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Design and experimental characterization of a solar cooker with a prismatic cooking chamber and adjustable panel reflectors

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Abstract

In this work, a novel solar cooker with the cooking chamber shaped like a Newton prism was designed, constructed and tested. The device is characterized by ease of construction, use and transportation. It is made of common and inexpensive materials. The proposed cooker is able to track the sun during its use through wheels placed at its base and a manual system to vary the inclination of the reflective surfaces. Experimental tests were carried out to characterize its thermal and optical performances and evaluate the wind's influence. In particular, two identical prototypes, one shielded from the wind and the other not, were simultaneously tested by tracking the reflective surfaces at optimal angles. Several tests were carried out without and with a load using water and glycerin as test fluids. The results showed that the solar cookers have good thermal performance even at medium-high temperatures. Both prototypes reached a stagnation temperature of about 137 °C. The shielded cooker usually brought 2 kg of water from 40 °C up to 90 °C in about two hours and 2 kg of glycerin from 40 °C up to 110 °C in less than three hours. These times were slightly longer for

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the unshielded prototype.

Keywords: Solar cooking; Sun tracking; Experimental; Cooker opto-thermal ratio

1 1. Introduction

Currently, a significant percentage of the world's energy consumption is due to cooking purposes. This is especially true for various developing countries 3 and rural areas of the world where, in some cases, more than 90% of the energy is consumed for cooking food [1]. However, in these areas, most of the energy 5 demand for cooking is covered by non-commercial fuels, leading to harmful pollution and environmental problems [2, 3]. Since many developing countries 7 are characterized by several days of the year with abundant solar radiation [4], 8 solar cooking can be considered a sustainable alternative to the conventional energy sources used for cooking. Of course, this aspect is also valid for many 10 developed countries. In fact, despite their shortcomings and limitations [5, 6], 11 solar cookers are usually more affordable and less environmentally harmful than 12 many of the most widespread cooking technologies. 13

In recent years, numerous designs of solar cookers characterized by different sizes and technologies have been reported in the literature [5, 7, 8, 9]. To overcome their limitations and improve their performances, various experimental and numerical studies analyzed possible modifications of solar cookers and their integration with thermal energy storage systems [6, 10, 11].

As explained by Aramesh et al. [5], solar cookers can be classified into three 19 main structural types: panel cookers, box cookers and concentrating cookers. As 20 they have the simplest design, the panel cookers are usually more cost-effective 21 and easier to build than other types of solar cookers. Given their simplicity 22 and flexibility, various designs of panel cookers have been developed in the last 23 decades [5, 7, 12]. Some examples are the Cookit [13], the Solar Funnel Cooker 24 [14], the Hot Pot [15], the Copenhagen Solar Cooker [16], and the Haines Solar 25 Cookers [17]. 26

Among the several designs of solar box cookers developed over the years, some very low-cost and simple prototypes have been designed and manufactured using inexpensive and recycled materials, such as cardboard boxes [12]. While various prototypes have been described in non-scientific literature (e.g., the Kyoto Solar Box Cooker [18] and the Jose Sol Cooker [19]), different scientific works presented designs and experimental characterizations of low-cost and simple box cookers. Some of the main literature studies concerning low-cost solar cookers are briefly described below.

Ozturk [20] manufactured a low-cost and simple solar box cooker from a plastic sheet box and a transparent plastic plate. The prototype was tested by using a commercial aluminum pot filled with water and its energy and exergy efficiencies were calculated. The results of the experimental tests showed that the average water temperature was only 73.2 °C, while the average energy and exergy efficiencies were 18.3 % and 2.2 %, respectively.

Mahavar et al. [21] designed a low-cost box cooker, known as Single Family Solar Cooker, that was tested with two aluminum cylindrical pots. The prototype has a small size and was manufactured using inexpensive materials. The experimental results showed that the cooker was able to cook two meals of soft load for two persons also in winter and its thermal performance parameters were comparable with those of other box solar cookers available in the literature.

Following the ASAE S580.1 Standard [22], Ebersviller and Jetter [23] exper-47 imentally compared the performances of a panel cooker, namely Hot Pot, with those of a parabolic cooker (Sun Chef Cooker) and a box cooker (Global Sun 49 Oven). The prototypes were tested by using the load ratio recommended by the 50 Standard, i.e., 7 kg of water per square meter of intercept area. A standardized 51 cooking power for the panel cooker equal to 25 W was obtained, which is lower 52 than the values obtained for the box cooker (65 W) and the parabolic cooker 53 (198 W). This outcome could be due to the aperture area of the panel cooker 54 lower than that of the other devices. The results obtained for other experimental 55 parameters confirmed the lower performance of the Hot Pot. 56

⁵⁷ Sagade et al. [24] experimentally analyzed the performance of a simple and

small solar box cooker with a booster reflector. A new parameter, namely 58 effective concentration ratio, was defined to assess the effectiveness of the booster 59 reflector. From the experimental tests performed with and without the booster 60 reflector, it was found that the new parameter enabled the assessment of the 61 effect of the booster reflector in the estimation of the opto-thermal performance 62 of the studied device. Moreover, the authors experimentally investigated the 63 thermal performance of the same solar box cooker tested with different working 64 fluids [25] and a modified cooking pot [26]. 65

The thermal performance of a simple solar box cooker with different reflec-66 tor configurations were experimentally evaluated by Weldu et al. [27]. From 67 the tests without load, the cooker with reflector tracking at the optimal angle 68 provided the highest values of the stagnation temperature (145.4 °C) and the 69 first figure of merit ($F_1 = 0.154 \text{ °C/(W/m^2)}$). As expected, the results of the 70 tests with water showed that the cooker configuration with reflector tracking 71 at the optimal angle and an aluminum pot ensured better thermal performance 72 than that of the configurations with a fixed angle of the reflector and a stainless 73 steel pot. 74

