototype ended by joining the two folded sheets of cardboard with adhesive tape and gluing the end zones. As explained by Müller (2022), it can be placed in a configuration for low-medium sun elevation (Fig. 2c) and one for medium-high sun elevation (Fig. 2d), according to sun elevation during tests.

2.3. Dual-Setting Panel Cooker (DSPC)

The Dual-setting panel cooker (DSPC), tested in this work and shown in Fig. 2e,f, follows the design conceived by Tan (Dual-Setting Panel Cooker, 2021). The peculiarity of this cooker is that, in relation to the sun elevation, it can assume two different configurations by varying

Table 1
Literature experimental works concerning solar panel cookers.

Solar cooker design	Test type	Year	Main results	Reference
Hybrid solar system developed from a solar panel cooker	–	2006	The prototype was designed for sterilization of medical equipment. It was showed that the device can be used for cooking and food preservation.	Kerr and Scott (2006)
Solar stove with a light funnel	Tests without load	2009	A maximum temperature of about 250 °C was achieved inside the stove.	Kaiyan et al. (2009)
Polyhedral, semicylindrical, birectangular, parabolic shaped solar panel cookers	Tests with water	2016	The four configurations were realized by recycling the cardboard packaging of humanitarian supplies. The tests showed that the parabolic shaped solar cooker ensured the best balance between ease of assembly and thermal performance.	Regattieri et al. (2016)
Solar panel cooker for high-temperature cooking	Tests without load	2018	The prototype allowed a azimuthal and zenithal manual orientation. It was able to reach a stagnation temperature of about 260 °C in sunny conditions.	Edmonds (2018)
Four solar funnel cookers with different funnel lengths	Tests with water	2020	The largest cooker ensured the best performance, reaching a maximum water temperature of about 93 °C in a time interval of about 4 h.	Chepkurui and Biira (2020)
HotPot solar cooker	Tests with water	2020	Following the ASAE S580.1 Standard (ASAE, 2013), the thermal performance of the panel cooker were compared with that of a box cooker and a parabolic cooker. The results showed that the panel cooker provided the lower performance.	Ebersviller and Jetter (2020)
Two low-cost reflective solar panel cookers	Tests with load	2021	The results showed that the studied cookers had poor thermal performance. In fact, the cooking pot loaded with rice and water reached a maximum temperature of only 80 °C in the best solar panel cooker.	Gupta et al. (2021)
Funnel solar cooker	Tests with water	2021	Two identical funnel cookers were tested by following the ASAE S580.1 Standard (ASAE, 2013) to investigate the influence of the type of pot lid (glass or metal). The results showed that the pot with the glass lid ensured a higher average standardized cooker power (73.9 W) than that provided by the pot with the black metal lid (50.6 W).	Ruivo et al. (2021)
Funnel solar cooker	Tests with water	2021	Two identical funnel cookers were tested by following the ASAE S580.1 Standard (ASAE, 2013) and a new improved approach presented in the study. It was proved that the proposed approach was robust since the results of the tested configurations were convergent.	Apaolaza-Pagoaga et al. (2021a)
Funnel solar cooker	Tests with glycerin	2021	The results of the load tests proved that the cooker with a glass cover reached temperatures in the range from 140 to 150 °C.	Apaolaza-Pagoaga et al. (2021b)
Copenhagen solar cooker	Tests without load and with water	2022	Four different configurations were simultaneously tested under the same weather conditions. The results of the tests without load showed that the performance of one configuration is more influenced by the solar altitude angle than the others. The tests with water were carried out by partly following the ASAE S580.1 Standard (ASAE, 2013) and showed that the linear trend of the standardized power is not universal.	Apaolaza-Pagoaga et al. (2022b)
Haines 2 solar cooker	Tests without load and with water	2022	Two devices were tested side-by-side in Malaga, Spain. The tests without load allowed to evaluate the influence of the solar altitude angle on cooker performance. The results of tests with water carried out by partly following the ASAE S580.1 Standard (ASAE, 2013) allowed to evaluate the influence of the solar altitude angle and the impact of using partial loads on their thermal performance.	Apaolaza-Pagoaga et al. (2022a)
Funnel solar cooker	Tests with glycerin	2022	Five devices were tested to investigate the influence of the aperture area on their performance. The results showed that also the smallest cooker can achieved the pasteurization temperature, and the efficiency of the largest cooker is close to that of a cooker with optimum aperture area.	Ruivo et al. (2022a)

the geometry of its basis: one for low-medium sun elevation (Fig. 2e) and one for medium-high sun elevation (Fig. 2f). Starting with a sheet of cardboard measuring 1300 × 900 mm, the cuts and folds were made according to the manual (Dual-Setting Panel Cooker, 2021).

2.4. Cookit solar cooker

The Cookit design chosen for this study and shown in Fig. 2g was proposed by Tan (Cookit, 2021; Tan, 2022). Unlike other designs of Cookit, the one developed by Tan (2022) can also take on a specific configuration for low-medium sun elevation. Starting from a square sheet of cardboard with a side of 900 mm, the folds and cuts were made as shown in the manual. The preparation of the cooker ended by inserting the bottom corners into appropriate slots, choosing the most suitable ones according to the position of the sun.

2.5. Working configuration of the four prototypes

The four prototypes were tested by placing them on the ground on cardboard sheets, thus eliminating the possibility of changing their inclination with respect to the horizontal plane and having only one degree of freedom for tracking the sun, i.e. the azimuth. Depending on the elevation of the sun during the tests, the Kimono, the Funnel and the DSPC solar cookers were placed in the proper configuration

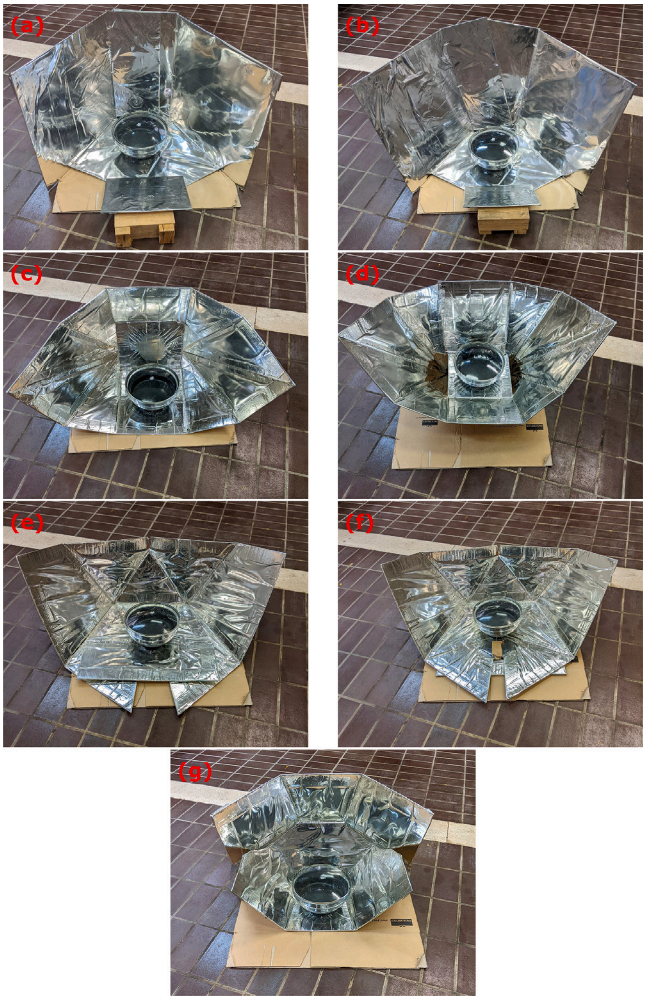

Fig. 2. Pictures of the four analyzed prototypes: (a) Kimono solar cooker for low-medium sun elevations; (b) Kimono solar cooker for medium-high sun elevations; (c) Funnel solar cooker for low-medium sun elevations; (d) Funnel solar cooker for medium-high sun elevations; (e) Dual Setting Panel Cooker for low-medium sun elevations; (f) Dual Setting Panel Cooker for medium-high sun elevations; (g) Cookit solar cooker for low-medium sun elevations.

between the two described above. Instead, only the configuration of the Cookit solar cooker for low-medium sun elevation was used in all the tests, since it was found to be suitable in all the test periods. It is worth pointing out that, as regards the configuration of the Kimono for medium-high sun elevation (Fig. 2b), a single fixed tilt angle of the rear panels was used in all the tests. Details regarding the configurations used in each measurement are reported in Section 4.

