



UNIVERSITÀ POLITECNICA DELLE MARCHE
Repository ISTITUZIONALE

Design, realization, and tests of a portable solar box cooker coupled with an erythritol-based PCM thermal energy storage

This is the peer reviewed version of the following article:

Original

Design, realization, and tests of a portable solar box cooker coupled with an erythritol-based PCM thermal energy storage / Coccia, G.; Aquilanti, A.; Tomassetti, S.; Comodi, G.; Di Nicola, G.. - In: SOLAR ENERGY. - ISSN 0038-092X. - 201:(2020), pp. 530-540. [10.1016/j.solener.2020.03.031]

Availability:

This version is available at: 11566/277022 since: 2024-11-22T15:13:49Z

Publisher:

Published

DOI:10.1016/j.solener.2020.03.031

Terms of use:

The terms and conditions for the reuse of this version of the manuscript are specified in the publishing policy. The use of copyrighted works requires the consent of the rights' holder (author or publisher). Works made available under a Creative Commons license or a Publisher's custom-made license can be used according to the terms and conditions contained therein. See editor's website for further information and terms and conditions.

This item was downloaded from IRIS Università Politecnica delle Marche (<https://iris.univpm.it>). When citing, please refer to the published version.

(Article begins on next page)

Design, realization, and tests of a portable solar box cooker coupled with an erythritol-based PCM thermal energy storage

Gianluca Coccia^{a,*}, Alessia Aquilanti^{a,b}, Sebastiano Tomassetti^a, Gabriele Comodi^a, Giovanni Di Nicola^a

^a*Marche Polytechnic University, Department of Industrial Engineering and Mathematical Sciences, Via Brezze Bianche 12, 60131, Ancona (Italy)*

^b*Technical University of Darmstadt, Institute of Construction and Building Materials, Franziska-Braun-Str. 3, 64287, Darmstadt (Germany)*

Abstract

Solar radiation is a variable energy source and the mismatch between the availability of such source and the domestic energy demand is a paramount challenge to deal with. For this reason, in this work a 4.08 concentration ratio portable solar box cooker coupled with a thermal energy storage (TES) based on a phase change material (PCM) was characterized through outdoor experimental tests. The TES is a double-wall stainless steel vessel, with the annular volume filled with 2.5 kg of erythritol. The portable solar box cooker was tested under 4 different experimental conditions: without load, with water, with silicone oil, and with silicone oil inserted in the erythritol-based TES. The load tests were divided into a heating and a cooling phase, in order to evaluate the cooker performance in absence of solar radiation. Results showed that equipping the portable solar box cooker with the erythritol-based TES allowed to extend the average load cooling time, in the range 125–100 °C, of around 351.16%.

Keywords: sugar alcohol; polyalcohol; experimental; heating phase; cooling phase

*Corresponding author. Tel: +39 0712204277, fax: +39 0712204770

Email addresses: g.coccia@univpm.it (Gianluca Coccia), a.aquilanti@pm.univpm.it (Alessia Aquilanti), s.tomassetti@pm.univpm.it (Sebastiano Tomassetti), g.comodi@univpm.it (Gabriele Comodi), g.dinicola@univpm.it (Giovanni Di Nicola)

1. Introduction

Solar cooking is considered one of the simplest and most promising applications to use solar energy. This is especially true for developing countries, where there is usually abundance of solar radiation (Cuce and Cuce, 2013; Kundapur, 2018; Esen, 2004). It is well-known that solar radiation represents a variable energy source and the mismatch between the availability of such source and the domestic energy demand is a paramount challenge to solve. This is the reason why there is so much interest in introducing and testing thermal energy storages (TESs) in solar cookers, in order to compensate and stabilize the absence and variability of the solar source (Sagade et al., 2019a).

During the last years, several studies conducted in India, Africa, and Central/South America, demonstrated that the use of solar cookers equipped with a TES helped to reduce the use of conventional fuels, such as firewood, animal manure and agricultural waste in rural areas, and liquefied petroleum gas, kerosene, electricity and coal in urban districts (Nahar, 2003; Schwarzer and Da Silva, 2003). Specifically, TES technology based on the use of phase change materials (PCMs) allows to absorb solar energy during the heating process, and to release thermal energy during the cooling process (Sharma et al., 2009; Esen et al., 1998; Esen and Ayhan, 1996; Esen, 2000). The two phases take advantage of the phase change processes occurring in the substance chosen as PCM, when it exists in a solid-liquid form.

A number of scientific studies discussed solar cookers coupled with TESs based on sensible substances and PCMs. In 1988, Ramadan et al. (1988) manufactured an inexpensive solar cooker tested with sand and barium hydroxide octa hydrate. The authors inserted the two substances around the cooking vessel and found that chemical decomposition could occur in the hydrate PCM.

Domanski et al. (1995) realized a double-wall aluminum vessel and filled the annular space with stearic acid and magnesium nitrate hexahydrate, in order to evaluate the possibility of evening cooking. Experimental tests proved that the solar box cooker efficiency in the discharging process was 3–4 times greater

31 than that of conventional solar cookers.

32 Haraksingh et al. (1996) manufactured a double-glazed flat-plate collector
33 containing a cooking chamber made of copper covered with a selective film.
34 The authors used coconut oil as sensible TES, which had a boiling point of
35 200 °C, was non-toxic and was readily available locally. They obtained an oil
36 bath temperature of 130 °C with two pans each containing 2 liters of water, and
37 water took about two and half hours to reach boiling.

38 Buddhi and Sahoo (1997) designed and tested a solar box cooker including
39 two aluminum trays. The cooking pot was inserted in the center of the inner
40 tray and the space between the two trays was filled with stearic acid. The
41 authors found that two batches could be cooked with one pot.

42 In 1997, Nandwani et al. (1997) manufactured a solar box cooker using a
43 PCM based on Vestolen A6016, a high-density-type polyethylene. The authors
44 found out that the maximum temperature variation of the absorber plate was
45 25 °C in the case of the normal tray and 10 °C in the storage plate without
46 cooking load. They also recorded that the normal tray had a temperature drop
47 of 95 °C, while the tray coupled with the PCM had a temperature drop of 49 °C,
48 when 2 liters of water were loaded.

49 Sharma et al. (2000) realized a TES based on a double-wall aluminum vessel
50 whose annular volume was filled with 2 kg of acetamide. The system was then
51 inserted in a solar cooker, and the authors found that this solution allowed the
52 possibility of evening cooking. In another study (Buddhi et al., 2003), the same
53 researchers showed that using a solar cooker with three reflectors and 4 kg of
54 acetanilide, evening cooking was possible even in wintertime.

55 Oturanç et al. (2002) built and tested an economical solar box cooker coupled
56 with a 7-liter oil tank used to keep the cooker warm after cooking. Experimental
57 results showed that the internal air temperature could be kept higher for the
58 following hours thanks to the oil reservoir, and that some foods such as potatoes,
59 rice and eggs could be cooked quicker.

60 In 2003, Nahar (2003) inserted a TES based on 5 kg of engine oil in a solar
61 box cooker. Several tests were conducted and compared with those obtained

62 from a cooker of equal size and made with the same materials, but not equipped
63 with the engine oil thermal storage. It was found that from 17:00 to 24:00, the
64 temperature inside the cooking chamber equipped with thermal storage was
65 23 °C higher. Additionally, rice took about 3 hours to cook perfectly in the
66 cooking chamber equipped with the TES, while this was not possible in the
67 system without heat storage.

68 Schwarzer and Da Silva (2003) proposed an indirect solar cooker consisting in
69 one or more flat-plate collectors connected to the cooking unit via a heat transfer
70 fluid (vegetable oil). The system included a heat storage tank, working with
71 the same fluid, that allowed the possibility of keeping the food warm for longer
72 periods and cooking at night. According to the authors, the main disadvantages
73 of the system lied in the high manufacturing cost and in the difficulty of finding
74 all the materials needed for construction in non-industrialized countries.

75 Sharma et al. (2005) studied the performance of an evacuated tube solar
76 collector (ETC) equipped with an erythritol-based TES used for cooking. The
77 authors of the study found that evening cooking was not affected by noon cook-
78 ing, and that the former using the erythritol-based TES was faster than the
79 latter.

80 In 2008, Hussein et al. (2008) realized and characterized an indirect solar
81 cooker with an elliptical cross section. The TES was based on magnesium-
82 nitrate-hexahydrate. Tests proved that the system could be used for heating or
83 keeping food hot at night and early morning.

