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Experimental characterization of a solar cooker with thermal energy storage based on solar salt

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Abstract. High temperature solar cooking allows to cook food fast and with good efficiency. An unavoidable drawback of this technology is that it requires nearly clear-sky conditions. In addition, evening cooking is difficult to be accomplished, particularly on the winter season during which solar radiation availability is limited to a few hours in the afternoon in most of countries. These restrictions could be overcome using a cooker thermal storage unit (TSU). In this work, a TSU based on solar salt was studied. The unit consists of two metal concentric cylindrical vessels, connected together to form a double-walled vessel. The volume between walls was filled with a certain amount of nitrate based phase change material (solar salt). In order to characterize the TSU, a test bench used to assess solar cooker performance was adopted. Experimental load tests with the TSU were carried out to evaluate the cooker performance. The obtained preliminary results show that the adoption of the solar salt TSU seems to allow both the opportunity of evening cooking and the possibility to better stabilize the cooker temperature when sky conditions are variable.

1. Introduction

Solar cooking is considered as one of the simplest and attractive ways of the utilization of solar thermal energy [1]. Energy for cooking is one of the fundamental uses in developing countries, where wood is still the primary energy source. In most of rural areas of Africa, the energy demand for cooking is supplied by non-commercial fuels (e.g., firewood, agricultural waste, cow dung, kerosene); in India, the energy required for cooking accounts for 36% of total primary energy consumption and 90% of rural households depend on biomass fuels [2]. In addition to the environmental and economic issues, the firewood use also causes some serious health problems such as burns, eye disorders, and lung diseases.

Solar cookers represent a possibility to meet the energy demand in the domestic sector of developing countries where, generally, there is abundance of solar radiation; e.g., a mean daily solar radiation of 5-7 kWh/m² and more than 275 sunny days in a year have been estimated [3]. However, the large-scale dissemination of solar cookers still remains limited as most of these devices are only used for research purposes [4]. The main obstacles to the dissemination of the



technology are the resistance to acceptance as it is a new technology, variable nature of solar radiation, limited space availability in urban areas, and higher initial costs [5].

In the last years, solar box cookers showed considerable developments in terms of performance and design [1]. A solar box cooker usually includes an insulated box with a transparent glass cover and mirrors to reflect direct solar radiation into the box. The inner part of the box is painted in black in order to maximize the absorption of solar energy. Box cookers are simple to manufacture, can be employed with minimal attendance during the cooking process, and can keep food warm for a long period of time.

A solar box cooker prototype with a high concentration ratio (10.78) was designed, realized, and tested by some of the authors in a previous work [6], based on their experience on parabolic trough collectors [7, 8, 9, 10]. Experimental tests with and without load were carried out, and showed that the prototype is able to cook food fast and at high temperature. Load tests were conducted with both water and peanut oil; 1 kg of the former fluid could be boiled in about 11 minutes, while the latter fluid was able to reach temperatures higher than 200 °C in around 41 minutes.

However, an unavoidable drawback of high temperature cooking obtained through elevated solar concentration is that only direct solar radiation can be exploited. This condition limits the cooker usability to clear-sky days and makes evening cooking difficult. These restrictions could be removed by adopting a cooker thermal storage unit (TSU). In particular, a TSU based on phase change materials (PCMs) allows both the opportunity of evening cooking and the possibility to better stabilize the cooker temperature when sky conditions are variable. Although a number of PCM-based TSUs was designed for solar cooker applications [11], none of those adopted solar salts to be used for temperatures up to about 150 °C. Therefore, a solar-salt-based TSU was designed, realized, and tested in DIISM (Department of Industrial Engineering and Mathematical Sciences) to be used with our solar cooker prototype.

2. Materials and Methods

The PCM-based thermal storage unit (TSU) described in this paper was designed and manufactured to store solar energy during sunshine periods. The stored thermal energy can be utilized to cook food in the evening or when solar radiation is low. A mixture composed by KNO_3 , NaNO_2 , and NaNO_3 (also commercially known as HITEC [12]) was used as latent heat storage material.

The following subsections describe the solar box cooker, the TSU, and the PCM mixture, respectively.