The actual aperture area of the solar panel cookers depends on the elevation of the sun during the tests and the specific configuration of the reflecting panels. However, to simplify the analysis of the results, average aperture areas (A_a) were considered to calculate the performance parameters. In particular, the A_a values of the cookers' configuration used for low-medium sun elevation were calculated considering the following average sun elevation: $\alpha_{sun,av} \sim 41°$. Instead, the values of the configuration for medium-high sun elevation were derived using $\alpha_{sun,av} \sim 62°$. These average sun elevations were estimated by means of the algorithms described by Meeus (1991), taking into account that the tests were carried out in September–October, March–April and July–August between 10:00 and 16:00 local solar time in Ancona. Table 2 shows the A_a values of the configuration of each solar cooker for low-medium sun elevation (configuration A) and the one for medium-high sun elevation (configuration B) calculated considering the

Table 2
Aperture areas of the four solar cookers.

Type of cooker	Aperture area, A_a (m^2)			
	Kimono	Funnel	DSPC	Cookit
Configuration A (low-medium sun elevation)	0.526	0.417	0.419	0.323
Configuration B (medium-high sun elevation)	0.540	0.420	0.440	–

aforementioned values of $\alpha_{sun,av}$. From Table 2, it can be noted that the A_a values of the Funnel cooker analyzed here are smaller than those of the Funnel cookers tested by Ruivo et al. (2021), Apaolaza-Pagoaga et al. (2021a,b) and Ruivo et al. (2022a).

3. Experimental setup and tests

In this section, the test bench designed to carry out the experimental campaign is presented, together with the parameters used to characterize the performance of the prototypes.

3.1. Test bench

The test bench used to carry out the tests is shown in Fig. 3. The four prototypes, arranged side by side, were tested simultaneously under the same external conditions and using identical receivers. Each receiver consisted of a black stainless-steel cake pan (diameter of 20 cm, height of 6 cm, volume of 1.8 dm^3, and mass of 0.12 kg) placed inside a glass bowl (diameter of 23 cm, height of 10 cm, volume of 2.9 dm^3, and mass of 0.85 kg) and covered by a 22 cm glass lid with a mass of 0.43 kg. The lid knob was removed in order to place the fluid temperature sensor in the center of the cake pan (Fig. 4). Water was used as testing fluid in the sets of tests with load.

The sensors used to record the absorber temperature, T_a, fluid temperature, T_f, and ambient temperature, T_{amb}, were T-type thermocouples with an uncertainty of ±1 °C. In the tests with load, the thermocouples used to measure the fluid temperature were placed at the center of each receiver through the hole in the knob and immersed 2 cm into the fluid. The thermocouple used for the ambient temperature was positioned in a shaded spot, so as not to be exposed to direct solar radiation. Direct normal solar irradiance, G_{bn}, was measured with an Eppley NIP (normal incidence pyrheliometer) with linearity ±0.5% in the range 0 to 1400 W/m^2. The thermocouples and pyrheliometer signals were collected via a Pico Technology TC-08 data logger connected to a laptop. The global horizontal solar irradiance was recorded using a pyranometer SR30-M2-D1 with linearity ±3.0% from 0 to 4000 W/m^2 placed horizontally near the solar cookers. By following the same procedure described by other authors (Aquilanti et al., 2022; Ruivo et al., 2021; Apaolaza-Pagoaga et al., 2022b,a; Ruivo et al., 2022a), the global normal solar irradiance, G_n, was obtained using the Liu-Jordan isotropic sky model (Kalogirou, 2013) considering an albedo value of 0.2.

3.2. Performance parameters

Given the same uncontrollable external variables such as wind, solar irradiance and ambient temperature, the aim of testing the four prototypes in parallel was to assess how the different devices with different geometries behaved in terms of thermal and optical performances.

The main parameters used to characterize the performance of the four panel solar cookers under no-load and load conditions are shown in Table 3. As also reported in recent works on panel solar cookers (Apaolaza-Pagoaga et al., 2022b,a), the stagnation condition (i.e., the equilibrium between the incoming heat due to the incident solar radiation and the outgoing heat due to thermal losses) was investigated. The no-load tests were made possible by the choice of the

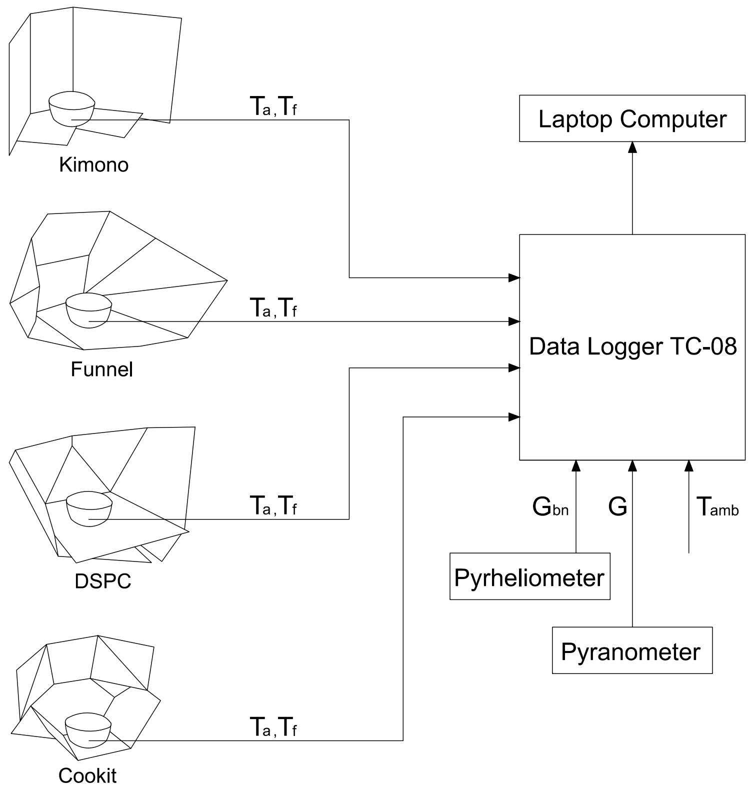

Fig. 3. Test bench: absorber temperature, T_a, testing fluid temperature, T_f, ambient temperature, T_{amb}, direct normal solar irradiance, G_{bn}, and global horizontal solar irradiance, G.

Fig. 4. A picture of the receiver.

receiver. In fact, as described above, the cake pan was placed inside a glass container and closed with a glass lid, making the system closed. It is important to point out that the values of the ambient temperature, T_{amb}, and the global normal solar irradiance, G_n, used to calculate the first figure of merit, F_1, correspond to those recorded when the absorber reaches its stagnation temperature, $T_{a,max}$.