84 El-Sebaii et al. (2009) studied the thermal cycling of two PCMs, magnesium
85 chloride hexahydrate and acetanilide. The authors found that the former sub-
86 stance was unstable and incompatible with either stainless steel or aluminum,
87 while the latter substance showed a good level of thermal stability and excellent
88 compatibility with aluminum.

89 In 2018, Coccia et al. (2018) designed, manufactured and tested a TES
90 consisting in a double-wall stainless steel vessel. The annular volume was loaded
91 with 4 kg of solar salt based on a ternary mixture of 53 wt% KNO_3 , 40 wt%
92 NaNO_2 , and 7 wt% NaNO_3 . The TES was inserted in a 10.78 concentration

ratio solar box cooker (Coccia et al., 2017) and several outdoor tests were carried out to assess the performance of the system. The authors found that the solar-salt-based TES dramatically improved the load thermal stabilization when solar radiation was absent: in the range 170–130 °C, the load cooling time was from 65.12% to 107.98% higher than that without the TES.

Following the methodology proposed in our previous works (Coccia et al., 2017, 2018), in the present study we report and discuss the results obtained for a 4.08 concentration ratio portable solar box cooker coupled with an erythritol-based TES. The novelty of the study lies in the fact that no experimental results for a direct solar cooker using erythritol as PCM are available. Another feature of the study is the systematic approach used to carry out and analyze the outdoor experimental tests, in particular as concerns the quantity of the test loads, solar exposition criteria, and the parameters chosen for the thermodynamic characterization of the solar cooker coupled with the TES.

The paper is organized as follows. Section 2 describes the design and manufacture of the portable solar box cooker, together with the materials used for its construction. The section also gives information about the thermal energy storage and the phase change material inserted in the solar cooker. Section 3 defines the experimental procedures and the test bench used to characterize the solar cooker system. Section 4 reports the results of the study. The conclusions of the work are provided in Section 5.

2. Design, manufacture, and materials

In this section, details about the design, realization, and materials used to produce the solar box cooker prototype, the thermal energy storage, and the phase change material (PCM) based on erythritol will be provided.

2.1. Solar box cooker

The proposed solar box cooker, shown in Figure 1, is composed by a wooden box containing a zinc-coated steel frame with the function of cooking chamber. The box has a glass cover on the top, which allows solar radiation to be

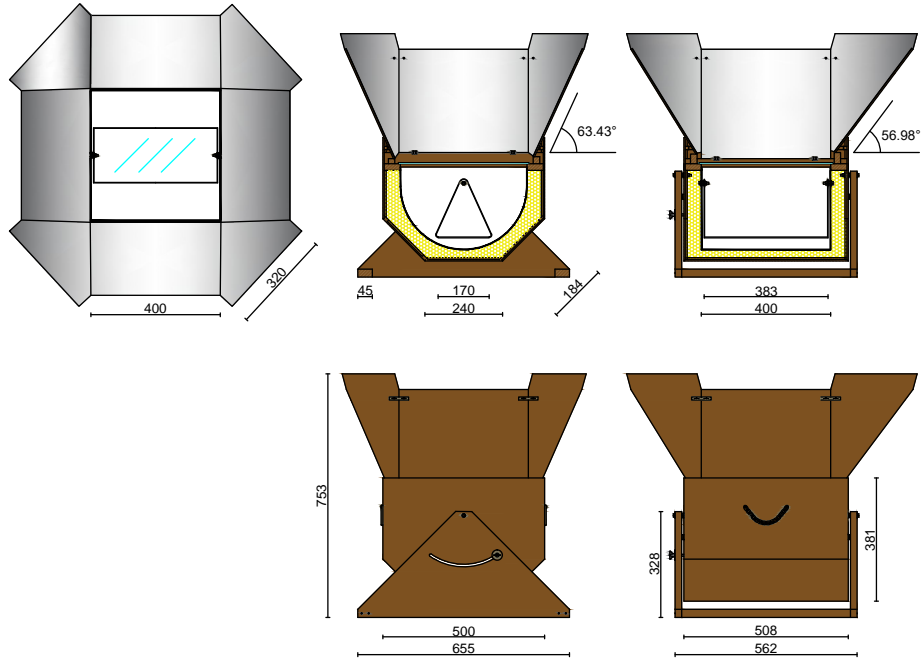


Figure 1: Views and cross-sections of the portable solar box cooker.

122 transmitted to the cooking chamber. The glass cover can be easily removed to
 123 allow loading of vessels. The higher part of the box is surrounded by 8 booster
 124 mirrors that allow an additional amount of solar radiation to be reflected and
 125 concentrated towards the cover and the cooking chamber. The cooker aperture
 126 area, A_a , is equal to 0.681 m^2 , while the glass cover area, A_g , is 0.167 m^2 . Thus,
 127 the cooker concentration ratio is:

$$128 \quad C = \frac{A_a}{A_g} = 4.08. \quad (1)$$

129 Additionally, the prototype has two border wooden hands that allow both its
 130 handling and its azimuthal orientation. A zenithal orientation is also possible
 131 as the cooker is able to rotate around the horizontal axis via a bolt moving into
 132 a runner. This rotation can be blocked with an external butterfly screw.

133 The cooker manufacturing process consisted of 4 consecutive phases: cooking
 134 chamber realization and painting; external structure realization; insulation with

135 glass wool; realization of the booster mirror system.

136 The cooking chamber walls were obtained starting from a stainless steel sheet
137 6/10 mm thick. The various pieces were cut, folded and finally riveted to form
138 the assembly. All joints have been sealed with a high temperature and non-toxic
139 sealant such as that used in commercial ovens. A tilting support is placed inside
140 the cooking chamber: its purpose is to keep the vessels steady when the solar box
141 cooker is being rotated, and is made from a stainless-steel sheet. The cooking
142 chamber was painted with a selective black coating (SOLKOTE HI/SORB-II)
143 generally used in more advanced solar thermal systems such as parabolic trough
144 collectors. This paint has a dual function: absorbing the maximum amount of
145 solar radiation and protecting the metal parts from oxidation. Respect to a
146 common black paint, the selective coating shows a solar absorptance factor of
147 about 90%, while its emissivity ranges from 0.20 to 0.49 depending on the dry
148 film thickness.

149 The external structure was realized starting from the side walls, which were
150 obtained by medium-density fiberboards (MDFs) 0.7 mm thick. In order to make
151 the external MDF structure more stable and resistant, fir laths were inserted
152 and joined inside the inner cavity. Handles were accommodated to support and
153 carry the entire solar cooker mass. The base of the cooker and the locking system
154 for its zenithal rotation were manufactured with more robust wooden panels,
155 instead. Finally, the cooking chamber was placed inside the external structure.
156 Its correct alignment was guaranteed thanks to fir spacers. A tempered glass
157 cover was placed on the upper part of the box to allow both solar radiation
158 transmittance and the loading/unloading of the vessels. The cover glass has a
159 solar transmittance factor of about 90%.

160 The cooking chamber metal walls were thermally insulated to reduce heat
161 losses and obtain higher operating temperatures. The thermal insulation con-
162 sisted of layers and flakes of glass wool inserted in the cavity between the cooking
163 chamber and the external MDF structure. To prevent the moisture from dam-
164 aging the wood panels, all the MDF elements were painted with a protective
165 coating.

166 The booster mirror system was realized with 8 reflective panels. Each panel
167 consisted of a wooden support on which an aluminum foil was glued. Among the
168 8 panels, 4 are square-shaped and attached to the box with hinges, while 4 are
169 wedge-shaped and inserted alternately between the square-shaped ones. In this
170 way, the booster mirror system assumes a funnel-type shape. The aluminum
171 sheets used are reflective foils (MIRO-SUN Weatherproof Reflective 90) able to
172 withstand atmospheric agents and guarantee an overall solar reflectance factor
173 of about 94%.

174 The cooker prototype has a maximum height of 75 cm and a mass of about
175 20 kg. Its overall cost is around 300 EUR (the most expensive item is the
176 booster mirror system). The prototype can be realized by three workers (one
177 specialized and two non-specialized) in about 50 hours.