2.1. Solar Box Cooker

A schematic of the considered solar box cooker prototype is shown in Figure 1. The cooker consists of a wooden large box containing a zinc-coated steel frame with the function of cooking chamber (also referred to as absorber). The chamber was painted with a special selective coating (SOLKOTE HI/SORB-II) that, respect to a common black paint, has an absorptance in the solar spectrum ranging from 0.88 to 0.94, and an emissivity from 0.20 to 0.49, depending on the dry film thickness and substrate. In the chamber, there is a vessel support able to rotate of 360°, in order to maintain the pots in balance.

A double transparent cover on the top of the box allows the solar radiation to be transmitted to the cooking chamber. Each cover has a diameter of 460 mm and is made of tempered glass, which is high resistant and suitable for solar thermal applications (the declared transmittance in the solar spectrum is about 0.90 and the reflection coefficient is 0.08).

The higher part of the box is circumscribed by a double row of booster mirrors (Figure 2). The mirrors were manufactured with special aluminum reflective foils (MIRO-SUN Weatherproof Reflective 90) glued on phenolic compound elements. Respect to traditional aluminum foils, these

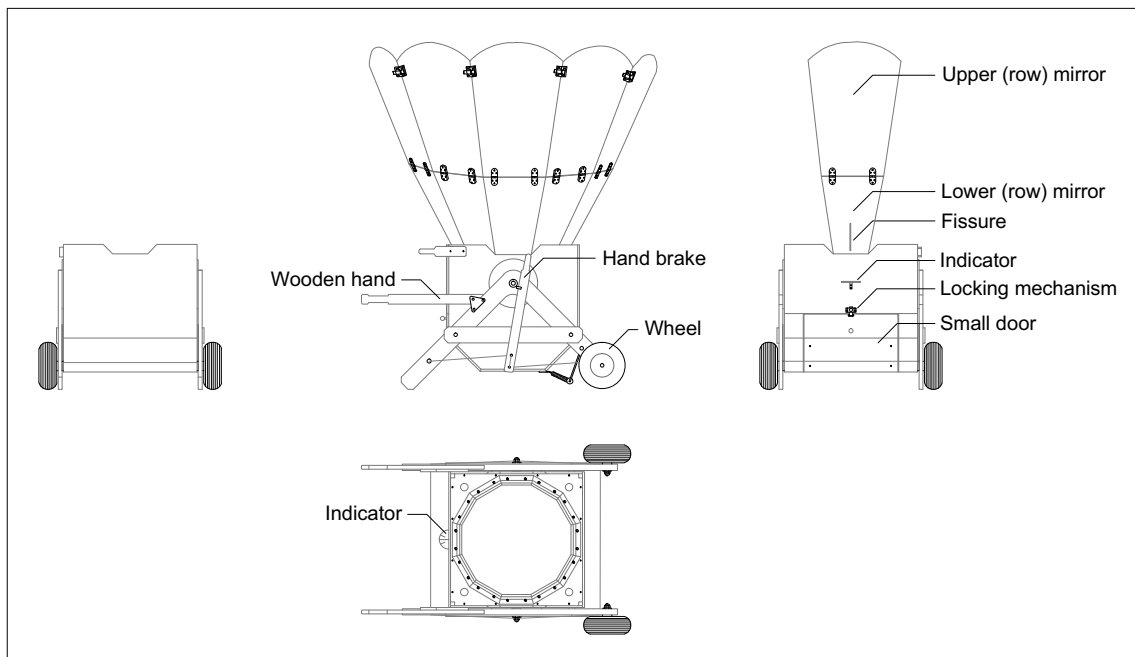


Figure 1. Solar box cooker prototype.

mirrors are able to withstand atmospheric agents and guarantee an overall reflection of about 0.94 in the solar spectrum, with a negligible dependence on the solar incident angle. Each row consists of 12 mirrors and has a different inclination angle respect to the horizontal plane. The upper row has an inclination angle of 70.45° and each mirror, which is 630 mm long, can be reclined to reduce the space occupied by the cooker when it is not working. Instead, the mirrors in the lower row (inclination angle of 63.80°) are trapezoidal and 616 mm long. One of the lower mirrors includes a fissure which allows solar radiation to be projected on an indicator, used to evaluate the correct cooker alignment respect to the sun. The overall aperture area is 1.789 m^2 .