Most of the parameters described in Table 3 were calculated in a time interval Δt_h necessary for the test fluid to evolve from the initial temperature T_1 to the final temperature T_2. As suggested by Funk (2000), $T_1 = 40\,°C$ and $T_2 = 90\,°C$ were chosen for the tests with water. The procedure proposed by Lahkar et al. (2012) was used to determine the COR parameter, starting from the Hottel–Whillier–Bliss equation expressed for solar cookers:

$$\eta = F'\eta_0 - \left(\frac{F'U_l}{C}\right)\chi, \tag{1}$$

where $\chi = (T_f - T_{amb})/G_n$ is the specific temperature difference and F' is the heat exchange efficiency factor. The data obtained from the experimental tests were used to identify the parameters $F'\eta_0$ and $F'U_l/C$, i.e. the intercept and the opposite value of the slope of the efficiency linear regression. Specifically, the total time interval Δt_h necessary for water to evolve from 40 to 90 °C was divided into sub-intervals of 5 min each. For each sub-interval, the average global normal solar irradiance, $G_{n,av}$, the average ambient temperature, $T_{amb,av}$, the average temperature of the tested fluid, $T_{f,av}$, the efficiency, η, and the specific temperature difference, χ, were determined. By plotting the efficiency η against the associated parameter χ for each identified sub-interval, it was possible to determine the linear regression equation of the efficiency curve and the coefficient of determination R^2. From the regression, the value of the intercept and the opposite value of the slope that correspond to the parameters $F'\eta_0$ and $F'U_l/C$, necessary for the determination of the COR parameter, were obtained.

It is important to note that the ASAE S580.1 Standard procedure (ASAE, 2013) for the calculation of the standardized power was not adopted because it is not physically consistent as Ruivo et al. (2022d) have recently demonstrated.

Finally, it is worth pointing out that only a qualitative description of the results of the most reliable tests is presented. In particular, the values of $T_{a,max}$ and Δt_h for each experimental test without and with load, respectively, are reported below. Instead, the average values of the other parameters for the three sets of tests are provided in Section 4.4.

Table 3
Parameters for the characterization of the solar cookers.

Parameter	Equation	Equation parameters
Test without load		
		G_n: global normal solar irradiance
First figure of merit (Mullick et al., 1987)	$F_1 = \frac{T_{a,max} - T_{amb}}{G_n}$	T_{amb}: ambient temperature
		$T_{a,max}$: absorber stagnation temperature
Test with load		
		A_a: aperture area of the solar cooker
Heating time interval	$\Delta t_h = t(T_2) - t(T_1)$	C: geometrical concentration ratio
		η_0: optical efficiency
Second figure of merit (Mullick et al., 1987)	$F_2 = \frac{F_1 m_f c_f}{A_a \Delta t_h} \ln \left[\frac{1 - \frac{1}{F_1}(T_1 - T_{amb,av})/G_{n,av}}{1 - \frac{1}{F_1}(T_2 - T_{amb,av})/G_{n,av}} \right]$	$G_{n,av}$: mean G_n measured at Δt_h
		m_f: mass of the test fluid
Overall efficiency (Khalifa et al., 1985)	$\eta_{av} = \frac{m_f c_f (T_2 - T_1)}{G_{n,av} A_a \Delta t_h}$	c_f: specific heat of the test fluid
		$T_{amb,av}$: mean T_{amb} measured at Δt_h
Cooker opto-thermal ratio (Lahkar et al., 2012)	$COR = \frac{\eta_0 C}{U_l}$	$t(T_1)$: starting time of the heating period
		$t(T_2)$: ending time of the heating period
		U_l: heat loss factor

Table 4
Summary of the tests without load of the first set of tests.

Quantity	Test 1				Test 2				Test 3			
Date	18/09/2020				05/10/2020				13/10/2020			
Type of cooker	Kimono	Funnel	DSPC	Cookit	Kimono	Funnel	DSPC	Cookit	Kimono	Funnel	DSPC	Cookit
Configuration	A	A	A	A	A	A	A	A	A	A	A	A
T_{amb} (°C)	24.91	24.99	25.18	25.11	22.26	22.14	21.56	21.74	13.76	13.72	13.14	13.82
G_n (W/m^2)	883.56	888.17	887.75	888.26	975.86	971.72	970.11	969.53	926.73	933.64	942.97	936.14
G_{bn} (W/m^2)	715.09	718.82	718.48	718.89	890.17	887.05	885.39	884.81	825.55	831.71	840.02	833.94
$T_{a,max}$ (°C)	138.78	133.01	122.79	127.79	135.32	135.87	114.85	125.82	113.40	116.19	104.53	113.82

4. Experimental results

In this section, the results obtained from the experimental campaign are reported and discussed. All the tests were carried out in Ancona, Italy, on the roof of the Department of Industrial Engineering and Mathematical Sciences (latitude 43.5871°N, longitude 13.5149°E) using the four prototypes in parallel and four identical receivers. As described in Section 2.5, all four prototypes were placed on the ground. In order to have all the prototypes properly exposed to solar radiation, a manual azimuthal tracking was carried out at regular intervals of about 15 min.

Three sets of measurements were carried out at different times of the calendar year to obtain an overall picture of the operation and performance of each of the four devices. They were tested under no-load and in load conditions, using water in the latter case. The three sets of tests were divided as follows:

- first set: September and October 2020;
- second set: between March and April 2021, and April 2022;
- third set: July and August 2021.

In planning the experimental campaign, the authors decided not to consider the coldest months of the year, i.e. winter months. Given that for the geographic position of Ancona, the ambient temperature and the solar irradiance recorded in this period are on average below 20 °C and 450 W/m^2, which are the minimum acceptable values indicated by the ASAE Standards (ASAE, 2013; Funk, 2003), tests with the studied panel cookers would have not led to suitable results.

As regards the effect of wind, it should be noted that its speed and direction were not detected. However, all solar cookers were shielded testing them near parapet walls and buildings with no overhead obstruction and clear line of sight to the sun.

4.1. First set of tests

The following measurements were carried out in September and October 2020: 3 no-load tests and 2 load tests with water. Since this is a period of low-medium sun elevation in Ancona, the configuration of the solar cookers for low-medium sun elevation was used in the tests. For this reason, the A_a values of configuration A have been employed for the calculation of the performance parameters of all the prototypes.

4.1.1. Tests without load

Three tests without load were carried out under different environmental conditions. Table 4 shows a summary of the tests with the quantities measured during the tests.

As an example, Fig. 5a shows the temperatures and the solar irradiances detected during the test of 18/09/2020 (test 1). As can be seen from Fig. 5a, the highest recorded absorber temperatures were approximately 138.78 °C, 133.01 °C, 122.79 °C and 127.79 °C for Kimono, Funnel, DSPC and Cookit, respectively.