178 2.2. Thermal energy storage

179 Figure 2 depicts the thermal energy storage (TES) used in the solar cooker.
180 The system is composed of two cylindrical stainless steel pots. The outer pot
181 has a diameter of 23 cm and was painted with a black coating to increase its
182 solar energy absorption. The inner pot, instead, has a diameter of 19 cm and
183 was filled with the testing fluid (water or silicone oil). Four bolts were used to
184 connect the two pots, and the corresponding annulus was filled with the PCM.

185 Two K-type thermocouples (T_{PCM1} and T_{PCM2} in Figure 2) were located in
186 two opposite stainless steel tubes, to detect the PCM temperature. The testing
187 fluid temperature, instead, was measured through a T-type thermocouple (T_f
188 in Figure 2) installed in the center of the TES.

189 2.3. Phase change material

190 The PCM used in the thermal energy storage is erythritol, a sugar polyal-
191 cohool that occurs naturally in some fruit and fermented foods. Being almost
192 noncaloric, erythritol is commercialized as a food additive and sugar substitute.
193 Referring to the literature, the main physical properties of this sugar derived
194 from alcohol are provided in Table 1.

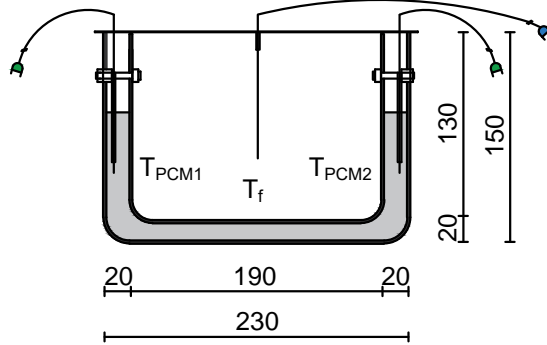


Figure 2: Thermal energy storage. T_{PCM1} and T_{PCM2} are two K-type thermocouples used to detect the PCM temperature, while T_f is a T-type thermocouple used to detect the testing fluid temperature.

Table 1: Thermophysical properties of erythritol.

Property	Value	Reference
T_{melt} ($^{\circ}\text{C}$)	117.7	Honguntikar and Pawar (2019)
L (kJ/kg)	339.8	Honguntikar and Pawar (2019); Shukla et al. (2008)
$c_{PCM,s}$ (20°C)(kJ/(kg K))	1.383	Shukla et al. (2008)
$c_{PCM,l}$ (140°C) (kJ/(kg K))	2.76	Honguntikar and Pawar (2019)
$\rho_{PCM,s}$ (20°C)(kg/m 3)	1480	Honguntikar and Pawar (2019)
$\rho_{PCM,l}$ (140°C) (kg/m 3)	1300	Honguntikar and Pawar (2019)

195 Erythritol was chosen as a PCM mainly due to its melting temperature (in
 196 the range $100\text{--}120^{\circ}\text{C}$), which guaranteed an optimal coupling with the solar
 197 box cooker under study, able to reach temperatures in the order of 200°C . The
 198 substance was also considered for being edible and non-toxic.

199 The erythritol considered in the present research is commercial-grade. In order
 200 to evaluate the sample quality, the sugar was analyzed using a Fourier Trans-
 201 form Infrared (FTIR) spectrometer (Spectrum GX I, Perkin Elmer). Spectra
 202 were acquired in reflection, using an attenuated total reflectance (ATR) crystal
 203 (DuraSampl IR II, SensIR Technologies) with a spectral resolution of 4 cm^{-1}
 204 from 4000 to 650 cm^{-1} . Each spectrum is the result of 16 consecutive scans.
 205 Figure 3 shows the results of the analysis by reporting the absorption data of the

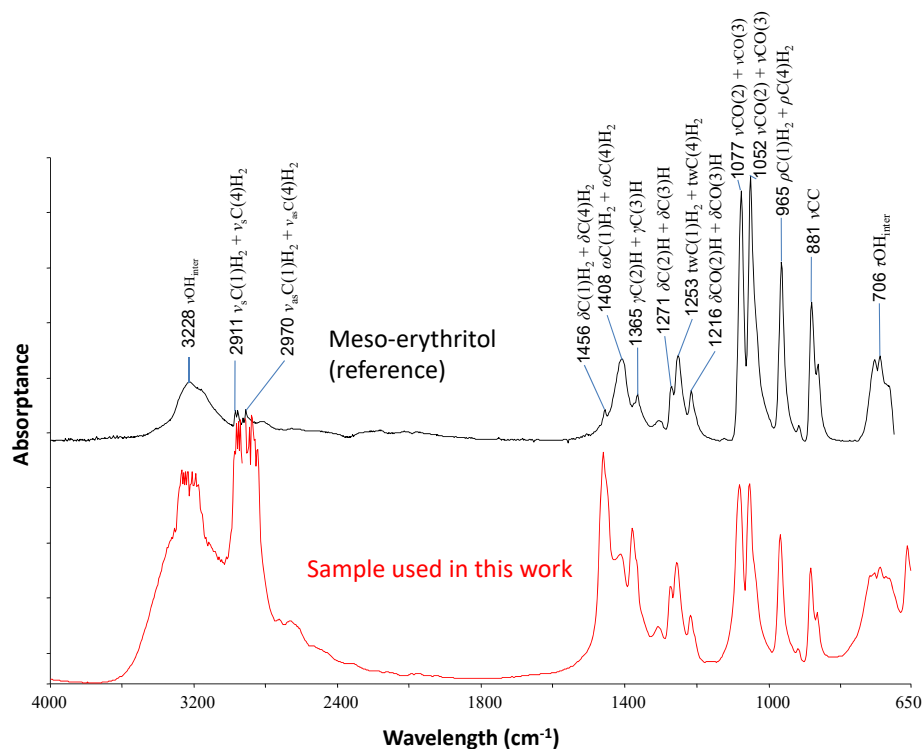


Figure 3: Erythritol sample analyzed with the FTIR spectrometer.

206 sample. The same figure reports the meso-erythritol data, that provide a direct
 207 comparison between the sample under study and the reference substance. As
 208 can be seen, despite being a commercial-grade substance, the erythritol sam-
 209 ple considered in the experiment does not contain relevant amounts of other
 210 components.

211 Erythritol was also tested with a differential scanning calorimeter (DSC) to
 212 evaluate its melting temperature and its latent heat of fusion. Three different
 213 samples of erythritol were analyzed with a NETZSCH DSC 214 Polyma at a
 214 rate of 1 K/min. The heat flow vs. temperature curves were obtained with the
 215 software NETZSCH Proteus 7.0 and are plotted in Figure 4. As can be seen,
 216 the melting phase is very repeatable among the three samples. The average
 217 melting temperature and latent heat of fusion were calculated to be 108.7°C

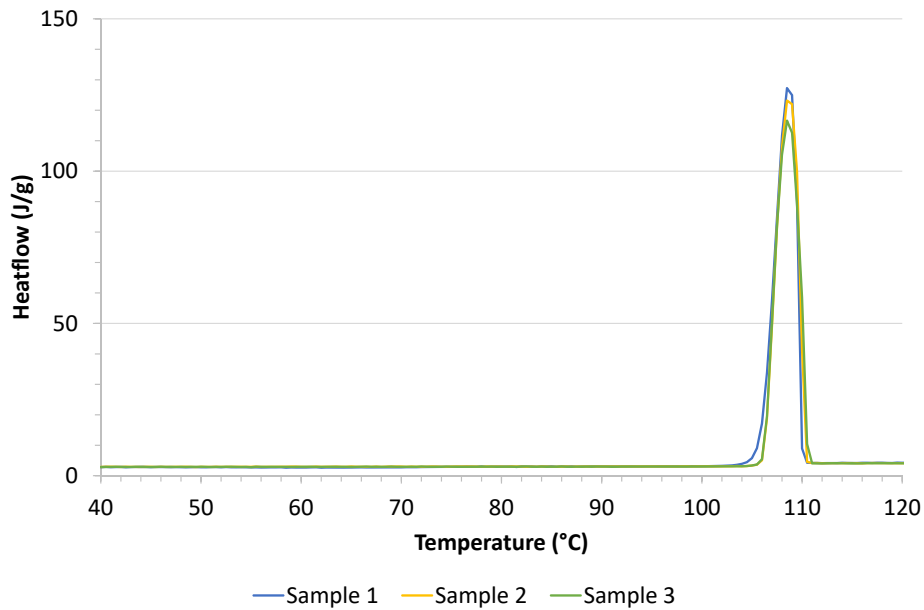


Figure 4: DSC analysis of the erythritol samples.

