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

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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

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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 than that of conventional solar cookers.

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

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

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

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

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

In 2003, Nahar (2003) inserted a TES based on 5 kg of engine oil in a solar box cooker. Several tests were conducted and compared with those obtained from a cooker of equal size and made with the same materials, but not equipped with the engine oil thermal storage. It was found that from 17:00 to 24:00, the temperature inside the cooking chamber equipped with thermal storage was 23 °C higher. Additionally, rice took about 3 hours to cook perfectly in the cooking chamber equipped with the TES, while this was not possible in the system without heat storage.

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

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

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

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

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

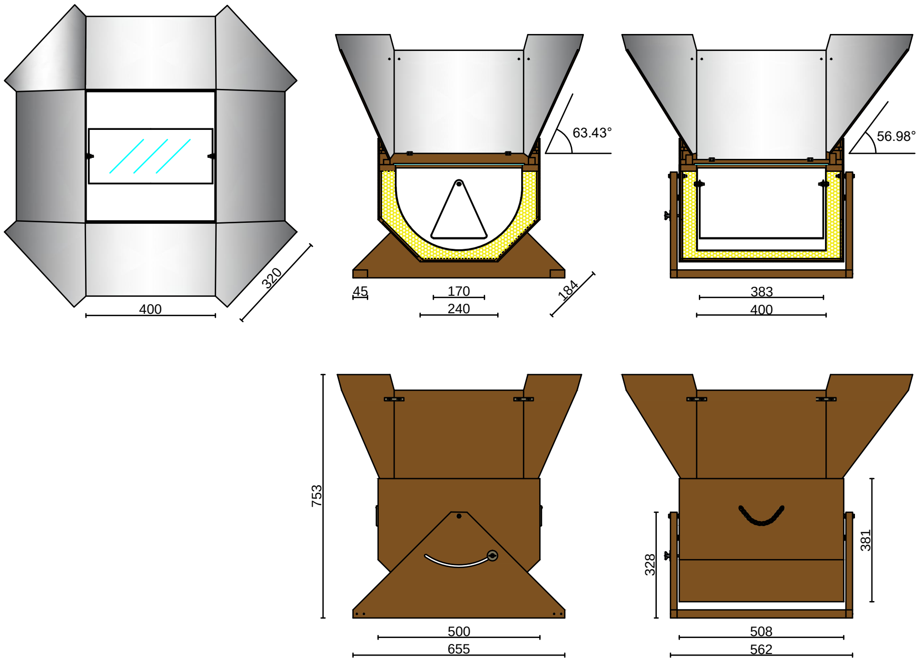

Figure 1: Views and cross-sections of the portable solar box cooker.

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

$$C = \frac{A_\mathrm{a}}{A_\mathrm{g}} = 4.08. \tag{1}$$

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

The cooker manufacturing process consisted of 4 consecutive phases: cooking chamber realization and painting; external structure realization; insulation with glass wool; realization of the booster mirror system.

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

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

The cooking chamber metal walls were thermally insulated to reduce heat losses and obtain higher operating temperatures. The thermal insulation consisted of layers and flakes of glass wool inserted in the cavity between the cooking chamber and the external MDF structure. To prevent the moisture from damaging the wood panels, all the MDF elements were painted with a protective coating.

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

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

2.2. Thermal energy storage

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

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

2.3. Phase change material

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

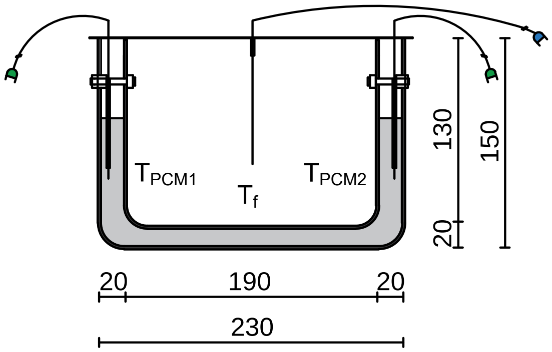

Figure 2: Thermal energy storage. T_{PCM1} and T_{PCM1} are two K-type thermocouples used to detect the PCM temperature, while T_{f} is a T-type thermocouple used to detect the testing fluid temperature.