From Table 4 and Fig. 5a, the following considerations can be made:

- Tests 1 and 2 are the ones that best describe the thermal performance of the panel cookers given the good environmental conditions detected (G_n and T_{amb}) and the repeatability of the values found for $T_{a,max}$. In fact, as shown in Fig. 5a, the trends of the four absorber temperatures of each cooker are extremely steep in the first part of the two tests and then flatten out at high temperatures, when equilibrium conditions are reached.
- Test 3 shows that ambient temperature plays a primary role in the performance of the devices. In fact, the average ambient temperature of the four cookers recorded in this test, 13.61 °C, is significantly lower than that recorded in the two previous tests (25.05 °C for test 1 and 21.93 °C for test 2). Despite G_n is comparable with those of the other tests, the significantly lower T_{amb} led to lower maximum absorber temperatures than those recorded in the other two tests.
- In general, the Kimono and the Funnel were the two devices that reached the highest maximum absorber temperatures when the environmental conditions were optimal, exceeding 130 °C in

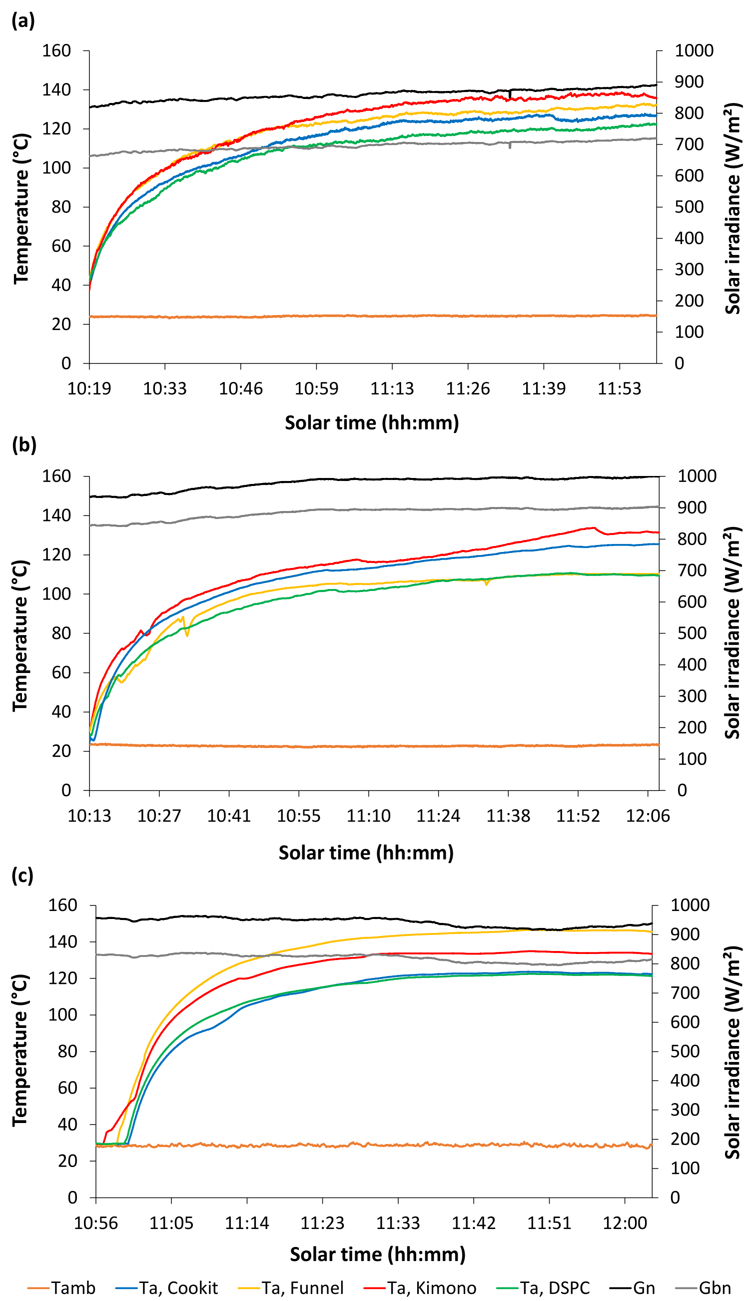

Fig. 5. Tests without load: (a) test 1, 18/09/2020; (b) test 7*, 01/04/2021; (c) test 13, 02/08/2021.

test 1 and test 2. However, it is worth noting that the Funnel is characterized by a lower aperture area than that of the Kimono. In test 3, instead, they suffered the most from the low ambient temperature, reaching much lower maximum absorber temperatures. However, also in this case, the values of $T_{a,max}$ for the Kimono and the Funnel were higher than 100 °C and comparable with those of the other two panel cookers.

4.1.2. *Tests with water*

Table 5 shows a summary of the two tests conducted with water. These tests were carried out using the same experimental setup and four identical receivers containing a mass of water of 1 kg each. Fig. 6a shows the solar irradiances and temperatures recorded during the test on 24/09/2020 (test 4). The global normal solar irradiance was about 862.31 W/m^2 and the average ambient temperature was 27.24 °C. Water took about 1 h to go from 40 to 90 °C in the Kimono and Funnel solar cookers. In this test, the heating time interval, Δt_h, was longer in the case of the Cookit, while the maximum water temperature recorded in the DSPC was 84.7 °C, as shown in Fig. 6a. Therefore, the water temperature recorded for the DSPC not only did not reach the boiling point temperature, but also did not reach 90 °C, the limit for the calculation of the parameters.

A similar behavior for the water temperature of the DSPC recorded in test 4 was also observed for the other test of Table 5. In fact, in all two tests (tests 4 and 5), the DSPC was never able to take water to a temperature above 90 °C. Consequently, it was not possible to calculate the parameters described in Table 3 in the temperature range from 40 °C to 90 °C for this cooker. For this reason, the results provided by the DSPC in the two tests are not reported in Table 5.

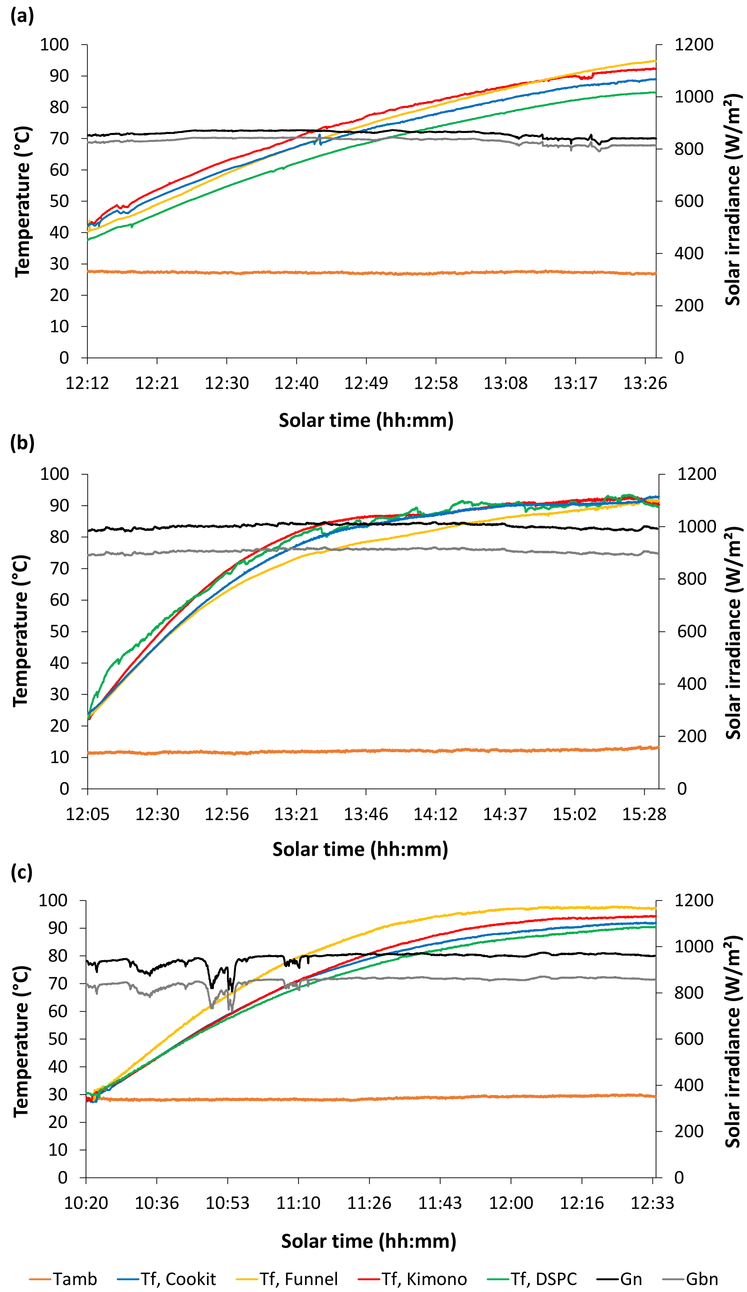

Fig. 6. Tests with water: (a) test 4, 24/09/2020; (b) test 9*, 24/03/2021; (c) test 14, 03/08/2021.