218 and 312.8 kJ/kg, respectively. Considering that the erythritol sample has a
 219 commercial-grade quality, the values obtained with the DSC are consistent with
 220 those reported in literature (Table 1).

221 Before being inserted inside the thermal storage system, a mass of about 2.5
 222 kg of erythritol was heated in an electric furnace at a temperature higher than
 223 100 °C for about 2 hours. This operation was repeated a second time. In this
 224 way, the possible presence of moisture in the sample was avoided. Later, the
 225 sample was inserted in the TES annulus and the whole system was heated in
 226 the electric furnace at about 200 °C for 2 hours. With the completion of this
 227 process, erythritol was finally ready to be used for experimental testing.

228 3. Experimental analysis

229 The characterization of the solar box cooker coupled with the PCM-based
 230 TES requires to determine a number of parameters that can be derived from
 231 experimental procedures widely described in literature (Sagade et al., 2019b).

232 In order to assess the cooker thermal performance, a specific test bench was
233 designed and set up. The test bench allowed to determine the performance
234 parameters in different time intervals for each test.

235 3.1. Experimental tests

236 Outdoor tests were conducted from May to October during the years 2017,
237 2018, and 2019 on the DIISM roof (latitude 43.5867 N, longitude 13.5150 E).
238 To guarantee a proper tracking of the sun, the cooker alignment with the sun
239 was adjusted about every 5–10 minutes.

240 Two different tests were carried out.

- 241 • Tests without load. They allowed to determine the maximum temperature
242 reachable by the solar cooker.

- 243 • Tests with load. These tests were carried out by loading the solar cooker
244 with a testing fluid, water or silicone oil. The former fluid was used due to
245 ease of comparison with the results obtained by other authors. The latter
246 fluid (Rhodorsil Oil 47 V 100), instead, was used to exceed the limit of
247 100 °C. This allowed to study the behavior of the cooker in the presence
248 and absence of the erythritol-based TES.

249 3.2. Test bench

250 The portable solar box cooker was experimentally characterized with the
251 test bench shown in Figure 5. Two T-type thermocouples were used to de-
252 tect the ambient (T_{amb}) and the testing fluid (T_f) temperatures, while K-type
253 thermocouples were used to measure the remaining temperatures.

254 An Eppley NIP (Normal Incidence Pyrheliometer, $\pm 0.5\%$ in the range 0–
255 1400 W/m²) was also used to measure direct normal irradiance (DNI). Diffuse
256 solar radiation was not taken into account in the present experiment as the
257 considered solar box cooker has a concentration ratio of 4.08, thus it can basically
258 work with direct solar radiation only.

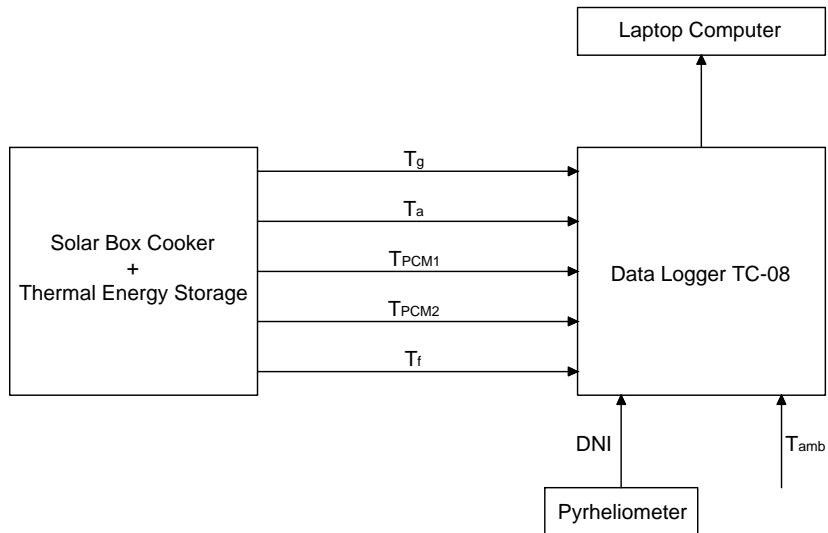


Figure 5: Test bench. T_g : glass temperature; T_a : absorber temperature; T_{PCM} : phase change material temperature; T_f : testing fluid temperature; T_{amb} : ambient temperature; DNI : direct normal irradiance.

259 The signals generated by the thermocouples and the pyrheliometer were
 260 acquired and processed by a Pico Technology TC-08 data logger, connected to
 261 a laptop computer.

262 3.3. Experimental parameters

263 Several experimental parameters have been discussed in literature to assess a
 264 solar cooker thermal performance. In this section, the parameters used to char-
 265 acterize the solar box cooker coupled with the PCM-based TES are reported.
 266 Although these parameters consider water as testing fluid, in the present work
 267 they were adapted to be used with silicone oil, too.

268 Before conducting any kind of tests with load, a solar box cooker should
 269 be tested under no-load conditions. In this way, it is possible to detect the
 270 maximum temperature reachable by the cooker, $T_{a,max}$, and its first figure of
 271 merit, F_1 , as defined by Mullick et al. (1987):

$$272 F_1 = \frac{T_{a,max} - T_{amb}}{DNI}, \quad (2)$$

273 where T_{amb} and DNI are the ambient temperature and direct normal irradiance
 274 recorded during the solar cooker stagnation.

275 Tests with load, instead, were divided into two phases: an initial heating
 276 phase and a following cooling phase. The heating phase simulated the system
 277 behavior in presence of solar radiation. In this case, the first parameter being
 278 calculated was Δt_{h} , the time required by the solar cooker to take water and
 279 silicone oil from $T_1 = 40$ to $T_2 = 90$ °C, and from $T_1 = 55$ to $T_2 = 125$ °C,
 280 respectively. The temperature range chosen for the silicone oil allowed to include
 281 the phase change of erythritol, that for the sample under consideration occurred
 282 at about 109 °C.

283 For the load tests, the second figure of merit, F_2 , was determined as (Mullick
 284 et al., 1987):

$$285 \quad F_2 = \frac{F_1 m_f c_f}{A_a \Delta t_{\text{h}}} \ln \left[\frac{1 - \frac{1}{F_1} (T_1 - T_{\text{amb,av}}) / DNI_{\text{av}}}{1 - \frac{1}{F_1} (T_2 - T_{\text{amb,av}}) / DNI_{\text{av}}} \right], \quad (3)$$

286 where m_f is the testing fluid mass, c_f is the testing fluid specific heat, A_a is
 287 the solar cooker aperture area, while DNI_{av} and $T_{\text{amb,av}}$ are, respectively, the
 288 average direct normal irradiance and the average ambient temperature over the
 289 time interval Δt_{h} . In Equation (3), F_1 is the first figure of merit determined
 290 through no-load tests with Equation (2).

291 During the heating phase, the parameters proposed by Khalifa et al. (1985)
 292 were also determined. In this case, the first parameter is the specific boiling
 293 time:

$$294 \quad t_s = \frac{\Delta t_{\text{h}} A_a}{m_f}, \quad (4)$$

295 while the second parameter is the characteristic boiling time (Khalifa et al.,
 296 1985):

$$297 \quad t_{\text{ch}} = t_s \frac{DNI_{\text{av}}}{DNI_{\text{ref}}}, \quad (5)$$

298 where DNI_{av} is the average direct normal irradiance during Δt_{h} , and DNI_{ref} is
 299 a reference direct normal irradiance (equal to 900 W/m²). The last parameter
 300 proposed by Khalifa et al. (1985) is the average overall thermal efficiency of the

Table 2: Summary of tests without load.

Quantity	Test 1	Test 2	Test 3
Date	23/05/2017	09/06/2017	13/06/2017
T_{amb} (°C)	29.39	23.39	31.27
DNI (W/m ²)	839.71	971.75	841.24
$T_{\text{a,max}}$ (°C)	197.30	187.42	189.10
F_1 (°C/(W/m ²))	0.20	0.17	0.19

solar cooker, defined as:

$$\eta_{\text{av}} = \frac{m_f c_f (T_2 - T_1)}{DNI_{\text{av}} A_a \Delta t_h}. \quad (6)$$

The cooling phase, instead, was introduced to simulate absence of solar radiation. During this phase, the solar cooker was shaded and the time Δt_c required by the silicone oil to reduce its temperature from $T_2 = 125^\circ\text{C}$ to $T_3 = 100^\circ\text{C}$ was recorded.