Table 1: Thermophysical properties of erythritol.

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

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

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

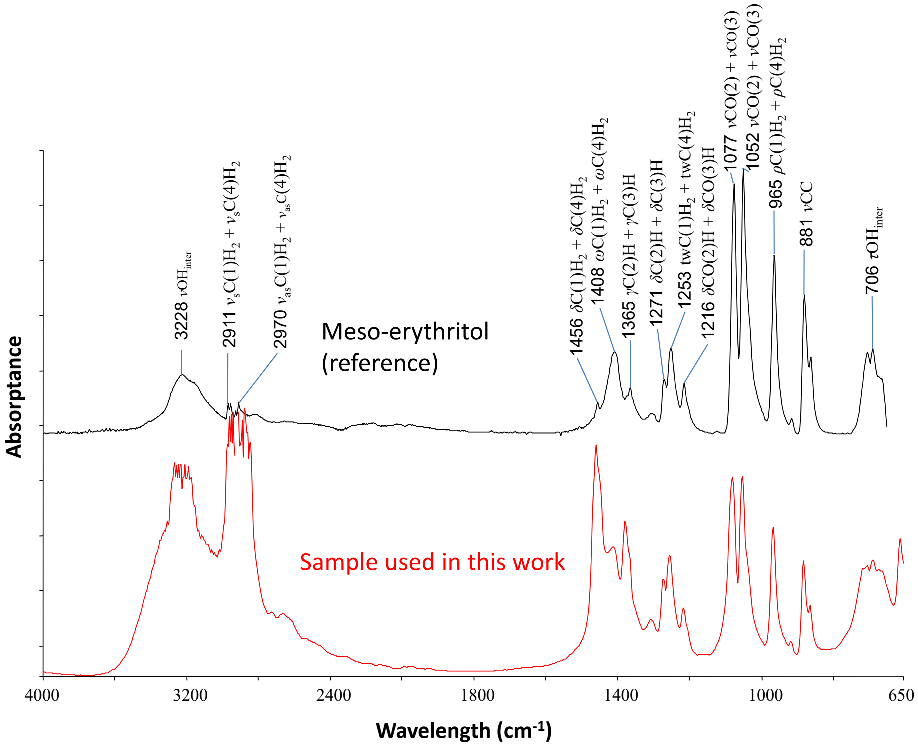

Figure 3: Erythritol sample analyzed with the FTIR spectometer.

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

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

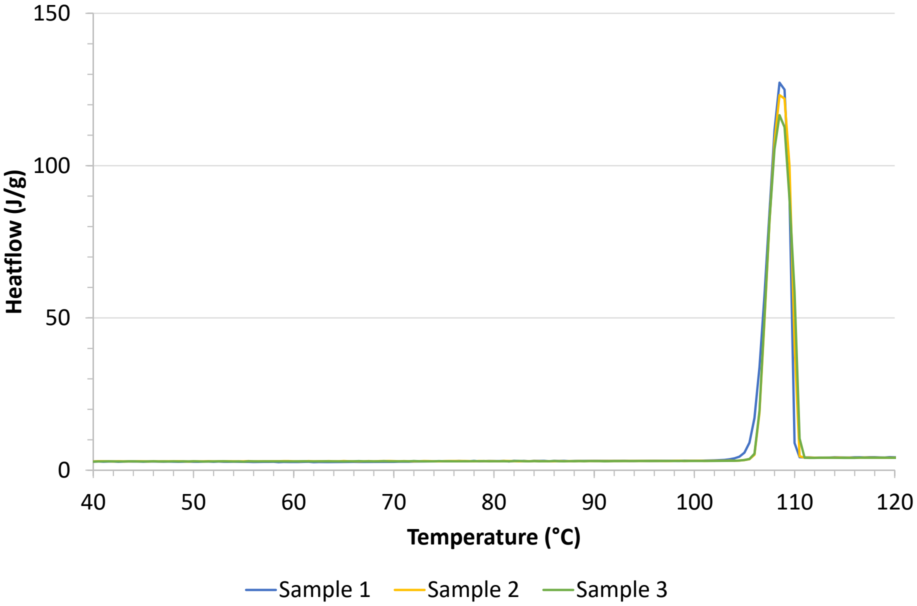

Figure 4: DSC analysis of the erythritol samples.