Ruivo et al. [28] simultaneously tested two identical funnel cookers by fol-75 lowing the ASAE S580.1 Standard [22] to investigate the influence of the type 76 of pot lid. They used one cooking pot in each cooker surrounded by a trans-77 parent cover and covered with a glass lid and a black metal lid, respectively. 78 A significant number of tests with water and a mixture of water and ice were performed in Malaga, Spain during a period with low sun elevation, with az-80 imuthal solar tracking. The results showed that the pot with the glass lid gave a 81 higher average standardized cooker power (73.9 W) than the pot with the black 82 metal lid (50.6 W). Four configurations of the Copenhagen Solar Cooker were 83 simultaneously tested by Apaolaza-Pagoaga et al. [29] under the same weather 84 conditions. From the tests without load, it was found that the performance of 85 one configuration is more influenced by the solar altitude angle than the others. 86 The results of the tests with water carried out by partly following the ASAE 87 S580.1 Standard [22] showed that the linear trend of the standardized power is 88

not universal, proving that the procedure for evaluating this parameter recom-89 mended by the Standard should be improved, as also demonstrated by Ruivo 90 et al. [30, 31]. Recently, two prototypes of Haines 2 Solar Cooker were experi-91 mentally analyzed side-by-side by the same authors in Malaga, Spain [32]. The 92 influence of the solar altitude angle on cooker performance was evaluated from 93 the tests without load. Instead, the influence of the solar altitude angle and 94 the impact of using partial loads on their thermal performance were analyzed 95 from the tests with water. Based on their results, the authors suggested that the influence of both solar altitude angle and partial loads should be considered 97 in future versions of ASAE S580.1 Standard [22]. 98

In this study, a low-cost and simple solar cooker having an innovative vari-99 able geometry, named Newton solar cooker (NSC), is presented. The proposed 100 solar cooker was experimentally tested and its performance expressed in terms 101 of efficiency was investigated. In particular, the purpose of this study was to 102 simultaneously test two identical NSC prototypes, one wind-shielded and the 103 other not, to determine their performances, also considering the influence of 104 wind. The following experimental outdoor campaign was developed: 3 tests 105 without load, 4 water tests and 4 glycerin tests were carried out. The method-106 ology followed to perform the tests is the same proposed in some of our previous 107 works [33, 34] and allows us to evaluate the main performance parameters used 108 in the scientific literature. 109

The paper is divided into the following sections. In Section 2, the charac-110 teristics of the NSC and the optical analysis of the device are discussed. The 111 optimal inclination angles of the primary and secondary reflectors for different 112 elevations of the sun obtained by a 2D model are also reported. Section 3 de-113 scribes the manufacturing steps of the prototype along with the materials used. 114 A cost analysis of all components is also given in this section. Section 4 de-115 fines the experimental parameters used to characterize the two tested devices 116 and the experimental setup designed for the outdoor campaign. Section 5 re-117 ports the results of the study, dividing them between no-load, water-loaded and 118 glycerin-loaded tests. The conclusions of the article are given in Section 6. 119

¹²⁰ 2. Design and optical analysis

The new solar cooker presented in this work, shown in Fig. 1, is based on 121 designs of a solar cooker with the cooking chamber shaped like a Newton prism, 122 named Newton solar cooker (NSC) [35, 36], developed by Matteo Muccioli, co-123 author of this work. In general, the NSC was designed to be easy to build and 124 use; in fact, its main strengths are the ease of construction, the ease of movement 125 and transportation, and the use of common and inexpensive materials. The 126 device can be constructed quickly since only common tools are required. It can 127 be easily transported since it can be easily disassembled and resealed. Moreover, 128 the presented solar cooker is affordable and easy to replicate because it can be 129 made of readily available materials with a quasi-zero cost. 130

Starting from the original versions of the NSC, which were never investigated 131 in scientific works, the construction features of the new version were chosen to 132 improve its thermal and optical performances. In this regard, the modifica-133 tions performed on the proposed NSC were based on some preliminary outdoor 134 tests where different insulating and reflecting materials and geometrical config-135 urations were evaluated. Fig. 2 shows the working scheme of the new device 136 presented here. It consists of a glass prism cooking chamber made of two tem-137 pered glass panes, a wooden panel placed at the base and two side doors. The 138 glass panes are supported by the two side panels and the two side doors. A 139 layer of thermal insulating material and a steel plate are placed at the base 140 of the chamber. Moreover, the device comprises two rotating reflector support 141 structures placed at the sides of the chamber: a longer support for the primary 142 reflective surface and a shorter one for the secondary reflective surface. A de-143 tailed description of the construction of the presented prototype is reported in 144 Section 3. 145

From Fig. 2, it can be understood that the device's geometry can be changed by varying θ_1 and θ_2 , i.e., the inclination angles of the primary and secondary reflectors with respect to the horizontal plane, respectively. This results in a change in the NSC aperture area (A_a) . The area A_a is calculated as the



Fig. 1: Newton solar cooker views (dimensions in mm).

projection of the area bounded by the outer edges of the prototype on a plane perpendicular to the direction of the sun's rays. By optimizing the values of θ_1 and θ_2 according to the elevation of the sun (H_{sun}) , it is possible to maximize the amount of solar radiation concentrated on the steel plate where the pot is placed.

To calculate optimal θ_1 and θ_2 values associated with different sun eleva-155 tions, a simplified 2D model to simulate the propagation of the solar rays on the 156 surfaces of the solar cooker was developed using MATLAB software [37]. In the 157 model, the solar rays are represented by vectors with an initial unit modulus 158 from the sun's direction. The solar cooker surfaces are modeled as obstacles 159 to the propagation of sun rays, dividing them between reflective surfaces (the 160 two reflectors) and glazed surfaces (the two glasses), according to the prototype 161 design. In particular, the reflective surfaces are characterized by specific values 162 of θ_1 and θ_2 . During the simulation, the sun's rays impact the various surfaces 163 of the solar cooker, which cause either reflection, transmission or absorption. To 164 compute the final amount of concentrated energy more realistically, the trans-165 mittance and reflectance values of the materials are used to correct the modulus 166 of the solar ray vectors at each transmission or reflection. The model also takes 167 into account possible multiple reflections between reflectors. A ray is no longer 168 propagated in the following two cases: the ray does not impact the cooker or the 169 ray hits the cooker surface where the pot is placed. The rays' moduli that meet 170 the first condition are neglected, while those that meet the second condition are 171 summed. The score assigned to a specific configuration of θ_1 and θ_2 for a given 172 $H_{\rm sun}$ is the sum of rays' moduli obtained at the end of the simulation of the 173 rays' propagation. 174