4. Experimental results

In this section, the results obtained through the experimental tests with and without load are provided. Load tests were carried out with water, silicone oil, and silicon oil with the PCM-based thermal energy storage. A final summary section was reported, too.

4.1. Tests without load

Three tests without load were carried out under different environmental conditions. A summary of the data collected for each test is provided in the Table 2.

As an example, Figure 6 shows the temperatures and the solar radiation detected during one of the tests. As can be seen, the maximum absorber temperature was about 189°C and the corresponding solar radiation and ambient temperature were, respectively, 841 W/m^2 and 31.27°C .

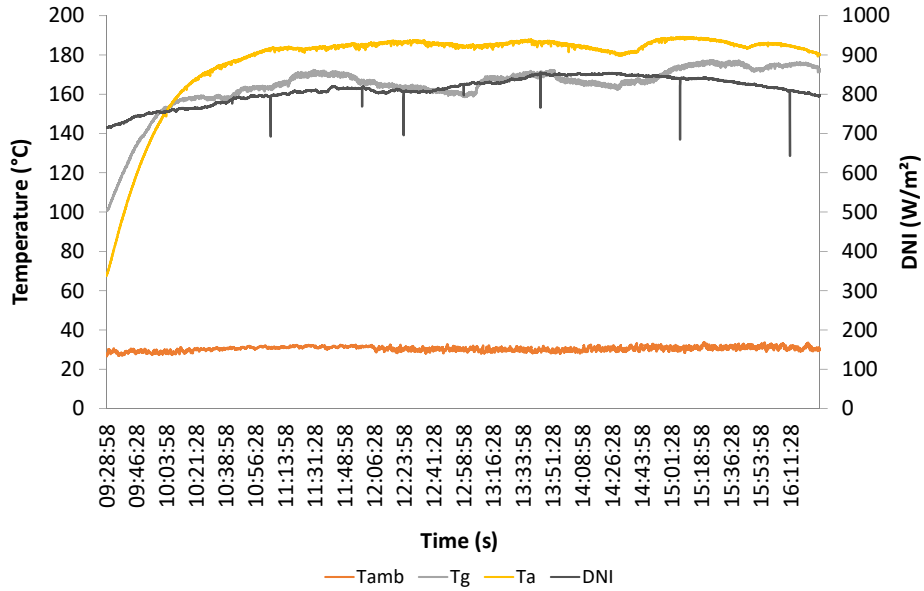


Figure 6: Test without load (13/06/2017).

320 The three F_1 values (Table 2) were then averaged, resulting in an average
 321 $F_1 = 0.19\text{ }^\circ\text{C}/(\text{W}/\text{m}^2)$. This value represents the first figure of merit of the
 322 solar box cooker under study. The value is lower than that of our previous solar
 323 cooker design (Coccia et al., 2017) (F_1 equal to $0.39\text{ }^\circ\text{C}/(\text{W}/\text{m}^2)$), but it should
 324 be noted that the previous cooker had a concentration ratio more than twice
 325 higher, and a better thermal insulation system.

326 4.2. Tests with water

327 A summary of the 5 outdoor tests carried out with water is reported in
 328 Table 3. The experimental parameters are referred to a time interval Δt_h during
 329 which water temperature rose from 40 to 90 °C. Tests were conducted with two
 330 different masses of water, 2 and 3 kg.

331 Figure 7 depicts the load test carried out on September 14, 2017 loading
 332 the solar cooker with 2 kg of water. The average direct normal irradiance was
 333 $867.18\text{ W}/\text{m}^2$ and the average ambient temperature was $25.00\text{ }^\circ\text{C}$ during the Δt_h
 334 interval. Water took about 1.68 hours to heat up in the range 40–90 °C. Tests

Table 3: Summary of tests with water.

Quantity	Test 4	Test 5	Test 6	Test 7	Test 8
Date	02/08/2017	14/09/2017	01/06/2018	20/06/2018	04/07/2018
m_f (kg)	2.0	2.0	3.0	3.0	3.0
T_1 ($^{\circ}\text{C}$)	40	40	40	40	40
T_2 ($^{\circ}\text{C}$)	90	90	90	90	90
DNI_{av} (W/m^2)	736.84	867.18	869.28	825.54	597.10
$T_{amb,av}$ ($^{\circ}\text{C}$)	36.59	25.00	27.23	28.29	27.88
Δt_h (h)	1.45	1.68	1.20	1.44	1.77
t_s ($\text{h m}^2/\text{kg}$)	0.49	0.57	0.27	0.33	0.40
t_{ch} ($\text{h m}^2/\text{kg}$)	0.40	0.55	0.26	0.30	0.27
η_{av}	0.16	0.12	0.25	0.22	0.24
F_2	0.09	0.07	0.14	0.12	0.16

335 conducted on different days showed similar trends. Referring again to Table 3,
336 it is possible to note that a larger mass of testing fluid positively influenced
337 the second figure of merit and the average thermal efficiency of the solar box
338 cooker. This effect is well-known in literature (Mullick et al., 1996) and can be
339 explained by considering that larger masses and volumes of vessels allow to use
340 the cooking chamber in a more efficient way.

341 Referring to our previous cooker design (Coccia et al., 2017), it can be noted
342 that the parameters t_s , t_{ch} , and η_{av} have similar values. Instead, the second
343 figure of merit F_2 shows lower results. This is due to the first figure of merit F_1 ,
344 which is lower for the cooker under study (Section 4.1). In Coccia et al. (2017),
345 comparisons with experimental studies of other authors are also available.

346 4.3. Tests with silicone oil

347 Five tests were performed using the cooker loaded with 1.5 kg of silicone oil
348 (Table 4 and 5, tests 9 to 13). The first two tests were conducted in June and
349 September 2018, while the remaining three were conducted in June 2019.

350 Figure 8 shows, for example, the temperatures and the direct normal irradi-
351 ance detected on September 27, 2018. During the period considered, DNI_{av} was
352 $882.77 \text{ W}/\text{m}^2$ and $T_{amb,av}$ was 17.35°C . It is possible to note that the test is

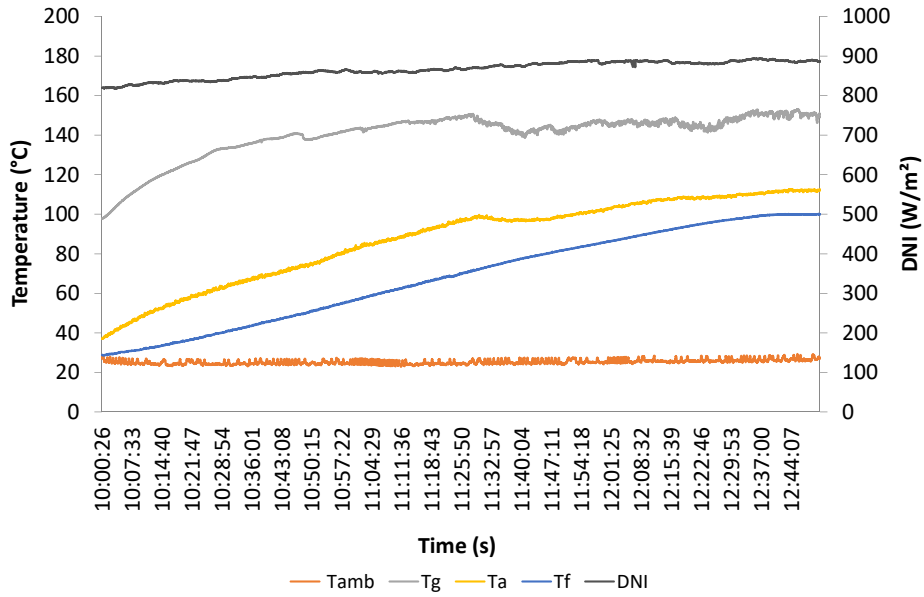


Figure 7: Test with water (14/09/2017).

353 divided into an initial heating phase and a following cooling phase. The former
 354 phase took about 1.58 hours to take the silicone oil temperature from 55 °C
 355 to 125 °C. The cooker average efficiency and its second figure of merit were
 356 lower than those determined with water, as silicone oil was tested at higher
 357 temperatures.