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

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

3. Experimental analysis

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

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

3.1. Experimental tests

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

Two different tests were carried out.

- Tests without load. They allowed to determine the maximum temperature reachable by the solar cooker.
- Tests with load. These tests were carried out by loading the solar cooker with a testing fluid, water or silicone oil. The former fluid was used due to ease of comparison with the results obtained by other authors. The latter fluid (Rhodorsil Oil 47 V 100), instead, was used to exceed the limit of 100 °C. This allowed to study the behavior of the cooker in the presence and absence of the erythritol-based TES.

3.2. Test bench

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

An Eppley NIP (Normal Incidence Pyrheliometer, ±0.5% in the range 0–1400 $\mathrm{W/m^2}$) was also used to measure direct normal irradiance (DNI). Diffuse solar radiation was not taken into account in the present experiment as the considered solar box cooker has a concentration ratio of 4.08, thus it can basically work with direct solar radiation only.

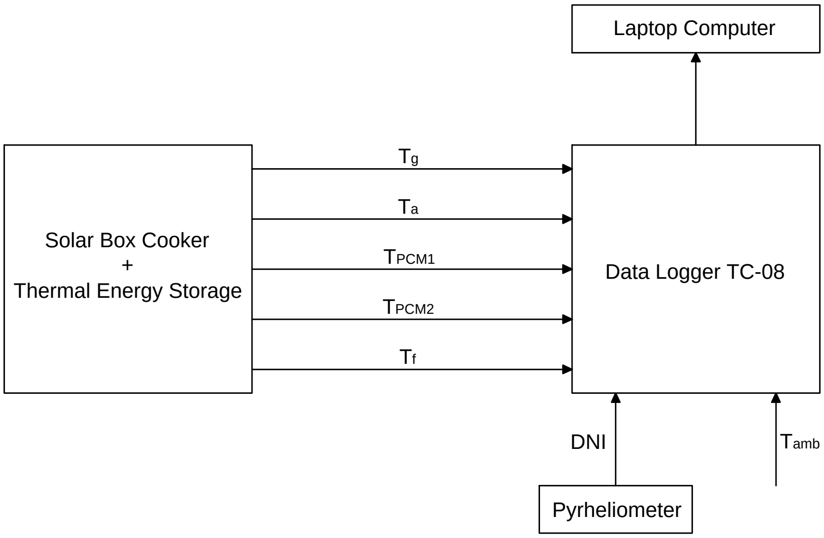

Figure 5: Test bench. T_g: glass temperature; T_a: absorber temperature; T_PCM: phase change material temperature; T_f: testing fluid temperature; T_amb: ambient temperature; *DNI*: direct normal irradiance.

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

3.3. Experimental parameters

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

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

$$F_1 = \frac{T_\mathrm{a,max} - T_\mathrm{amb}}{DNI}, \tag{2}$$

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

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

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

$$F_2 = \frac{F_1 m_{\mathrm{f}}\, c_{\mathrm{f}}}{A_{\mathrm{a}} \Delta t_{\mathrm{h}}} \ln \left[\frac{1 - \frac{1}{F_1}(T_1 - T_{\mathrm{amb,av}})/DNI_{\mathrm{av}}}{1 - \frac{1}{F_1}(T_2 - T_{\mathrm{amb,av}})/DNI_{\mathrm{av}}} \right], \tag{3}$$

where m_{f} is the testing fluid mass, c_{f} is the testing fluid specific heat, A_{a} is the solar cooker aperture area, while DNI_{av} and $T_{\mathrm{amb,av}}$ are, respectively, the average direct normal irradiance and the average ambient temperature over the time interval Δt_{h}. In Equation (3), F_1 is the first figure of merit determined through no-load tests with Equation (2).