For the latitude of Ancona, Italy (latitude of 43.5871°N), discretized with 1degree steps, the optimal configurations of θ_1 and θ_2 values that got the highest scores were determined using the Particle Swarm Optimization algorithm [38]. As an example, the optimal values of θ_1 and θ_2 at 12:00 solar time on the days of the equinox, summer solstice and winter solstice are reported below: • Spring Equinox, 20/03/2022: $H_{sun} = 46.24^{\circ}, \theta_1 = 76.40^{\circ}, \theta_2 = 22.99^{\circ};$

180

• Summer Solstice, 21/06/2022: $H_{sun} = 69.79^{\circ}, \theta_1 = 96.09^{\circ}, \theta_2 = 47.62^{\circ};$

• Winter Solstice, 21/12/2022: $H_{sun} = 22.97^{\circ}$, $\theta_1 = 56.49^{\circ}$, $\theta_2 = 2.33^{\circ}$.

Fig. 3 shows the score (on the z-axis) for each pair of θ_1 (x-axis) and θ_2 (y-axis), again for 12:00 solar time on the equinox, summer solstice, and winter solstice days.

To adjust the solar cooker geometry according to the sun elevation, the optimal θ_1 and θ_2 pairs associated with each sun elevation were used by the operator during the experimental campaign. Table 1 shows the optimal values of θ_1 and θ_2 for H_{sun} between 50 and 70°, with the corresponding aperture area of the NSC.



Fig. 2: Working scheme of the Newton solar cooker.



Fig. 3: Score (z-axis) obtained by a 2D model for the distribution of the solar radiation on the NSC for each pair of θ_1 (x-axis) and θ_2 (y-axis) at 12:00 solar time: a) Spring Equinox, 20/03/2022; b) Summer Solstice, 21/06/2022; c) Winter Solstice, 21/12/2022.

Hsun	$ heta_1$	θ_2	$A_{\rm a}$
(°)	(°)	(°)	(m^2)
50	80.29	34.72	0.394
52	81.21	35.92	0.396
54	83.16	37.44	0.401
56	84.28	39.48	0.401
58	86.43	39.93	0.410
60	88.10	41.79	0.413
62	90.28	42.67	0.421
64	91.19	43.82	0.421
66	93.18	44.99	0.426
68	94.06	46.83	0.423
70	96.85	47.76	0.434

Table 1: Newton solar cooker optimal configurations in Ancona for different sun elevationsand corresponding aperture areas.

¹⁹¹ 3. Manufacture and assembly

The manufacturing steps of the proposed Newton solar cooker, shown in Fig. 1, are the following: 1) construction of the base panel; 2) cutting and assembly of supports; 3) construction of the side doors; 4) construction of the cooking chamber; 5) arrangement of the reflectors and final assembly. Each step is described in this section. In addition, details about manufacturing costs are provided.

198 3.1. Construction of the base panel

A $600 \times 600 \times 20$ mm multilayer poplar wood panel was used as the base on 199 which the other elements of the cooker rest. Two poplar wood panels measuring 200 $600 \times 100 \times 20$ mm were fixed with screws at the top of the base panel along 201 two opposite edges. Their task is to keep two tempered glass panes that form 202 the glass prism cooking chamber in position, preventing them from sliding out-203 wards and guaranteeing the closure of the cooking chamber. To facilitate the 204 prototype's usage and ensure its manual alignment to solar radiation, the base 205 panel was fitted with 3 wheels. 206

207 3.2. Cutting and assembly of supports

To form the support arms for the primary panel reflectors, two bars with 208 a length of 650 mm were cut using a metal saw starting from a square steel 209 hollow profile with a 20×20 mm cross-section. As shown in Fig. 4a, the square 210 metal bars were fixed and anchored to the base of the solar cooker using angle 211 brackets. The angle brackets were fastened to the bars using a self-locking 212 system to allow the entire support system to change the angle for proper sun 213 tracking. The primary reflectors were fastened to the support arms through 214 eight 100-mm-long pieces that were first cut from an aluminum C-profile and 215 then attached vertically to the reflectors using double-sided adhesive tape. In 216 addition, the two square bars were fixed together with a metal rod at the top 217 to make the entire system more stable. 218



Fig. 4: Detail of the connection of the reflector supports to the wooden base: a) primary reflectors and b) secondary reflectors.

To form the support arms for the secondary reflectors, two profiles of 300 219 mm in length were cut using an aluminum saw starting from a 1000 mm long 220 aluminum L-profile with a 30×30 mm cross-section. To make the reflector sup-221 ports more stable during use, the aluminum profiles were reinforced by joining 222 them to 350 mm long wooden strips with a 20×20 mm square section. As 223 evident in Fig. 4b, the wooden supports were fixed and anchored to the base 224 of the solar cooker in the same way as the square metal bars. The secondary 225 reflectors were fixed to the aluminum supports and held in position by magnets. 226

227 3.3. Construction of the side doors

In addition to the base panel and glass surfaces, the cooking chamber was obtained by using two side doors that support the glass surfaces. The side doors, made of solid fir wood, are in the shape of an isosceles triangle with dimensions $400 \times 332 \times 30$ mm and are fitted with a handle on one side to facilitate their movement during testing. Moreover, the mobile doors allow varying the volume of the cooking chamber, adapting it to the pot and the load being used. An aluminum film was applied to the handle-free surface of the triangular doors and secured with adhesive tape with a twofold purpose: to reflect the direct sun's rays at the doors inside the cooking chamber, thus reducing the dispersion of radiation, and to prevent that the steam generated inside the cooking chamber penetrates the wood of the doors, affecting its thermal insulation resistance.

240 3.4. Construction of the cooking chamber

The base of the cooking chamber was thermally insulated by inserting a 430 \times 375 \times 8 mm cork panel over the poplar wood base. The cork panel was shaped to fit perfectly into the section created between the poplar base and the two side panels anchored to it. A steel plate measuring 420 \times 365 \times 1 mm was placed on top of the cork layer. The plate was painted with a high-performance black paint to increase its ability to absorb heat from solar radiation.