From the results reported in Table 5 and Fig. 6a, several considerations can be outlined:

- It is evident that the DSPC shows worse performance with respect to the other tested prototypes. Hence, the geometry of DSPC seems to be not suitable for the sun elevation of this period of the year in Ancona since it is not able to concentrate solar radiation with good optical efficiency in the receiver.
- Despite the configuration of DSPC and Funnel for low-medium sun elevation have very similar aperture areas (0.419 m^2 and 0.417 m^2, respectively), the two cookers performed very differently during the tests. This can be due to the DSPC geometry, which resulted to be not suitable for low-medium sun elevations, as mentioned above.
- In test 4, which was characterized by the best environmental conditions, the time required by water to go from 40 °C to 90 °C was on average shorter for the Kimono and Funnel cookers when compared with the Cookit. This confirms that the design of these two cookers is well suited also for low-medium sun elevations.
- The not optimal environmental conditions during test 5 caused a large increase in the time required by water to reach 90 °C for all cookers; in particular, this time doubled for the Kimono and Funnel, but it remained still lower than that of the Cookit.

4.2. Second set of tests

The following measurements were carried out in March, April 2021 and in April 2022: 3 no-load tests and 2 load tests with water. Although these months are a period of medium sun elevation in Ancona, the configuration of the Kimono and DSPC for low-medium sun elevation was used in all the tests. Instead, both the configurations of the Funnel for low-medium solar elevation and that for medium-high solar elevation were tested. Consequently, the corresponding A_a values reported

Table 5
Summary of the water load tests of the first set of tests.

Quantity	Test 4			Test 5		
Date	24/09/2020			09/10/2020		
Type of cooker	Kimono	Funnel	Cookit	Kimono	Funnel	Cookit
Configuration	A	A	A	A	A	A
m_f (kg)	1.0	1.0	1.0	1.0	1.0	1.0
T_1 (°C)	40	40	40	40	40	40
T_2 (°C)	90	90	90	90	90	90
$G_{n,av}$ (W/m^2)	862.37	863.02	858.95	779.02	778.29	813.98
$G_{bn,av}$ (W/m^2)	814.75	814.51	811.42	638.66	638.06	667.32
$T_{amb,av}$ (°C)	27.24	27.24	27.22	19.81	19.82	19.66
Δt_h (h)	1.09	1.06	1.27	2.26	2.20	2.88

in Table 2 have been considered in the calculation of the performance parameters of each prototype.

4.2.1. Tests without load

Three tests without load were carried out under different environmental conditions. Table 6 shows a summary of the tests with the measured quantities. In the tests with an asterisk, the configuration of the Funnel for low-medium sun elevation (configuration A) was used.

As an example, Fig. 5b shows the ambient and the absorber temperatures and the variation of the solar irradiances detected during the test of 01/04/2021 (test 7*). All the solar cookers were tested with the configuration A. As can be seen from Fig. 5b, the highest recorded absorber temperatures were approximately 133.77 °C, 110.29 °C, 110.67 °C and 125.54 °C for the Kimono, Funnel, DSPC and Cookit, respectively.

In general, as with the tests without load in the first set of tests, the Kimono was the device that usually achieved the highest absorber temperatures. Instead, the maximum absorber temperatures achieved by the configuration A of the Funnel were lower than those ensured by the Kimono. On the other hand, the results of test 8 where the Funnel was used with the configuration for medium-high sun elevation (configuration B) showed that this device reached the highest maximum absorber temperature. This proves that the configuration B of the Funnel is more suitable for this period of the year in Ancona. In this second set, the Cookit also managed to achieve high maximum absorber temperatures due to the medium sun elevation recorded during the test period.

4.2.2. Tests with water

Table 7 shows a summary of the two tests carried out by loading the receiver with water. Also in this case, the configuration of Funnel for low-medium sun elevation (configuration A) was employed in the test with an asterisk. Fig. 6b shows the trend of the fluid temperatures inside the four prototypes and the solar irradiances recorded during the test on 24/03/2021 (test 9*). The average $G_{n,av}$ and $T_{amb,av}$ recorded during the test were 1007.49 W/m^2 and 11.90 °C, respectively. In all the cookers, water took more than 2 h to go from 40 to 90 °C. The time required for the fluid to reach 90 °C was 2.21 h for the Kimono and 2.22 h for the Cookit. Instead, it was longer for the other devices: 2.48 h for the DSPC and 2.89 h for the Funnel.

From Table 7 and Fig. 6b, the following considerations can be made:

- Unlike the first set of tests, in this second set it was more difficult to carry out satisfactory tests due to the variable weather conditions recorded during the months of March and April in Ancona. In fact, there were some days that were very cold and windy.
- Test 9* was characterized by a very low average ambient temperature equal to 11.90 °C but also by a very high global normal solar irradiance of about 1007.49 W/m^2, which remained almost unchanged throughout the test (Fig. 6b). These external environmental conditions during the test allowed all the devices to bring water to its boiling point in a relatively short time (2.89 h for the Funnel was the longest time needed).
- While the time required by water to reach 90 °C for the Kimono and Cookit cookers was similar in the two tests, there was a significant difference between the Δt_h of the Funnel in tests 9* and 10. In fact, the Δt_h values recorded in test 9* (where the Funnel was tested with the configuration A) was about 43% longer than that recorded in test 10 (where the Funnel was tested with the configuration for medium-high sun elevation, i.e. configuration B). Aside from the different weather conditions in the tests, these results seem to show that the configuration B of the Funnel ensures better thermal performance in this period of the year in Ancona.
- While in test 9* the DSPC was able to bring water temperature above 90 °C, this did not happen in test 10, where this device brought the temperature of water slightly above 80 °C. This last outcome confirms that the geometry of DSPC could not be suitable to bring water to boiling point in the tested weather conditions.

4.3. Third set of tests

The following measurements were carried out in July and August 2021: 3 no-load tests and 2 tests with water. Since this is a period of medium-high sun elevation in Ancona, the configuration of the Kimono, Funnel and DSPC for medium-high sun elevation was used during all the tests. Consequently, the A_a values of configuration B (reported in Table 2) have been employed for the calculation of the performance parameters of all prototypes.

4.3.1. Tests without load

Three no-load tests were carried out under different environmental conditions. Table 8 shows a summary of the measured quantities. In this third set of tests, while the geometries of Kimono, Funnel and DSPC were modified for higher sun elevations, the configuration of the Cookit for low-medium solar elevation was used.

As an example, Fig. 5c shows the ambient and the absorber temperatures, and the variation of solar irradiances recorded during the test on 02/08/2021 (test 13). As can be seen from Fig. 5c, the maximum temperatures reached by the absorbers were approximately 134.93 °C, 146.53 °C, 122.51 °C and 123.68 °C for Kimono, Funnel, DSPC and Cookit, respectively.