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

$$t_{\mathrm{s}} = \frac{\Delta t_{\mathrm{h}} A_{\mathrm{a}}}{m_{\mathrm{f}}}, \tag{4}$$

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

$$t_{\mathrm{ch}} = t_{\mathrm{s}} \frac{DNI_{\mathrm{av}}}{DNI_{\mathrm{ref}}}, \tag{5}$$

where DNI_{av} is the average direct normal irradiance during Δt_{h}, and DNI_{ref} is a reference direct normal irradiance (equal to $900\,\mathrm{W/m^2}$). The last parameter 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
$T_{\mathrm{a,max}}$ (°C)	197.30	187.42	189.10
F_1 (°C/(W/m^2))	0.20	0.17	0.19

solar cooker, defined as:

$$\eta_{\mathrm{av}} = \frac{m_{\mathrm{f}}\, c_{\mathrm{f}} (T_2 - T_1)}{DNI_{\mathrm{av}} A_{\mathrm{a}} \Delta t_{\mathrm{h}}}. \tag{6}$$

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 $T_2 = 125\,°\mathrm{C}$ to $T_3 = 100\,°\mathrm{C}$ 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.

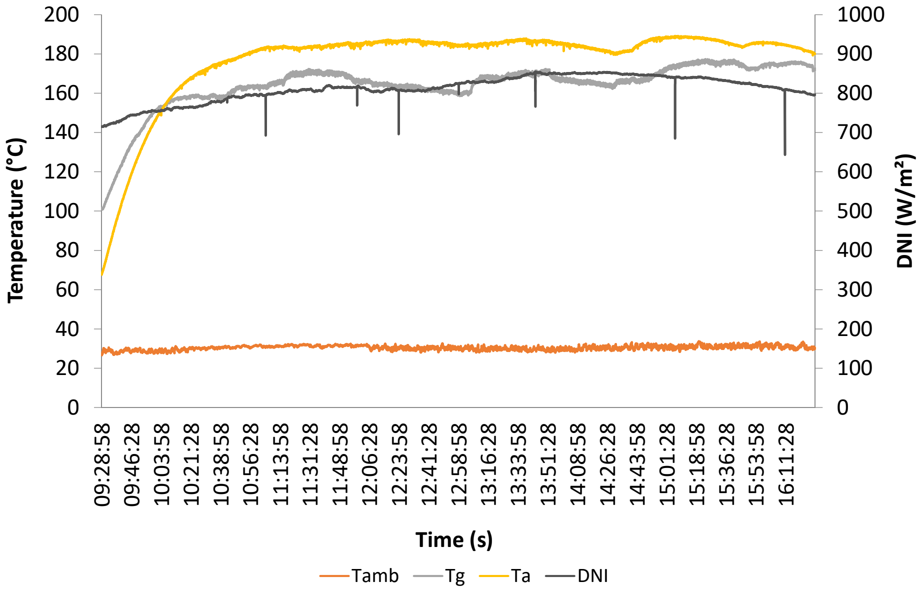

Figure 6: Test without load (13/06/2017).

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

4.2. Tests with water

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

Figure 7 depicts the load test carried out on September 14, 2017 loading the solar cooker with 2 kg of water. The average direct normal irradiance was $867.18\,\mathrm{W}/\mathrm{m}^2$ and the average ambient temperature was 25.00 °C during the Δt_{h} 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 (°C)	40	40	40	40	40
T_2 (°C)	90	90	90	90	90
DNI_av (W/m^2)	736.84	867.18	869.28	825.54	597.10
$T_\mathrm{amb,av}$ (°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 (h m^2/kg)	0.49	0.57	0.27	0.33	0.40
t_ch (h m^2/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