Two panes of tempered extra-clear glass measuring 380×480 mm and 4 mm thick make up the actual cooking chamber. The two panes of glass were placed on the triangular side doors and held in place by the two poplar wood panels. A gap was left on the top to prevent condensation inside the cooking chamber by spacing the two glass panes about 2 mm. This allows for improving the cooking performance of the device.

253 3.5. Arrangement of the reflectors and final assembly

Polymethylmethacrylate (PMMA) sheets were used for the reflective surfaces because of the material's low cost and to allow the operator to work safely. The presented configuration consists of 4 reflectors on 3 planes. The primary reflective surface consists of two 600×400 mm reflectors placed one above the other on the same plane, thus forming a single 600×800 reflector. The secondary reflective surface is made up of two 300×400 mm reflectors in a V configuration. The four reflectors were fixed to the supports, as described in Section 3.2.

261 3.6. Cost analysis

Table 2 shows the materials used for the construction of the prototype, with 262 the related costs. The highest costs are given by the PMMA reflectors, the 263 extra-clear tempered glass and the steel plate. These are the components that 264 most influence the optical (the first two) and thermal efficiency (the last one) 265 of the device. It is evident that the use of recycled or widely used materials, 266 such as wood, to make the main parts of the device (i.e., the base structure, 267 the side doors and the reflector supports) helped to keep the final cost low. 268 The prototype construction took two working days by a team of two unskilled 269 workers. 270

Table 2: Cost analysis of the prototype.

Item	Cost (EUR)
Panel reflectors	45.00
Extra clear tempered glass	40.00
Steel plate	30.00
Wood (structural frame, side doors	15.00
and handles)	
Aluminum L-profile	10.00
Insulating cork layer	10.00
Miscellaneous	40.00
Total	190.00

271 4. Experimental tests and setup

In this section, the types of tests carried out, the test fluids chosen and the instrumentation used in the outdoor experimental campaign are described. Then, the main parameters used to characterize the NSC are presented.

275 4.1. Experimental setup

Fig. 5 shows the experimental setup used during the experimental cam-276 paign. Two identical prototypes of NSC were placed on the ground and tested 277 simultaneously under the same outdoor conditions. One of the two devices was 278 shielded with a wind shielding system specifically constructed for the experi-279 mental campaign. The cooking chamber of each prototype was loaded with a 280 black stainless-steel pot containing the fluid to be tested. The pot has a diam-281 eter of 200 mm, a height of 130 mm, a thickness of 2 mm and a mass of 476 282 283 g.

The recorded quantities during the tests were the absorber plate temperatures of the two devices $(T_{\rm a})$, the fluid temperatures inside the pots $(T_{\rm f})$, the ambient temperature $(T_{\rm amb})$, the direct normal solar irradiance $(G_{\rm bn})$, and the global horizontal solar irradiance (G).

The sensors used to record the temperatures were T-type thermocouples with an uncertainty of ± 1 °C. In detail, the one used to record the fluid temperature was immersed in the studied fluid and held in place throughout the test. The thermocouple for the absorber plate temperature was fixed to the plate using high-temperature adhesive tape, shielding it from direct exposure to the sun. Instead, the one used to record the ambient temperature was placed in a shady place to avoid influencing the measurement.

The direct normal solar irradiance was recorded using an Eppley NIP pyrheliometer (normal incidence pyrheliometer) with a one-second response and linearity $\pm 0.5\%$ from 0 to 1400 W/m^2 . T-thermocouples and pyrheliometer signals were collected by a Pico Technology TC-08 datalogger and sent to a computer. The global horizontal solar irradiance was measured using a pyranometer SR30-M2-D1 with linearity $\pm 3.0\%$ from 0 to 4000 W/m^2 placed horizontally near the



Unshielded NSC

Fig. 5: Experimental setup. T_{a} : absorber temperature; T_{f} : testing fluid temperature; T_{amb} : ambient temperature; G_{bn} : direct normal solar irradiance; G: global horizontal solar irradiance.

tested prototypes. By following the same procedure described by other authors [28, 29, 32, 39], the global normal solar irradiance (G_n) was calculated using the Liu Jordan isotropic sky model [40] considering an albedo of 0.2.

304 4.2. Experimental parameters

Given the growing interest in the study and manufacture of solar cookers, there is a need for common procedures and standards to be followed for the characterization of the prototypes under investigation. These standards indicate the parameters and procedures to be followed to characterize the optical and thermal performance of these devices.

Table 3 shows the parameters used to characterize the NSC performance dur-310 ing the tests with and without load. The experimental campaign was divided 311 into two phases: the first tests were carried out by testing the devices with-312 out load while all the remaining tests were carried out by loading the cooking 313 chamber with a fluid. The first tests with no load were used to reach the stag-314 nation condition of the devices, i.e., the balance between heat input and heat 315 loss output. These tests are necessary to identify the first figure of merit (F_1) 316 associated with the device. It should be noted that for the determination of F_1 317 (Table 3), the considered values of ambient temperature (T_{amb}) and global nor-318 mal solar irradiance (G_n) are those associated with the maximum temperature 319 value reached by the plate during the test. 320

Load tests were carried out by loading the cooking chamber of each device with a black painted pot containing a test fluid. The selected fluids were water and glycerin. Water was selected because the obtained results could be easily comparable with those obtained by other researchers. Glycerin was selected because it is widely used to test the performance of solar cookers [25, 26, 39].

For the tests with water, as suggested by Funk [45], the parameters described in Table 3 were calculated over a time interval $\Delta t_{\rm h}$ required to raise the temperature of the fluid from 40 °C to 90 °C. In addition, the parameters were adapted and calculated to determine the behavior of the devices under investigation when tested with glycerin. The selected glycerin temperature range within which all parameters were calculated was 40–110 °C.