In all the tests, despite its lower aperture area, the Funnel reached maximum absorber temperatures similar or higher than those of the Kimono, exceeding 145 °C in test 13. Instead, the maximum absorber temperatures achieved by the other solar cookers were generally lower of about 10–20 °C than those ensured by the Kimono and Funnel. However, it is important to remark that the Cookit was tested using the configuration for low-medium sun elevations.

4.3.2. Tests with water

The results obtained from the tests using water as test fluid are summarized in Table 9. Fig. 6c shows the trend of water temperatures recorded in the four devices, ambient temperature and solar irradiances during the test on 03/08/2021 (test 14). The average values of $G_{n,av}$ and $T_{amb,av}$ recorded were 945.62 W/m^2 and 28.42 °C, respectively. Water took approximately 1 h to cover the 50 °C temperature range when tested with the Funnel. The time required for the fluid to reach 90 °C for the other devices was longer: 1.29 h for the Kimono, 1.62 h for the Cookit and 1.89 h for the DSPC. The four devices were able to take water temperature to more than 90 °C for both tests on 03/08/2021 (tests 14 and 15).

In this third set of measurements, it can be clearly seen that the high global normal solar irradiance and the high ambient temperature recorded during the testing period had a positive influence on the success of the tests. In general, in fact, all the devices, thanks also to the change in their geometries making them suitable for high sun elevations, were able to guarantee water boiling at sea level.

Table 6
Summary of the tests without load of the second set of tests.

Quantity	Test 6*				Test 7*				Test 8			
Date	29/03/2021				01/04/2021				28/04/2022			
Type of cooker	Kimono	Funnel	DSPC	Cookit	Kimono	Funnel	DSPC	Cookit	Kimono	Funnel	DSPC	Cookit
Configuration	A	A	A	A	A	A	A	A	A	B	A	A
T_{amb} (°C)	18.23	18.86	19.42	18.89	23.21	23.18	23.46	23.45	15.98	15.88	15.95	15.40
G_n (W/m^2)	926.52	937.84	909.49	932.14	996.92	996.28	995.53	995.32	983.79	982.54	983.50	986.13
G_{bn} (W/m^2)	805.47	815.14	788.03	808.41	902.17	902.69	900.89	899.03	920.30	919.13	920.03	922.49
$T_{a,max}$ (°C)	122.59	118.30	98.16	104.88	133.77	110.29	110.67	125.54	131.00	157.15	114.76	124.37

Table 7
Summary of the water load tests of the second set of tests.

Quantity	Test 9*				Test 10			
Date	24/03/2021				26/04/2022			
Type of cooker	Kimono	Funnel	DSPC	Cookit	Kimono	Funnel	DSPC	Cookit
Configuration	A	A	A	A	A	B	A	A
m_f (kg)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
T_1 (°C)	40	40	40	40	40	40	–	40
T_2 (°C)	90	90	90	90	90	90	–	90
$G_{n,av}$ (W/m^2)	1008.68	1004.41	1007.52	1008.80	1005.76	1006.21	–	1010.82
$G_{bn,av}$ (W/m^2)	911.11	909.00	910.18	911.38	889.38	889.77	–	893.85
$T_{amb,av}$ (°C)	11.88	12.00	11.89	11.90	19.26	19.26	–	19.40
Δt_h (h)	2.21	2.89	2.48	2.22	2.12	1.65	–	2.60

Table 8
Summary of the tests without load of the third set of tests.

Quantity	Test 11				Test 12				Test 13			
Date	21/07/2021				22/07/2021				02/08/2021			
Type of cooker	Kimono	Funnel	DSPC	Cookit	Kimono	Funnel	DSPC	Cookit	Kimono	Funnel	DSPC	Cookit
Configuration	B	B	B	A	B	B	B	A	B	B	B	A
T_{amb} (°C)	33.06	32.78	32.63	33.34	28.21	29.33	28.43	29.49	27.90	29.31	28.07	29.19
G_n (W/m^2)	947.62	946.91	950.31	950.51	916.51	919.63	925.58	928.68	926.98	929.12	926.63	929.09
G_{bn} (W/m^2)	764.02	763.45	766.19	766.35	748.01	746.16	751.44	755.13	797.58	799.72	797.23	799.62
$T_{a,max}$ (°C)	132.23	137.54	127.53	126.31	141.81	139.89	118.65	120.97	134.93	146.53	122.51	123.68

Table 9
Summary of the water load tests of the third set of tests.

Quantity	Test 14				Test 15			
Date	03/08/2021				03/08/2021			
Type of cooker	Kimono	Funnel	DSPC	Cookit	Kimono	Funnel	DSPC	Cookit
Configuration	B	B	B	A	B	B	B	A
m_f (kg)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
T_1 (°C)	40	40	40	40	40	40	40	40
T_2 (°C)	90	90	90	90	90	90	90	90
$G_{n,av}$ (W/m^2)	945.49	936.23	951.73	949.02	917.12	933.83	921.83	928.17
$G_{bn,av}$ (W/m^2)	844.78	836.51	850.35	847.93	829.05	844.16	833.31	839.05
$T_{amb,av}$ (°C)	28.35	28.22	28.63	28.49	29.10	28.96	29.10	29.15
Δt_h (h)	1.29	0.98	1.89	1.62	1.84	0.99	1.50	1.32

4.4. Comparison for the three sets of tests

A final comparison of the results obtained for the studied solar cookers with and without load in the three measurement sets is given in this section. Tables 10 and 11 show the average values of the parameters calculated for the no-load tests and tests with water, respectively, for the three set of measurements. The average values of the global normal solar irradiance and ambient temperature are also reported in these tables.

From Table 10, some considerations can be pointed out:

- All three sets of tests show how outdoor environmental conditions affect the performance of the tests positively or negatively. Ambient temperature, in particular, plays a fundamental role in the thermal performance of the four devices. In the third set of tests, characterized by a higher $T_{amb,av}$ compared to those of the others, the average values of $T_{a,max}$ are higher in all the tested solar panel cookers, but especially in the Funnel. In detail, the average $T_{a,max}$ for the Funnel is higher of about 13 °C in the third set with respect to the other sets.
- In the three measurement sets, all the solar cookers were averagely able to bring the absorber plate to temperatures above 100 °C. However, in all the sets of tests, the DSPC reached temperatures lower than that of the other prototypes.
- In general, the Kimono and the Funnel showed the highest maximum temperatures reached by the absorber. This behavior occurred in all three measurement tests, indicating the good functioning of these two panel cookers throughout the year for low to high sun elevations.
- From the average values of first figure of merit, F_1, it is possible to note that they are similar in all the three sets of measurements. In particular, the average F_1 parameters for the Kimono and the Funnel are always higher with respect to the other two devices, proving that the first two cookers showed a better performance.

Table 10
Average results of the tests without load for all the sets of measurements.

Set	$G_{n,av}$	$T_{amb,av}$	Kimono		Funnel		DSPC		Cookit	
			$T_{a,max}$	F_1	$T_{a,max}$	F_1	$T_{a,max}$	F_1	$T_{a,max}$	F_1
	W/m^2	°C	°C	°C/(W/m^2)	°C	°C/(W/m^2)	°C	°C/(W/m^2)	°C	°C/(W/m^2)
1st	931.20	20.20	129.17	0.117	128.36	0.116	114.06	0.101	122.48	0.110
2nd	968.83	19.33	129.12	0.113	128.58	0.112	107.86	0.092	118.26	0.102
3rd	933.13	30.15	136.19	0.115	141.32	0.119	122.90	0.099	123.65	0.099

Table 11
Average results of the tests with water for all the sets of measurements.