358 Even if a direct comparison cannot be accomplished since different masses
 359 and temperature ranges were considered, the heating tests with silicone oil can
 360 be compared with those carried out with our previous cooker design (Coccia
 361 et al., 2018). Results show that the portable solar cooker under study has
 362 slightly worse t_s , t_{ch} , η_{av} , and F_2 . Again, this is due to the inferior concentration
 363 ratio and thermal insulation of the new cooker.

364 When the silicone oil temperature was higher than 130 °C, the solar cooker
 365 was closed to solar radiation and left cooling down. During the cooling phase,
 366 the average ambient temperature was 17.35 °C and the silicone oil required 0.31
 367 hours to take its temperature from 125 to 100 °C (Table 5).

Table 4: Summary of the heating tests with silicone oil and silicone oil + PCM.

Quantity	Test 9	Test 10	Test 11	Test 12	Test 13	Test 14	Test 15	Test 16	Test 17
Date	11/06/2018	27/09/2018	11/06/2019	12/06/2019	17/06/2019	24/07/2018	11/09/2018	12/09/2018	25/09/2018
m_f (kg)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
m_{PCM} (kg)	-	-	-	-	-	2.5	2.5	2.5	2.5
T_1 (°C)	55	55	55	55	55	55	55	55	55
T_2 (°C)	125	125	125	125	125	125	125	125	125
DN_{av} (W/m ²)	767.22	882.77	720.04	601.80	751.80	834.99	855.53	867.96	946.62
$T_{amb,av}$ (°C)	31.38	17.35	30.35	28.15	28.83	28.62	26.70	28.14	19.33
Δt_h (h)	1.11	1.58	1.27	1.01	0.95	1.94	2.30	3.35	2.52
t_s (h m ² /kg)	0.50	0.72	0.57	0.46	0.43	0.88	1.04	1.52	1.14
t_{ch} (h m ² /kg)	0.43	0.71	0.46	0.31	0.36	0.82	0.99	1.47	1.20
η_{ev}	0.08	0.05	0.08	0.11	0.10	0.04	0.04	0.02	0.03
F_2	0.06	0.04	0.06	0.13	0.08	0.03	0.03	0.02	0.02

Table 5: Summary of the cooling tests with silicone oil and silicone oil + PCM.

Quantity	Test 9	Test 10	Test 11	Test 12	Test 13	Test 14	Test 15	Test 16	Test 17
Date	11/06/2018	27/09/2018	11/06/2019	12/06/2019	17/06/2019	24/07/2018	11/09/2018	12/09/2018	25/09/2018
m_f (kg)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
m_{PCM} (kg)	-	-	-	-	-	2.5	2.5	2.5	2.5
T_2 (°C)	125	125	125	125	125	125	125	125	125
T_3 (°C)	100	100	100	100	100	100	100	100	100
$T_{amb,av}$ (°C)	29.24	17.35	29.69	29.02	28.46	29.77	26.46	27.57	19.87
Δt_c (h)	0.45	0.31	0.50	0.48	0.46	1.88	2.19	2.03	1.67

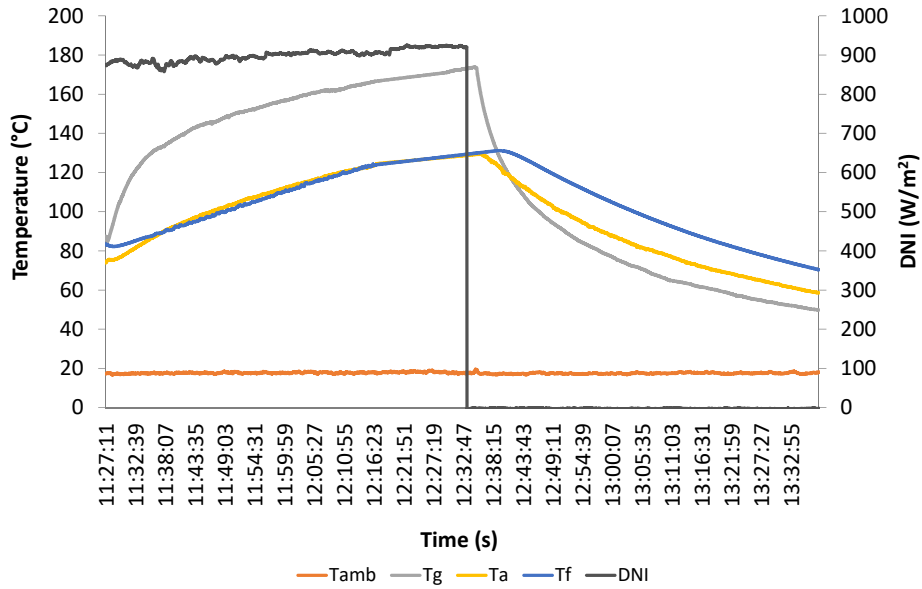


Figure 8: Test with silicone oil (27/09/2018).

368 4.4. Tests with silicone oil and PCM

369 The behavior of the solar box cooker coupled with the PCM-based thermal
 370 storage unit was studied by carrying out 4 outdoor tests in the months of July
 371 and September 2018. The thermal storage system, including 2.5 kg of erythritol,
 372 was filled with 1.5 kg of silicone oil. The results of the experimental tests are
 373 summarized in Table 4 and 5 (tests 14 to 17), which refer to the heating phase
 374 and the cooling phase, respectively.

375 Figure 9 shows the results obtained on September 25, when DNI_{av} was
 376 946.62 W/m^2 and $T_{amb,av}$ was $19.33 \text{ }^\circ\text{C}$. From Figure 9, it is possible to note
 377 that the PCM temperatures measured by the two opposite thermocouples are
 378 almost the same. During the heating phase, the PCM temperature shows a
 379 change of slope at around $109 \text{ }^\circ\text{C}$, value that identifies the melting point of the
 380 erythritol. When the solar cooker was used with the TES, the heating process
 381 required about 2.52 hours to take the silicone oil temperature from 55 to $125 \text{ }^\circ\text{C}$.
 382 In comparison, the silicone oil test carried out on September 27, 2018 required
 383 about 1.58 hours for the heating process in the same temperature range. The

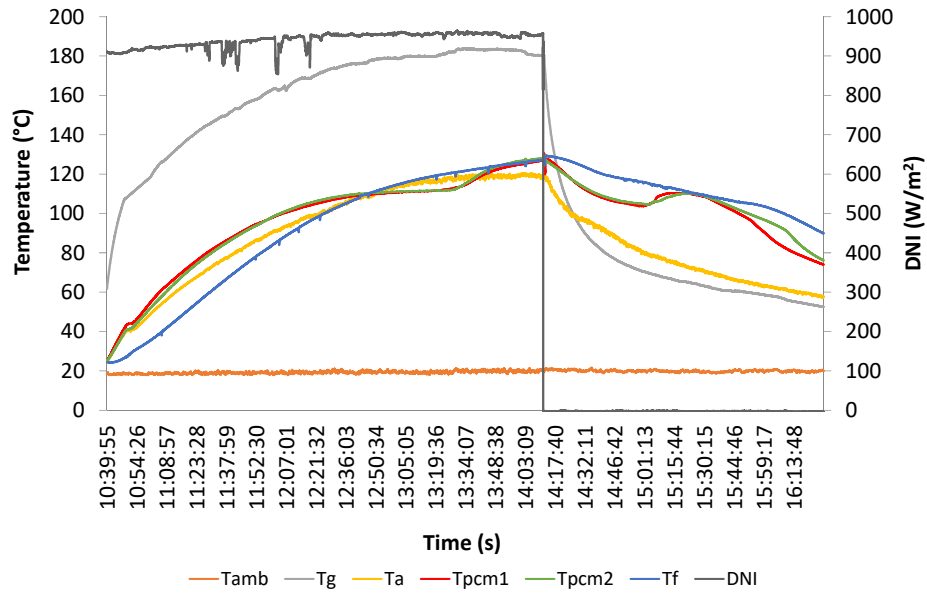


Figure 9: Test with silicone oil and PCM (25/09/2018).

384 increase in the heating time, along with the penalties associated to the cooker
 385 average efficiency and the second figure of merit, are due to the presence of the
 386 additional mass of PCM.

387 A comparison with our previous cooker design (Coccia et al., 2018) shows
 388 only slightly lower t_s , t_{ch} , η_{av} , and F_2 . However, it should be noted that different
 389 masses, temperature ranges, and PCMs were considered with the two cookers.