Lahkar et al. [44] proposed a procedure to determine the cooker opto-thermal ratio (COR) starting from the Hottel-Whillier-Bliss equation for solar cookers:

- 334
- 335

$$\eta = F'\eta_0 - \left(\frac{F'U_1}{C}\right)\chi,\tag{1}$$

336

where $\chi = (T_{\rm f} - T_{\rm amb})/G_{\rm n}$. The parameters $F'\eta_0$ and $F'U_{\rm l}/C$ of the equation can be identified from the data obtained from the experimental tests. These are

Experimental parameter	Equation	Equation parameters
First figure of merit [41]	$F_1 = rac{T_{ m a,max} - T_{ m amb}}{G_{ m n}}$	$A_{\rm a}$ = aperture area of the solar cooker
		$c_{\rm f}$ = specific heat of the test fluid
Heating time interval	$\Delta t_{ m h} = t(T_2) - t(T_1)$	C = geometrical concentration ratio
		$G_{ m n}={ m global}$ normal solar irradiance
Second figure of merit [41]	$F_{2} = \frac{F_{1}m_{\rm f}c_{\rm f}}{A_{\rm a}\Delta t_{\rm h}} \ln \left[\frac{1 - \frac{1}{F_{1}}(T_{\rm l} - T_{\rm amb,av})/G_{\rm n,av}}{1 - \frac{1}{F_{1}}(T_{2} - T_{\rm amb,av})/G_{\rm n,av}} \right]$	$G_{\mathrm{n,av}}=\mathrm{mean}\;G_{\mathrm{n}}$ measured at Δt_{h}
	1	$G_{ m n,ref} = 900 { m W/m^2} \; ({ m for} \; t_{ m s} \; { m calculation})$
Specific boiling time [42]	$t_{ m s}=rac{\Delta t_{ m h}A_{ m a}}{m_{ m f}}$	$\eta_0={ m optical}$ efficiency
		F' = heat exchange efficiency factor
Characteristic boiling time [42]	$t_{ m ch} = t_{ m s} rac{G_{ m n,ref}}{G_{ m n,ref}}$	$m_{ m f}={ m mass}$ of the test fluid
		$T_{ m amb}= m ambient$ temperature
Overall efficiency [42]	$\eta_{\mathrm{av}} = rac{m_{\mathrm{f}} \mathrm{c}_{\mathrm{f}}(T_2 - T_1)}{G_{\mathrm{n},\mathrm{av}} A_{\mathrm{a}} \Delta t_{\mathrm{h}}}$	$T_{\mathrm{a},\mathrm{max}}=\mathrm{absorber}$ stagnation temperature
		$T_{ m amb,av} = m mean \ T_{ m amb}$ measured at $\Delta t_{ m h}$
Utilizable efficiency [43]	$\eta_{\mathrm{u}} = rac{m_{\mathrm{f}} \mathrm{c}_{\mathrm{f}} (T_2 - T_{\mathrm{amb}, \mathrm{av}})}{G_{\mathrm{n}, \mathrm{av}} A_{\mathrm{a}} \Delta t_{\mathrm{h}}}$	$T_{ m f,av}={ m mean}~T_{ m f}$ measured at $\Delta t_{ m h}$
		$t(T_1) = $ starting time of the heating phase
Cooker opto-thermal ratio [44]	$COR = \frac{\eta_0 C}{U_1}$	$t(T_2) = ext{ending time of the heating phase}$
		$U_{ m l}={ m heat\ loss\ factor}$
Maximum achievable fluid temperature [44]	$T_{\rm fx} = T_{\rm amb,av} + \frac{F' \eta_0 G_{\rm n,av}}{F' U_l / C}$	
	O^{1}/O^{1}	

Table 3: Experimental parameters for the characterization of the Newton solar cooker.

the intercept and the opposite value of the slope of the efficiency line regression. 339 The total time interval to cover the chosen temperature range for water 340 (40–90 °C) and glycerin (40–110 °C) is divided into sub-intervals of 5 minutes 341 each. For each sub-interval, the average global normal solar irradiance, the 342 average ambient temperature, the average test fluid temperature, the efficiency 343 and the parameter χ are determined. Plotting the thermal efficiency η against 344 the parameter χ for each identified sub-interval, it is possible to identify the 345 regression line of the efficiency curve and its coefficient of determination R^2 . 346 The regression line's intercept and opposite value of the slope correspond to the 347 parameters $F'\eta_0$ and $F'U_1/C$, which are necessary for the determination of the 348 COR parameter. 349

Finally, it is worth to point out that the ASAE S580.1 Standard [22] procedure for the calculation of the standardized power was not used here because it is not physically consistent, as recently showed by Ruivo et al. [46].

353 4.3. Experimental tests

The experimental campaign was carried out in June 2021 on the roof of the Department of Industrial Engineering and Mathematical Sciences (latitude 43.5871°N, longitude 13.5149°E). As mentioned above, two identical Newton solar cooker prototypes were made and tested at the same time avoiding shaded areas in the test area. To understand the wind effect, one of the two devices was shielded from the wind during the tests.

With reference to wind intensity, Fig. 6 shows the average wind speed 360 recorded in a location near the testing area (latitude 43.6098°N, longitude 361 $13.5105^{\circ}E$) during the time slot when the measures were conducted. The data 362 were collected from the website of the Marche Region – Civil Protection Service 363 [47]. It is evident that, in all the tests, these values exceed the limit of 1 m/s 364 imposed by the ASAE standard [22, 48]. For this reason, following the same 365 strategy adopted by other authors [23], the prototypes were tested by placing 366 them near the parapets and walls of buildings, shielding them from direct wind 367 exposure. 368



Fig. 6: Average wind speed recorded in Ancona, Italy during the testing period.

During the tests, the operator maintained the cooking chamber and the 369 reflector system of the two devices always pointed towards the sun direction. 370 Additionally, to make the best use of the reflective surfaces and to concentrate 371 as much solar radiation as possible into the cooking chamber, the elevation of 372 the sun (H_{sun}) was checked every 20 minutes and the θ_1 and θ_2 angles of the 373 primary and secondary reflective surfaces were adjusted according to Table 1. 374 Every tested configuration of the cooker was recorded by the operator in terms 375 of H_{sun} , θ_1 and θ_2 angles. These values were averaged across the test duration 376 to obtain $H_{sun,av}$, $\theta_{1,av}$ and $\theta_{2,av}$ for each test. The average aperture area 377 $(A_{a,av})$ was calculated in a similar fashion. These quantities were used for the 378 calculation of the parameters. 379

380 5. Experimental results

In this section, the results obtained from tests conducted with and without load are reported.