Test	$G_{n,av}$	$T_{amb,av}$	Kimono				Funnel				DSPC				Cookit			
			Δt_h	η_{av}	F_2	COR	Δt_h	η_{av}	F_2	COR	Δt_h	η_{av}	F_2	COR	Δt_h	η_{av}	F_2	COR
	W/m^2	°C	h			°C/(W/m^2)	h			°C/(W/m^2)	h			°C/(W/m^2)	h			°C/(W/m^2)
1st	825.81	23.50	1.68	0.09	0.17	0.100	1.63	0.12	0.21	0.108	–	–	–	–	2.08	0.13	0.24	0.094
2nd	1007.46	15.60	2.17	0.05	0.10	0.079	2.27	0.07	0.12	0.081	2.48	0.06	0.16	0.093	2.41	0.08	0.16	0.082
3rd	935.43	28.75	1.57	0.08	0.12	0.081	0.99	0.15	0.23	0.101	1.70	0.09	0.15	0.076	1.47	0.14	0.23	0.078

Table 11 reports the values of the overall efficiency, η_{av}, the second figure of merit, F_2, and the COR parameter for the three sets of measurements. These properties were calculated for each device in the fluid temperature range 40–90 °C. The average values of $G_{n,av}$, $T_{amb,av}$ and Δt_h of the four devices are also provided in Table 11. The parameters of the DSPC are not reported for the first set of measurements, since it also did not reach 90 °C in all the tests. As shown in Figs. 7–9, the reported values of the COR parameter for the three measurement sets were calculated according to the following procedure. The efficiencies η of all the tests of each set, calculated for each sub-interval, were plotted against the term χ; then, the regression line and the coefficient of determination R^2 of each solar cooker were determined. Using the value of the intercept and the opposite value of the slope of this regression, which correspond to the parameters $F'\eta_0$ and $F'U_l/C$, respectively, the COR parameter was obtained.

From Table 11, the following considerations can be outlined:

- In the load tests, it is even more evident how the outdoor environmental conditions influence the performance of the tests. In the second set of tests, the average time required for the water to reach 90 °C in all the cookers was higher than the average values of the other sets. In fact, $T_{amb,av}$ of the second set of measurements was lower than those of the other sets, despite the value of $G_{n,av}$ was higher. This aspect is also evident in the calculated parameters of the four devices, which are generally lower in the second measurement set.
- As shown by the results, despite the Funnel and the DSPC have very similar aperture areas, the two devices behave completely differently during the tests. The geometry of the DSPC is not suitable for low sun elevations, as proved by the tests of the first set where it was never able to bring water at temperatures higher than 90 °C. Probably, it lacks suitably inclined surfaces able to optimally convey the low solar radiation towards the receiver.
- The Funnel is the devices that, on average, recorded the shortest time in the first and third sets of measurements. Instead, in the second set, the average time of the Kimono was the shortest. This result confirms that the design of the Kimono and Funnel is suitable for low to high sun elevations. Fig. 10 shows the trends of water temperatures recorded in all the tests when the fluid was tested with the Kimono. From this figure, it is evident once again that the effect of low ambient temperature prevails heavily on the high solar irradiance values, impairing the Kimono capability of bringing water to boiling.
- A variability in the parameters of the devices for the three measurements sets, probably due to the variation in the configurations used, is evident. However, from their values it is possible to assess that all cookers showed good performance parameters at medium-high sun elevations, while the DSPC showed some limitations at low-medium sun elevations.

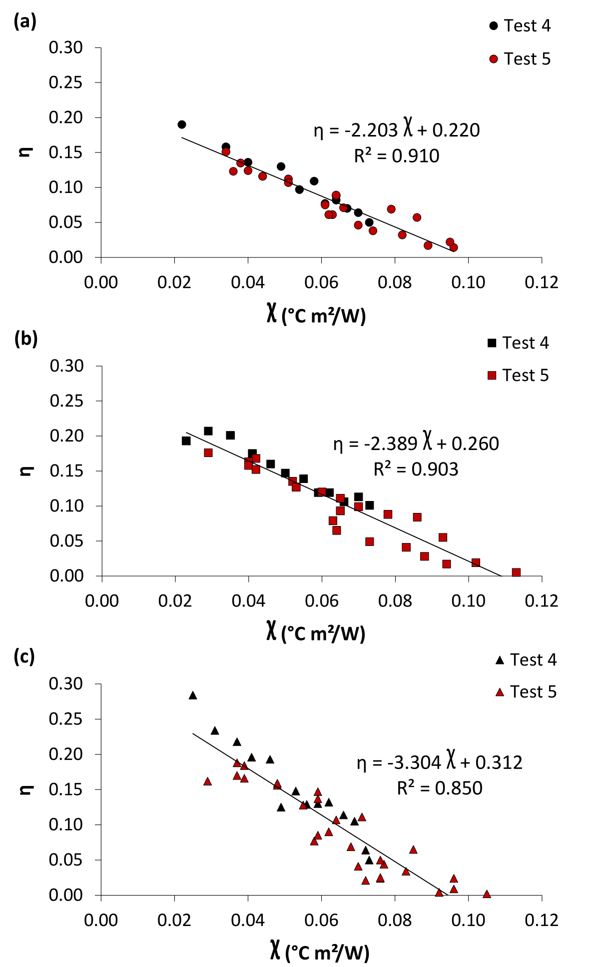

Fig. 7. Efficiency with water for the first set of tests: (a) Kimono solar cooker; (b) Funnel solar cooker; (c) Cookit solar cooker.

The average values of the COR parameter of the studied Funnel can be compared with those of the Funnel prototypes tested by Ruivo et al. (2022a) at high sun elevations using glycerin as load. The literature values are higher than that of the device studied in this work. In fact,

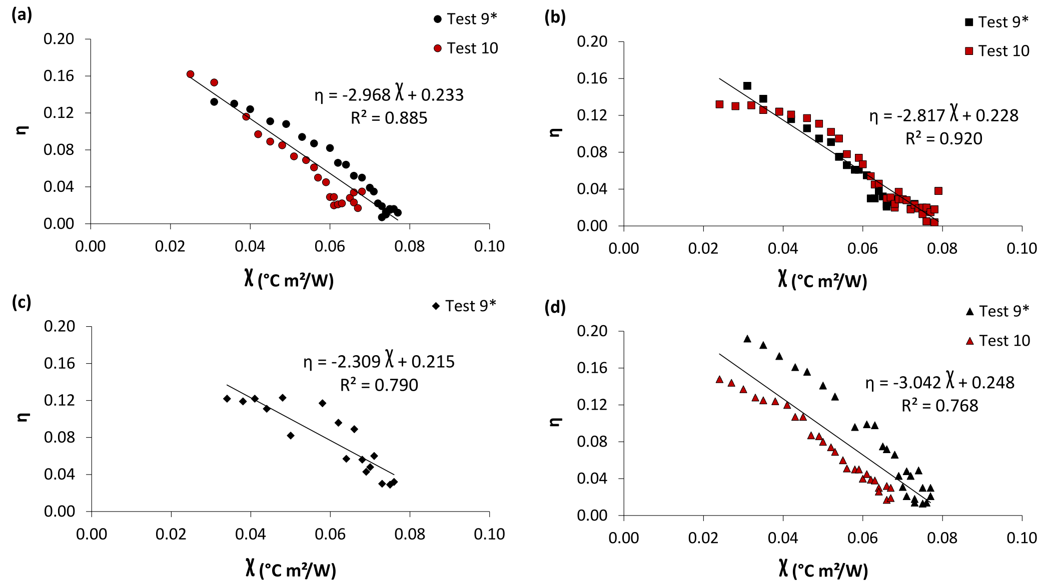

Fig. 8. Efficiency with water for the second set of tests: (a) Kimono solar cooker; (b) Funnel solar cooker; (c) DSPC; (d) Cookit solar cooker.