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

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

4.3. Tests with silicone oil

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

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

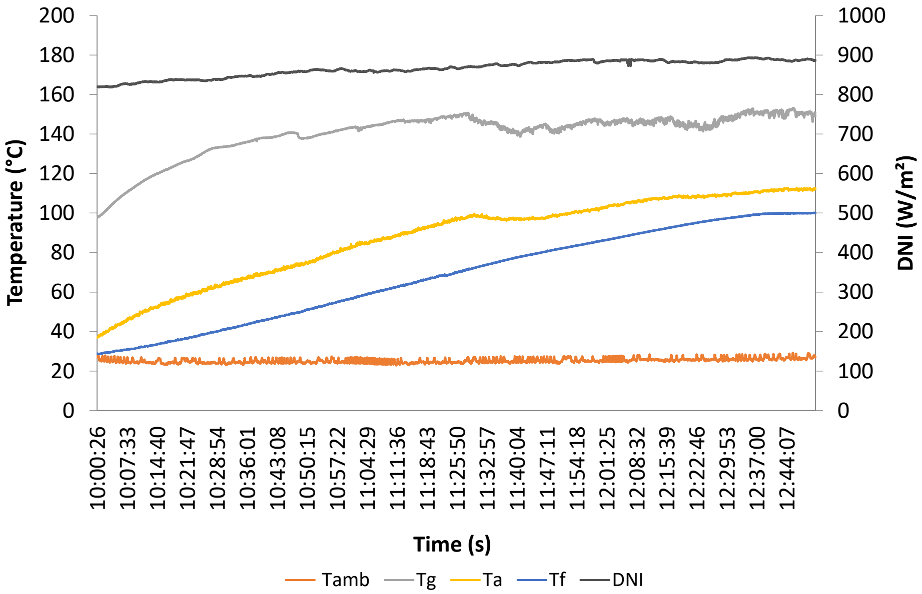

Figure 7: Test with water (14/09/2017).

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

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

When the silicone oil temperature was higher than 130 °C, the solar cooker was closed to solar radiation and left cooling down. During the cooling phase, the average ambient temperature was 17.35 °C and the silicone oil required 0.31 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
DNI_{av} (W/m^2)	767.22	882.77	720.04	601.80	751.80	834.99	855.53	867.96	946.62
$T_{\mathrm{amb,av}}$ (°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_{av}	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
$T_\mathrm{amb,av}$ (°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

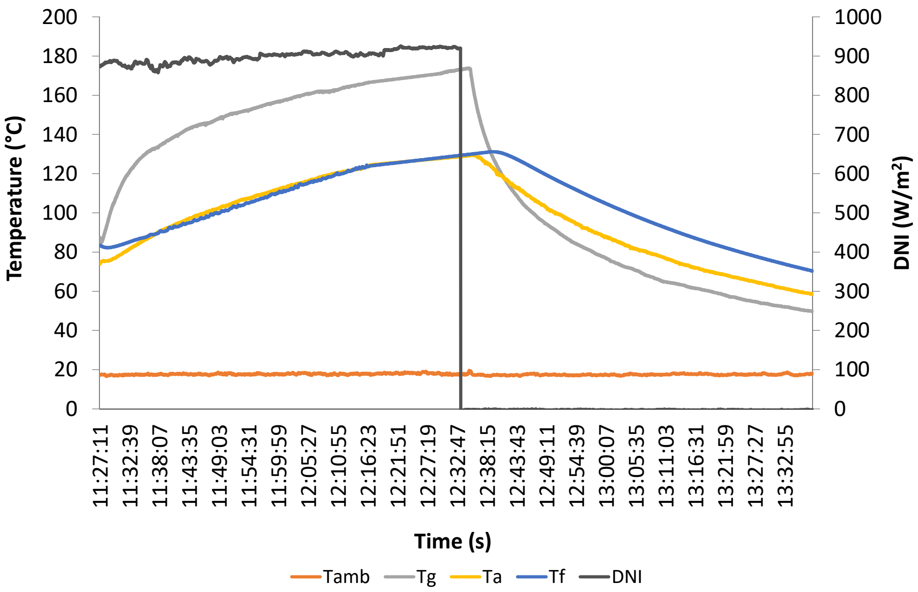

Figure 8: Test with silicone oil (27/09/2018).