Quantity	Test	1	Test	2	Test	3
Date	31/05/	2021	03/06/	2021	30/06/	2021
Type of cooker	Unshielded	Shielded	Unshielded	Shielded	Unshielded	Shielded
$H_{ m sun,av}$ (°)	65.64	65.64	56.22	56.22	62.34	62.34
$ heta_{1,\mathrm{av}}$ (°)	92.48	92.48	84.90	84.90	89.98	89.98
$ heta_{2,\mathrm{av}}$ (°)	45.14	45.14	38.83	38.83	42.93	42.93
$A_{\rm a,av} ({\rm m}^2)$	0.425	0.425	0.401	0.401	0.421	0.421
$T_{\rm amb}$ (°C)	21.07	20.99	30.05	29.70	32.60	33.40
$G_{\rm n}~({\rm W/m^2})$	981.19	977.35	908.86	907.25	936.19	932.46
$G_{\rm bn}~({\rm W/m^2})$	925.74	923.02	866.71	865.17	859.29	858.67
$T_{\rm a,max}$ (°C)	125.66	120.81	137.47	137.36	133.95	129.07
$F_1 (^{\circ}C/(W/m^2))$	0.107	0.102	0.118	0.119	0.108	0.103

Table 4: Summary of tests without load.

383 5.1. Tests without load

Three tests without load were carried out under different external conditions. 384 Table 4 shows the environmental conditions associated with the maximum tem-385 perature reached by the absorber plate $(T_{a,max})$ and the F_1 parameter calcu-386 lated for each device in each test. Table 4 also shows the average sun elevation 387 $(H_{\rm sun,av})$, the average angles θ_1 and θ_2 and the average aperture area $(A_{\rm a,av})$ 388 for the reported tests. From Table 4, it can be noted that similar values of 389 $T_{\rm a,max}$ and F_1 were obtained for the two devices in each test. The temperature 390 trends of the absorber plate of the unshielded and shielded NSC prototypes for 391 the test of 03/06/2021 (test 2) are shown in Fig. 7. As can be seen, the max-392 imum temperature reached by the absorber plate was about 137 °C for both 393 NSC prototypes. This maximum temperature $(T_{a,max})$ was associated with a 394 global normal solar irradiance and an ambient temperature of $908.86\,\mathrm{W/m^2}$ and 395 30.05 °C for the unshielded NSC and 907.25 W/m² and 29.70 °C for the shielded 396 NSC. 39

For the three tests without load, the following average values of the F_1 were obtained: $F_{1,av} = 0.111 \,^{\circ}C/(W/m^2)$ for the unshielded device and $F_{1,av} = 0.108 \,^{\circ}C/(W/m^2)$ for the shielded prototype. The values of $F_{1,av}$ were used for



Fig. 7: Test without load (03/06/2021, test 2).

calculating the second figure of merit (F_2) for the tests with the load.

402 5.2. Tests with water

Four outdoor tests were performed by loading each NSC device with 2 kg of water. Table 5 shows the main parameters for each test calculated in the fluid temperature range between 40 and 90 °C.

Fig. 8 shows the trends of water temperatures, ambient temperature and global and direct normal solar irradiances for test 4 (01/06/2021). The average global normal solar irradiance was 1050.80 W/m^2 , while the average ambient temperature was 21.65 °C. The fluid took 127 minutes when tested with the unshielded NSC and 128 minutes when tested with the shielded device to go from 40 °C to 90 °C.

Fig. 9 shows the water trends obtained with the two prototypes during all water tests. From Fig. 9, it is possible to see that, even though the tests were carried out on days characterized by different solar irradiances and ambient temperatures, the trends in water temperatures are very similar. It can also be noted that, in each test, the time taken for the water to reach 90 °C was

	Test	4	Test	5	Test	9	Test	7
Date	01/06/	2021	01/06/	2021	09/00/	2021	17/06/	2021
Type of cooker	Unshielded	Shielded	Unshielded	Shielded	Unshielded	Shielded	Unshielded	Shielded
$H_{ m sun,av}$ (°)	58.60	58.60	61.26	61.26	63.13	63.13	62.96	62.96
$\theta_{1,\mathrm{av}}$ (°)	87.04	87.04	88.81	88.81	90.46	90.46	90.41	90.41
$ heta_{2,\mathrm{av}}$ (°)	39.59	39.59	41.98	41.98	43.45	43.45	43.26	43.26
$A_{ m a,av}~({ m m}^2)$	0.411	0.411	0.416	0.416	0.417	0.417	0.419	0.419
$m_{ m f}~(m kg)$	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
T_1 (°C)	40	40	40	40	40	40	40	40
T_2 (°C)	90	90	06	06	60	06	06	06
$G_{ m n,av}~({ m W/m^2})$	1051.95	1049.64	951.90	954.14	824.15	830.93	918.31	918.31
$G_{\mathrm{bn,av}}~(\mathrm{W/m^2})$	908.40	906.41	908.93	911.07	696.92	702.65	738.05	738.12
$T_{\rm amb,av}$ (°C)	22.03	21.99	23.69	23.59	23.76	23.54	30.22	30.21
$\Delta t_{ m h}~({ m min})$	127	128	122	118	170	134	112	113
$t_{ m s}~({ m hm^2/kg})$	0.44	0.44	0.42	0.41	0.59	0.47	0.39	0.40
$t_{ m ch}~({ m h}{ m m}^2/{ m kg})$	0.51	0.51	0.45	0.43	0.54	0.43	0.40	0.40
$\eta_{ m av}$	0.13	0.13	0.15	0.15	0.12	0.15	0.16	0.16
$\eta_{ m u}$	0.17	0.17	0.19	0.20	0.16	0.20	0.19	0.19
F_2	0.21	0.21	0.25	0.27	0.24	0.31	0.26	0.26
$F'\eta_0$	0.247	0.255	0.271	0.329	0.285	0.345	0.279	0.268
$F'U_{\rm l}/C~({\rm W/m^2~^\circ C})$	2.722	2.866	2.683	3.750	2.879	3.424	2.804	2.552
$COR~(W/m^2 \circ C)$	0.091	0.089	0.101	0.088	0.099	0.101	0.100	0.105
$T_{\rm fx}$ (°C)	117.56	115.37	119.93	107.24	105.19	107.26	121.68	126.49
R^2	0.974	0.941	0.867	0.886	0.910	0.909	0.929	0.948

Table 5: Summary of tests with water.