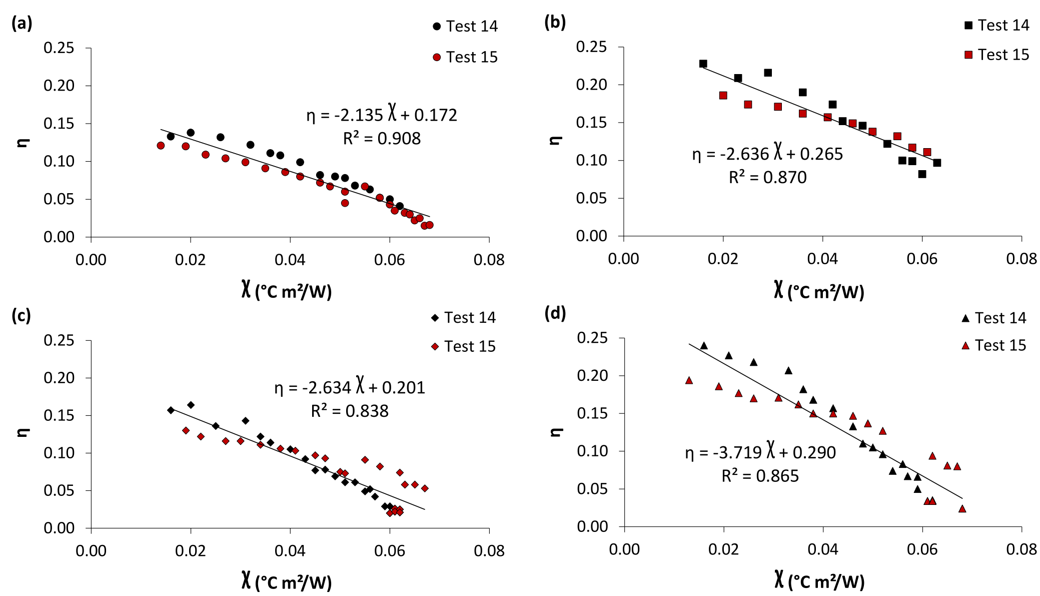

Fig. 9. Efficiency with water for the third set of tests: (a) Kimono solar cooker; (b) Funnel solar cooker; (c) DSPC; (d) Cookit solar cooker.

they ranges from 0.1075 to 0.1471 °C/(W/m^2). This difference can be due to the following aspects: optical properties of the reflecting panels and receiver; shape of the reflecting panels; cooking set and mass of load.

5. Conclusions

In this paper, four cost-effective solar panel cookers, i.e., Kimono, Funnel, Dual-setting panel cooker, Cookit, were assembled and tested in outdoor conditions under different sun elevation angles. The cookers were generally tested with two configurations, in order to maximize the collection of solar energy with different positions of the sun. Experimental tests were carried out both in no-load conditions and with load, using water as test fluid.

The results of the analysis showed that the Kimono and the Funnel solar cookers are the devices with the best performance under all sun elevation angles. The Cookit solar cooker, instead, resulted to be a good option at medium elevations. As regards the Dual-setting panel cooker, it should be noted that, for low sun elevations, it was not able to guarantee water boiling (at the sea level), while this condition was reached in some tests conducted at medium sun elevations.

A general consideration that can be derived from the present study is that solar panel cookers can be efficient and simple solutions for cooking purposes. They can be manufactured with inexpensive and common materials, such as cardboard, and no skilled personnel is required for their construction. In order to fully exploit their potential, however, a good value of global normal solar irradiance should be available ($G_n > 800$ W/m^2). But this necessary condition is not sufficient to guarantee a good performance of panel cookers; in fact, it is also important to have other favorable atmospheric conditions, in particular high outdoor temperature and low wind.

Future research developments will include additional experimental tests to present a more systematic analysis of the performance of the cookers and their testing using different configurations and/or alternative test fluids, such as glycerin or silicone oil, in order to evaluate their thermal performance also at medium-high temperatures.

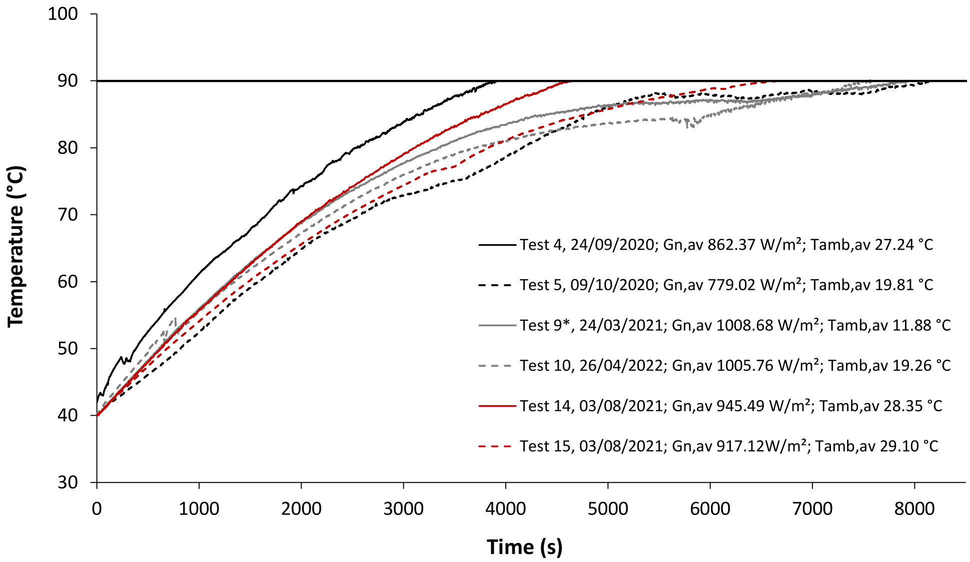

Fig. 10. Kimono water temperature trend divided by measurement sets.

Nomenclature

Latin Symbols	
A	Area (m^2)
C	Concentration ratio
COR	Cooker opto-thermal ratio (°C/(W/m^2))
c	Specific heat (J/(kg °C)
F_1	First figure of merit (°C/(W/m^2))
F_2	Second figure of merit
F'	Heat exchange efficiency factor
$F'\eta_0$	Optical efficiency factor
$F'U_l$	Heat loss factor (W/m^2 °C)
G	Global horizontal solar irradiance (W/m^2)
G_{bn}	Direct normal solar irradiance (W/m^2)
G_n	Global normal solar irradiance (W/m^2)
m	Mass (kg)
T	Temperature (°C)
T_{fx}	Maximum achievable fluid temperature (°C)
t	Time (s)
Greek Symbols	
α_{sun}	Sun elevation (°)
η	Efficiency
η_0	Optical efficiency
χ	Specific temperature difference (°C/(W/m^2))
Subscripts	
a	Absorber, aperture
amb	Ambient
av	Average
f	Fluid
h	Heating
max	Maximum
u	Utilizable
Acronyms	
DSPC	Dual-setting panel cooker

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CRediT authorship contribution statement

Alessia Aquilanti: Methodology, Validation, Investigation, Visualization, Writing – original draft. **Sebastiano Tomassetti:** Investigation, Validation, Visualization, Writing – original draft. **Gianluca Coccia:** Validation, Writing – review & editing. **Matteo Muccioli:** Conceptualization, Writing – review & editing. **Giovanni Di Nicola:** Project administration, Supervision, Writing – review & editing.

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.

Data availability

Data will be made available on request.

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