390 The cooling phase, instead, required 1.65 hours to decrease the testing
 391 fluid temperature from 125 to 100 °C. During this phase, the average ambient
 392 temperature was 19.87 °C. Respect to the case without the PCM-based TES
 393 ($\Delta t_c = 0.31$ h), the silicone oil cooling time increased by more than 5 times.

394 In Figure 9, it is also possible to see that a supercooling phenomenon takes
 395 place in the PCM, i.e. the substance does not solidify immediately below the
 396 freezing temperature but its crystallization occurs only after a lower temperature
 397 (around 105 °C) is reached. This effect is well-known in literature (Safari et al.,
 398 2017) and, in the TES under study, could be due to heterogeneous nucleation at
 399 the surface of the vessel containing the PCM. Even though supercooling leads

400 to lower crystallization temperatures and, therefore, to a not optimal thermal
401 storage performance (Safari et al., 2017), in Figure 9 it is possible to see that the
402 erythritol supercooling curve rises and stabilizes at the solidification tempera-
403 ture (109 °C) immediately upon crystallization. Thus, the penalty associated to
404 the phenomenon is minimal.

405 4.5. Summary and comparison of tests with and without PCM

406 To quantify in a systematic way both benefits and disadvantages of using
407 a solar box cooker coupled with a PCM-based TES, in this section a specific
408 methodology is proposed. The procedure requires to analyze separately the
409 heating and the cooling phases of the tests carried out with silicone oil only (tests
410 from 9 to 13) and with silicone oil and PCM (tests from 14 to 17). Specifically,
411 it is necessary to compare the heating ($\Delta t_{h,oil}$ and $\Delta t_{h,oil+PCM}$) and cooling
412 times ($\Delta t_{c,oil}$ and $\Delta t_{c,oil+PCM}$) calculated for the two test sets. In this way, it
413 is possible to determine the incremental time necessary to heat up the testing
414 fluid coupled with the PCM (which is a detrimental effect associated to the use
415 of a TES in a solar box cooker), and the incremental time during the cooling
416 phase (which is the desired effect derived from the use of a TES solution in a
417 solar box cooker).

418 Starting from the heating phase, Table 4 highlights that when the solar box
419 cooker is used with the erythritol-based TES (tests from 14 to 17), its heating
420 phase is slower and its experimental parameters are generally worse. Evidently,
421 this is due to the additional mass of PCM loaded and to its corresponding latent
422 heat of fusion. The heating time Δt_h varies with environmental conditions and
423 can be influenced by the frequency with which the operator adjusts the solar
424 cooker orientation. However, such external factors seemed not to influence the
425 typical heating time considerably.

426 Table 6 provides the average heating times of the experimental tests carried
427 out with silicone oil ($\Delta t_{h,oil}$, average of the Δt_h provided in Table 4 for the tests
428 9–13), and with silicone oil and PCM ($\Delta t_{h,oil+PCM}$, average of the Δt_h provided
429 in Table 4 for the tests 14–17). The same table reports the corresponding average

Table 6: Average, best and worst heating times of the tests with silicone oil and with silicone oil + PCM provided in Table 4. The best case refers to the silicone oil longest heating time and silicone oil + PCM shortest heating time; the opposite for the worst case. Deviations are calculated as the percentage difference between the heating times of the two test sets.

Quantity	Average	Best	Worst
$\Delta t_{h,oil}$ (h)	1.18 (tests 9–13)	1.58 (test 10)	0.95 (test 13)
$\Delta t_{h,oil+PCM}$ (h)	2.53 (tests 14–17)	1.94 (test 14)	3.35 (test 16)
Deviation (%)	114.41	22.78	252.63

430 deviation, calculated as the percentage difference between the average silicone oil
 431 + PCM heating time (2.53 hours) and the average silicone oil heating time (1.18
 432 hours). Therefore, when the solar cooker is coupled with the PCM, the heating
 433 time is increased by an average 114.41% respect to the average performance
 434 obtained with silicone oil only.

435 On the other hand, the “best” deviation indicates that, in the most favorable
 436 condition, i.e. when the heating time assumes the highest value for silicone oil
 437 (test 10, 1.58 hours) and the lowest value for silicone oil and erythritol (test 14,
 438 1.94 hours), the percentage difference between the two cases is low and equal to
 439 22.78%. Instead, in the “worst” case, i.e. when silicone oil only heats up quickly
 440 (test 13, 0.95 hours) and heats up slowly in the PCM-based TES (test 16, 3.35
 441 hours), the resulting maximum deviation is equal to 252.63%.

442 In the same fashion of Table 4, Table 5 reports the data recorded during
 443 the cooling phases of the outdoor tests. In this case, the cooling time Δt_c is
 444 only influenced by the ambient temperature, which is always near 30 °C with
 445 the exception of two tests (10 and 17), when it is lower than 20 °C. Actually,
 446 the Δt_c results of the two tests reflect the ambient temperature drop. However,
 447 the advantage derived by the use of the PCM-based TES is evident, resulting
 448 in a significant extension of the cooker thermal stability.

449 Table 7 provides the average cooling times of the tests carried out with
 450 silicone oil only ($\Delta t_{c,oil}$, average of the Δt_c provided in Table 5 for the tests 9–
 451 13), and with silicone oil and PCM ($\Delta t_{c,oil+PCM}$, average of the Δt_c provided in

Table 7: Average, best and worst cooling times of the tests with silicone oil and with silicone oil + PCM provided in Table 5. The best case refers to the silicone oil shortest cooling time and silicone oil + PCM longest cooling time; the opposite for the worst case. Deviations are calculated as the percentage difference between the cooling times of the two test sets.

Quantity	Average	Best	Worst
$\Delta t_{c,oil}$ (h)	0.43 (tests 9–13)	0.31 (test 10)	0.50 (test 11)
$\Delta t_{c,oil+PCM}$ (h)	1.94 (tests 14–17)	2.19 (test 15)	1.67 (test 17)
Deviation (%)	351.16	606.45	234.00

452 Table 5 for the tests 14–17). Additionally, Table 7 reports the average deviation
 453 calculated as the percentage difference between the two test sets; an increase of
 454 around 351.16% was found.

455 The “best” case, which occurred for the shortest $\Delta t_{c,oil}$ of silicone oil only
 456 (test 10, 0.31 hours) and the longest $\Delta t_{c,oil+PCM}$ of silicone oil and PCM (test
 457 15, 2.19 hours), resulted in a maximum deviation equal to 606.45%. While in
 458 the “worst” case, which was determined based on the longest cooling time for
 459 silicone oil only (test 11, 0.50 hours) and the shortest cooling time for silicone
 460 oil and PCM (test 17, 1.67 hours), the minimum deviation was calculated to
 461 be 234.00% (in any case, more than 3 times respect to the silicone oil reference
 462 case). A substantial enhancement of the cooker thermal stability in absence of
 463 solar radiation was therefore obtained even in the worst case considered.

464 Finally, comparing the results of the portable solar cooker under study with
 465 those obtained with our previous design (Coccia et al., 2018), it can be seen
 466 that the average deviation of the heating time is slightly longer (114.41% vs.
 467 82.41%), but this is also true for the average deviation of the cooling time,
 468 which is far superior (351.16% vs. 88.58%). Again, it is important to note that
 469 a precise comparison is not possible due to the different masses, temperatures,
 470 and PCMs considered in the two works.

471 5. Conclusions

472 In this work, a 4.08 concentration ratio portable solar box cooker equipped
473 with a thermal energy storage (TES) based on a phase change material (PCM)
474 was designed, manufactured, and characterized through outdoor experimental
475 tests. The phase change material used with the solar cooker was commercial-
476 grade erythritol, a sugar polyalcohol that showed a melting point of about
477 109 °C.

478 The portable solar box cooker was tested without load (stagnation test),
479 with water, with silicone oil, and with silicone oil inserted in the erythritol-
480 based TES. The results of the outdoor experimentation allowed to determine
481 the main thermodynamic parameters used to characterize a solar box cooker.
482 Also, it was found that the presence of the erythritol-based TES stabilizes and
483 extends the use of the portable solar box cooker when the solar source is absent
484 or intermittent. The average load cooling time in the range 125–100 °C was
485 determined to be about 351.16% larger than that without the TES solution.
486 This result proves the effectiveness of the proposed system.