Fig. 8: Test with water (01/06/2021, test 4).

about the same for the two devices. In detail, this time was slightly longer in
the case of the unshielded device (on average 133 minutes) with respect to the
shielded one (on average 123 minutes). A decrease in the time required by the
fluid tested in the shielded prototype is evident in test 6 (09/06/2021). The
time taken by the unshielded NSC was 170 minutes while the time taken by the
shielded device was 134 minutes.

In general, the shortest time was recorded in the test of 17/06/2021 (test 423 7): 112 minutes for the unshielded NSC and 113 minutes for the shielded NSC. 424 During the test an average global normal solar irradiance of $918.31 \,\mathrm{W/m^2}$ and 425 an average ambient temperature of 30.22 °C were recorded. Comparing tests 4 426 and 5 with test 7, it can be seen that the first two were characterized by higher 427 values of $G_{n,av}$ and $G_{bn,av}$ than the latter. Despite that, their Δt_h are higher 428 than that of test 7, showing that $T_{\rm amb}$ could affect the device performance more 429 than the solar irradiance. In fact, this temperature was much higher in test 7 430 than in tests 4 and 5 (30.22 °C vs. 21.6 °C and 23.6 °C). However, the influence 431 of a lower solar irradiance is evident in tests 5 and 6 that showed a similar 432



Fig. 9: Water temperature trends.

ambient temperature; in fact, a longer time for water to reach the boiling point 433 was registered in test 6 (average $\Delta t_{\rm h}$ of 152 min and $G_{\rm n}$ of 827.54 W/m²) with 434 respect to test 5 (average $\Delta t_{\rm h}$ of 120 min and $G_{\rm n}$ of 953.02 W/m²). 435

To better characterize the devices under investigation, in addition to the 436 average efficiency (η_{av}) and the specific and characteristic boiling times (t_s and 437 $t_{\rm c}$), the following parameters were calculated: the COR parameter and the 438 maximum temperature reachable by the fluid (T_{fx}) . 439

To calculate these parameters, the water temperature range 40-90 °C was 440 divided into sub-intervals of 5 minutes each. For each sub-interval, the averages 441 of the global normal solar irradiance $(G_{n,av})$, ambient and fluid temperatures 442 $(T_{\rm amb,av} \text{ and } T_{\rm f,av})$, and efficiency (η) were determined together with the pa-443 rameter χ . Fig. 10 shows the thermal efficiency η plotted against χ for each 444 identified sub-interval. From the points, it was possible to obtain the regression 445 line of the efficiency curve and its coefficients that correspond to the parameters 446 $F'\eta_0$ (intercept of the line) and $F'U_1/C$ (opposite value of the slope of the line). 447 448

From the parameters calculated for the different tests (Table 5), it can be pointed out that their values for the unshielded device are usually similar to those of the shielded NSC in all the tests. However, it is also possible to note that, while the optical efficiency factor $F'\eta_0$ of the two prototypes is almost constant, the heat loss factor $F'U_1/C$ shows wider variations that depend on the average ambient temperature and wind speed.

455 5.3. Tests with glycerin

Four outdoor tests were performed by loading each pot with 2 kg of glycerin. Table 6 shows the results obtained for two NSC prototypes in the tests. The parameters reported in this table were calculated in the glycerin temperature range between 40 and 110 °C.

Fig. 11 shows the trends of glycerin temperatures, ambient temperature and global and direct normal solar irradiances recorded on 04/06/2021 (test 9). The average global normal solar irradiances was 963.96 W/m^2 , while the average ambient temperature was $26.88 \,^{\circ}$ C. The fluid took 199 minutes when tested with the unshielded NSC and 187 minutes when tested with the shielded device to cover the temperature range of $40-110 \,^{\circ}$ C.

Fig. 12 shows the glycerin trends obtained with the unshielded and shielded NSC devices during all the performed tests. From Fig. 12, it is possible to note that, as in the case of the water tests, the curves follow a very similar trend even though the external conditions were different.

However, it is worthwhile noting that the effect of shielding is more evident in the tests with glycerin. In fact, the times required for the fluid to go from 40 to 110 °C were generally longer in the case of the unshielded solar cooker. This is especially evident in tests 8 (03/06/2021) and 10 (22/06/2021): $\Delta t_{\rm h}$ were 236 and 214 minutes, respectively, for the unshielded NSC and 174 and 175 minutes, respectively, for the shielded NSC.

As for the water tests, to best characterize the two prototypes, the *COR* parameter and $T_{\rm fx}$ were calculated in addition to $\eta_{\rm av}$, $t_{\rm s}$ and $t_{\rm ch}$. The same procedure described for the water tests was used. The only difference was that the



Fig. 10: Efficiency of the cookers tested with water (01/06/2021, test 4): a) unshielded Newton solar cooker and b) shielded Newton solar cooker.