4.4. Tests with silicone oil and PCM

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

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

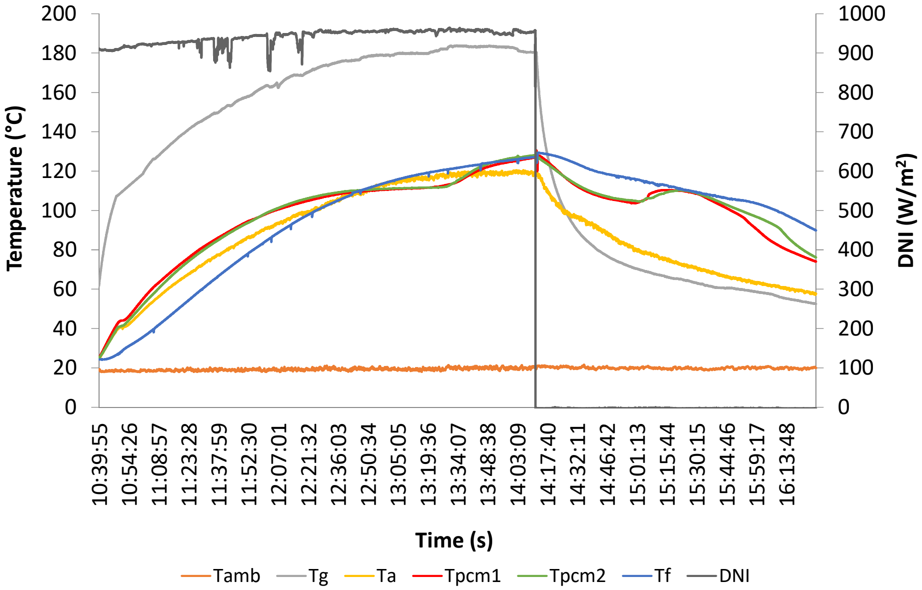

Figure 9: Test with silicone oil and PCM (25/09/2018).

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

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

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

In Figure 9, it is also possible to see that a supercooling phenomenon takes place in the PCM, i.e. the substance does not solidify immediately below the freezing temperature but its crystallization occurs only after a lower temperature (around 105 °C) is reached. This effect is well-known in literature (Safari et al., 2017) and, in the TES under study, could be due to heterogeneous nucleation at the surface of the vessel containing the PCM. Even though supercooling leads to lower crystallization temperatures and, therefore, to a not optimal thermal storage performance (Safari et al., 2017), in Figure 9 it is possible to see that the erythritol supercooling curve rises and stabilizes at the solidification temperature (109 °C) immediately upon crystallization. Thus, the penalty associated to the phenomenon is minimal.

4.5. Summary and comparison of tests with and without PCM

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

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

Table 6 provides the average heating times of the experimental tests carried out with silicone oil ($\Delta t_{\mathrm{h,oil}}$, average of the Δt_{h} provided in Table 4 for the tests 9–13), and with silicone oil and PCM ($\Delta t_{\mathrm{h,oil+PCM}}$, average of the Δt_{h} provided 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
$\Delta t_{\mathrm{h,oil}}$ (h)	1.18 (tests 9–13)	1.58 (test 10)	0.95 (test 13)
$\Delta t_{\mathrm{h,oil+PCM}}$ (h)	2.53 (tests 14–17)	1.94 (test 14)	3.35 (test 16)
Deviation (%)	114.41	22.78	252.63

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

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

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

Table 7 provides the average cooling times of the tests carried out with silicone oil only ($\Delta t_{\mathrm{c,oil}}$, average of the Δt_{c} provided in Table 5 for the tests 9–13), and with silicone oil and PCM ($\Delta t_{\mathrm{c,oil+PCM}}$, 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
$\Delta t_{\mathrm{c,oil}}$ (h)	0.43 (tests 9–13)	0.31 (test 10)	0.50 (test 11)
$\Delta t_{\mathrm{c,oil+PCM}}$ (h)	1.94 (tests 14–17)	2.19 (test 15)	1.67 (test 17)
Deviation (%)	351.16	606.45	234.00

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

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

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

5. Conclusions

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

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

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Nomenclature

Latin Symbols

A	Area (m^2)
C	Concentration ratio
c	Specific heat ($\mathrm{kJ/(kg\,K)}$
DNI	Direct normal irradiance ($\mathrm{W/m}^2$)
F_1	First figure of merit ($^\circ\mathrm{C}/(\mathrm{W/m}^2)$)
F_2	Second figure of merit
L	Latent heat of fusion (kJ/kg)
m	Mass (kg)
T	Temperature (°C)
t	Time (s)

Greek Symbols

Δ	Delta difference
η	Thermal efficiency
ρ	Density ($\mathrm{kg/m}^3$)

Subscripts

a	Absorber, aperture
amb	Ambient
av	Average
c	Cooling
ch	Characteristic

f	Fluid
g	Glass
h	Heating
l	Liquid
max	Maximum
melt	Melting
min	Minimum
ref	Reference
s	Specific, solid

Acronyms

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

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