487 Acknowledgments

488 The authors would like to express their gratitude to Eng. Gianni Crovatto,
489 for his support and assistance during the solar box cooker design. The authors
490 would also like to thank Gabriele Gabrielli, for his assistance during the solar
491 cooker manufacture process, and to Carla Conti, for her valuable help with the
492 chemical analysis of erythritol. Another acknowledgment goes to the researchers
493 of the Institute of Construction and Building Materials of the Technical Univer-
494 sity of Darmstadt, Germany, for their availability and assistance with the DSC
495 analysis of erythritol.

496 Nomenclature

497 *Latin Symbols*

498	A	Area (m^2)
499	C	Concentration ratio
500	c	Specific heat ($\text{kJ}/(\text{kg K})$)
501	DNI	Direct normal irradiance (W/m^2)
502	F_1	First figure of merit ($^\circ\text{C}/(\text{W}/\text{m}^2)$)
503	F_2	Second figure of merit
504	L	Latent heat of fusion (kJ/kg)
505	m	Mass (kg)
506	T	Temperature ($^\circ\text{C}$)
507	t	Time (s)

508

509 *Greek Symbols*

510	Δ	Delta difference
511	η	Thermal efficiency
512	ρ	Density (kg/m^3)

513

514 *Subscripts*

515	a	Absorber, aperture
516	amb	Ambient
517	av	Average
518	c	Cooling
519	ch	Characteristic

520	f	Fluid
521	g	Glass
522	h	Heating
523	l	Liquid
524	max	Maximum
525	melt	Melting
526	min	Minimum
527	ref	Reference
528	s	Specific, solid

529

530 *Acronyms*

531	DIISM	Department of Industrial Engineering and Mathematical Sciences
532	DSC	Differential Scanning Calorimeter
533	FTIR	Fourier Transform Infrared
534	ETC	Evacuated Tube Collector
535	FPC	Flat Plate Collector
536	MDF	Medium-density Fiberboard
537	NIP	Normal Incidence Pyrheliometer
538	PCM	Phase Change Material
539	TES	Thermal Energy Storage
540	UNIVPM	Marche Polytechnic University

541

542 **References**

- 543 Buddhi, D., Sahoo, L., 1997. Solar cooker with latent heat storage: design and
544 experimental testing. *Energy Conversion and Management* 38, 493–498.
- 545 Buddhi, D., Sharma, S., Sharma, A., 2003. Thermal performance evaluation of
546 a latent heat storage unit for late evening cooking in a solar cooker having
547 three reflectors. *Energy Conversion and Management* 44, 809–817.
- 548 Coccia, G., Di Nicola, G., Pierantozzi, M., Tomassetti, S., Aquilanti, A., 2017.
549 Design, manufacturing, and test of a high concentration ratio solar box cooker
550 with multiple reflectors. *Solar Energy* 155, 781–792.
- 551 Coccia, G., Di Nicola, G., Tomassetti, S., Pierantozzi, M., Chieruzzi, M., Torre,
552 L., 2018. Experimental validation of a high-temperature solar box cooker with
553 a solar-salt-based thermal storage unit. *Solar Energy* 170, 1016–1025.
- 554 Cuce, E., Cuce, P., 2013. A comprehensive review on solar cookers. *Applied*
555 *Energy* 102, 1399–1421.
- 556 Domanski, R., El-Sebaili, A., Jaworski, M., 1995. Cooking during off-sunshine
557 hours using PCMs as storage media. *Energy* 20, 607–616.
- 558 El-Sebaili, A., Al-Amir, S., Al-Marzouki, F., Faidah, A., Al-Ghamdi, A., Al-
559 Heniti, S., 2009. Fast thermal cycling of acetanilide and magnesium chloride
560 hexahydrate for indoor solar cooking. *Energy Conversion and Management*
561 50, 3104–3111.
- 562 Esen, M., 2000. Thermal performance of a solar-aided latent heat store used for
563 space heating by heat pump. *Solar Energy* 69, 15–25.
- 564 Esen, M., 2004. Thermal performance of a solar cooker integrated vacuum-tube
565 collector with heat pipes containing different refrigerants. *Solar Energy* 76,
566 751–757.
- 567 Esen, M., Ayhan, T., 1996. Development of a model compatible with solar as-
568 sisted cylindrical energy storage tank and variation of stored energy with time

569 for different phase change materials. *Energy Conversion and Management* 37,
570 1775–1785.

571 Esen, M., Durmuş, A., Durmuş, A., 1998. Geometric design of solar-aided latent
572 heat store depending on various parameters and phase change materials. *Solar*
573 *Energy* 62, 19–28.

574 Haraksingh, I., Mc Doom, I., Headley, O.S.C., 1996. A natural convection flat-
575 plate collector solar cooker with short term storage. *Renewable Energy* 9,
576 729–732.

577 Honguntikar, P., Pawar, U., 2019. Characterization of erythritol as a phase
578 change material. *International Journal for Science and Advance Research in*
579 *Technology* 5.

580 Hussein, H., El-Ghetany, H., Nada, S., 2008. Experimental investigation of
581 novel indirect solar cooker with indoor PCM thermal storage and cooking
582 unit. *Energy Conversion and Management* 49, 2237–2246.

583 Khalifa, A., Taha, M., Akyurt, M., 1985. Solar cookers for outdoors and indoors.
584 *Energy* 10, 819–829.

585 Kundapur, A., 2018. *A Treatise on Solar Cookers*. First ed.

586 Mullick, S., Kandpal, T., Kumar, S., 1996. Testing of box-type solar cooker:
587 second figure of merit F2 and its variation with load and number of pots.
588 *Solar Energy* 57, 409–13.

589 Mullick, S., Kandpal, T., Saxena, A., 1987. Thermal test procedure for box-type
590 solar cookers. *Solar Energy* 39, 353–360.

591 Nahar, N., 2003. Performance and testing of a hot box storage solar cooker.
592 *Energy Conversion and Management* 44, 1323–1331.

593 Nandwani, S.S., Steinhart, J., Henning, H., Rommel, M., Wittwer, V., 1997.
594 Experimental study of multipurpose solar hot box at Freiburg, Germany.
595 *Renewable Energy* 12, 1–20.

596 Oturanç, G., Özbalta, N., Güngör, A., 2002. Performance analysis of a solar
597 cooker in Turkey. *International Journal of Energy Research* 26, 105–111.

598 Ramadan, M., Aboul-Enein, S., El-Sebaei, A., 1988. A model of an improved
599 low cost-indoor-solar-cooker in tanta. *Solar & Wind Technology* 5, 387–393.

600 Safari, A., Saidur, R., Sulaiman, F., Xu, Y., Dong, J., 2017. A review on
601 supercooling of phase change materials in thermal energy storage systems.
602 *Renewable and Sustainable Energy Reviews* 70, 905–919.

603 Sagade, A.A., Samdarshi, S., Lahkar, P., 2019a. Ensuring the completion of
604 solar cooking process under unexpected reduction in solar irradiance. *Solar*
605 *Energy* 179, 286–297.

606 Sagade, A.A., Samdarshi, S., Lahkar, P., Sagade, N.A., 2019b. Experimental
607 determination of the thermal performance of an intermediate temperature
608 solar box cooker with a hybrid cooking pot. *Renewable Energy* .

609 Schwarzer, K., Da Silva, M., 2003. Solar cooking system with or without heat
610 storage for families and institutions. *Solar Energy* 75, 35–41.

611 Sharma, A., Chen, C., Murty, V., Shukla, A., 2009. Solar cooker with latent
612 heat storage systems: A review. *Renewable and Sustainable Energy Reviews*
613 13, 1599–1605.

614 Sharma, S., Buddhi, D., Sawhney, R., Sharma, A., 2000. Design, development
615 and performance evaluation of a latent heat storage unit for evening cooking
616 in a solar cooker. *Energy Conversion and Management* 41, 1497–1508.

617 Sharma, S., Iwata, T., Kitano, H., Sagara, K., 2005. Thermal performance of a
618 solar cooker based on an evacuated tube solar collector with a PCM storage
619 unit. *Solar Energy* 78, 416–426.

620 Shukla, A., Buddhi, D., Sawhney, R., 2008. Thermal cycling test of few selected
621 inorganic and organic phase change materials. *Renewable Energy* 33, 2606–
622 2614.