	Test	×	Test	6	Test	10	Test	11
Date	03/06/:	2021	04/06/	2021	22/06/	2021	29/06/	2021
Type of cooker	Unshielded	Shielded	Unshielded	Shielded	Unshielded	Shielded	Unshielded	Shielded
$H_{ m sun,av}$ (°)	60.93	60.93	60.48	60.48	63.77	63.77	61.39	61.39
$\theta_{1,\mathrm{av}}$ (°)	88.69	88.69	88.53	88.53	90.98	90.98	89.19	89.19
$ heta_{2,\mathrm{av}}$ (°)	40.75	40.75	40.73	40.73	43.75	43.75	41.64	41.64
$A_{\rm a,av}~({\rm m^2})$	0.414	0.414	0.413	0.413	0.419	0.419	0.416	0.416
$m_{ m f}~(m kg)$	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
T_1 (°C)	40	40	40	40	40	40	40	40
T_2 (°C)	110	110	110	110	110	110	110	110
$G_{ m n,av}~(m W/m^2)$	1058.05	1048.19	962.39	965.53	934.34	934.96	910.08	910.85
$G_{\mathrm{bn,av}}~(\mathrm{W/m^2})$	879.44	871.25	837.81	846.06	766.25	766.75	744.91	745.54
$T_{ m amb,av}$ (°C)	24.06	23.43	26.78	26.94	31.05	30.92	32.10	32.12
$\Delta t_{ m h} ({ m min})$	236	174	199	187	214	175	140	146
$t_{ m s}~({ m hm^2/kg})$	0.81	0.60	0.60	0.64	0.75	0.61	0.49	0.51
$t_{ m ch}~({ m hm^2/kg})$	0.96	0.70	0.64	0.69	0.78	0.63	0.49	0.51
$\eta_{ m av}$	0.06	0.08	0.09	0.08	0.08	0.09	0.12	0.11
$\eta_{ m u}$	0.08	0.10	0.11	0.10	0.09	0.10	0.13	0.13
F_2	0.12	0.17	0.19	0.18	0.15	0.19	0.24	0.24
$F'\eta_0$	0.156	0.204	0.216	0.206	0.177	0.230	0.265	0.295
$F'U_{\rm l}/C~({\rm W/m^2~^\circ C})$	1.682	2.124	2.240	2.046	1.776	2.347	2.810	3.206
$COR \ (^{\circ}C/(W/m^2))$	0.093	0.096	0.096	0.100	0.100	0.098	0.094	0.092
$T_{\rm fx}$ (°C)	122.14	124.27	119.65	123.99	124.17	122.54	117.93	116.03
R^2	0.932	0.957	0.883	0.968	0.922	0.883	0.856	0.910

Table 6: Summary of tests with glycerin.



Fig. 11: Test with glycerin (04/06/2021, test 9).



Fig. 12: Glycerin temperature trends.

temperature range from 40 to 110 °C was considered to calculate the parameters. Fig. 13 shows the efficiency (η) referring to test 10 (04/06/2021). Also in this case, the values of the calculated parameters are very similar in each test (Table 6). As for the tests with water, the optical efficiency factor ($F'\eta_0$) of the two prototypes is almost constant, while wider variations of the heat loss factor ($F'U_1/C$) are evident.

Finally, from Tables 5 and 6, it can be pointed out that, for the same mass of fluid, the average thermal efficiency (η_{av}) for the tests with glycerin is lower than that for the tests with water; this outcome can be due to the higher temperatures used to test glycerin.



Fig. 13: Efficiency of the cookers tested with glycerin (04/06/2021, test 9): a) unshielded Newton solar cooker and b) shielded Newton solar cooker.

489 6. Conclusions

In this work, a new solar cooker with variable geometry, called Newton 490 solar cooker, was designed, constructed and experimentally tested through an 491 outdoor campaign. The presented device is easy to build, given the few simple 492 steps required in its manufacturing. It is easy to use and transport, given its 493 low weight and the possibility of disassembling the reflective surfaces and folding 494 the reflector supports. In addition, it is mainly made of common and available 495 materials such as wood and glass, making it inexpensive. To track the sun and 496 to maximize the amount of solar radiation concentrated on the cooking chamber, 497 the Newton solar cooker can change the inclination of the reflectors and rotate 498 through wheels. 499

During the experimental campaign, an unshielded prototype was simultane-500 ously tested with an identical prototype that was shielded from the wind. The 501 two prototypes with tracking reflective surfaces at optimal angles were tested 502 both without load and by loading a pot with water or glycerin. The no-load 503 tests revealed that both prototypes were able to bring the cooker plate to a 504 stagnation temperature of approximately 137 °C. The water tests showed that 505 the shielded Newton solar cooker was capable of boiling 2 kg of water in ap-506 proximately two hours. This time was slightly longer (on average 133 minutes) 507 in the case of the unshielded device. From the glycerin tests, it was found that, 508 to raise the temperature of 2 kg of glycerin from 40 °C to 110 °C, the shielded 509 Newton solar cooker took 170 minutes on average, while the unshielded device 510 took 197 minutes on average. The use of glycerin showed that the studied cooker 511 can reach medium-high temperatures with good efficiency. 512

In conclusion, it can be stated that the presented solar cooker is easy to use, cost-effective and non-hazardous thanks to its simplicity and the use of common and recyclable materials. The proposed device is also suited for developing countries where it can be considered as a promising and environmentally friendly alternative to traditional cooking methods.

Nomenclature 518

Latin Symbols 519

524

525

526

 F_2

- Area (m^2) A520
- CConcentration ratio 521 Cooker opto-thermal ratio $(^{\circ}C/(W/m^2))$ COR522 Specific heat $(J/(kg \circ C))$ c523 First figure of merit $(^{\circ}C/(W/m^2))$ F_1

Second figure of merit

- F'Heat exchange efficiency factor
- $F'\eta_0$ Optical efficiency factor 527
- Heat loss factor $(W/m^2 \circ C)$ $F'U_1$ 528
- Global horizontal solar irradiance (W/m^2) ${G}$ 529
- Direct normal solar irradiance (W/m^2) $G_{\rm bn}$ 530
- Global normal solar irradiance (W/m^2) G_{n} 531
- $H_{\rm sun}$ Sun elevation ($^{\circ}$) 532
- Mass (kg) 533 m
- Temperature (°C) T534
- Maximum achievable fluid temperature (°C) $T_{\rm fx}$ 535
- Time (min) t536
- 537
- Greek Symbols 538
- Efficiency η 539
- **Optical** efficiency η_0 540
- θ Reflector angle $(^{\circ})$ 541

542

543 Subscripts

544	a	Absorber, aperture
545	amb	Ambient
546	av	Average
547	ch	Characteristic
548	f	Fluid
549	h	Heating
550	max	Maximum
551	ref	Reference
552	S	Specific, solid
553	u	Utilizable
554		
555	A cronyms	
556	NSC	Newton solar cooker
557	PMMA	Polymethylmethacrylate
558		
559		
	D 4	
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