The prototype has two border wooden hands and two wheels that allow both its movement and its azimuthal orientation. In addition, a zenithal orientation is possible as the cooker is able to rotate around the horizontal axis.

2.2. Thermal Storage Unit

A thermal storage unit used to hold the cooking vessel was designed and realized as shown in Figure 3. The TSU has two hollow concentric stainless steel cylinders of diameter 260 mm and 220 mm; the internal pot is 150 mm deep, while the external pot is black in order to enhance solar energy absorption. The annular space was filled with PCM, while the internal pot was used to load the testing fluid. The two pots were connected through four stainless steel bolts. Two small stainless steel tubes were welded to two opposite bolts in order to host two K-type thermocouples, used to measure the PCM temperature in two different points ($T_{\text{PCM},1}$ and $T_{\text{PCM},2}$). Another K-type thermocouple, fixed at the center of the inner pot, was used to measure the testing fluid temperature.

2.3. Molten Salt Based PCM

The saline nitrates used in this work were NaNO_2 , NaNO_3 , and KNO_3 (purchased from Sigma-Aldrich and Campoverde Srl). Starting from these base components, the PCM was prepared according to the recommendations reported by [12]. The anhydrous nitrates were obtained by heating in two stages: at 140°C for 4 hours, and at 250°C for 8 hours. Once this thermal treatment was accomplished, the salts were carefully handled to avoid water absorption.

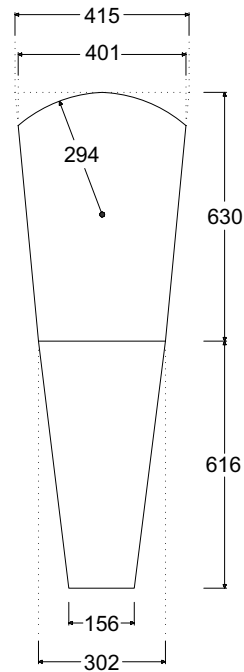


Figure 2. Solar box cooker mirrors.

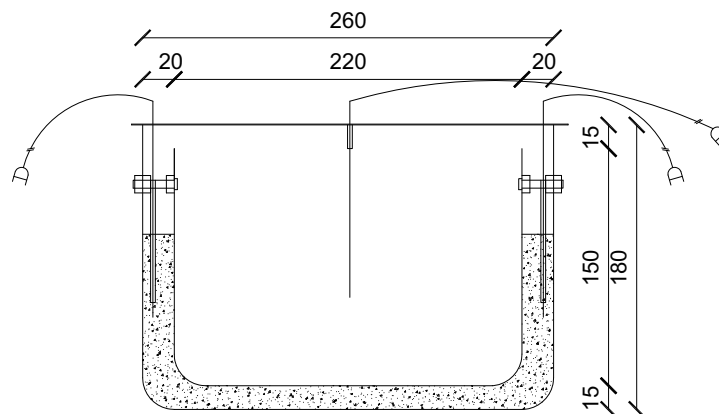


Figure 3. Thermal storage unit.

Afterwards, the mixed formulation (53 wt% KNO_3 , 40 wt% NaNO_2 , and 7 wt% NaNO_3 for an overall mass of about 4 kg) was inserted in the annular volume of the thermal storage unit. Finally, the TSU including the salts was inserted in an electric furnace and heated at 350°C for about 2 hours. In this way, the PCM was definitely realized and the TSU was ready to be used for testing.

The ternary mixture is reported to have a melting point of about 142°C and a fusion enthalpy of 82 kJ/kg [12]. In order to verify the phase transitions, the thermal storage unit with the PCM was put in an electric furnace to be heated up to melting. Then, the furnace was turned off to let the PCM cooling and solidifying. In this way, it was possible to determine the PCM temperature curve, as shown in Figure 4 and 5.

As can be noted from Figure 4, a first transition occurs at about 94°C due to water evaporation. Instead, the actual PCM melting point can be observed at about 143°C , confirming

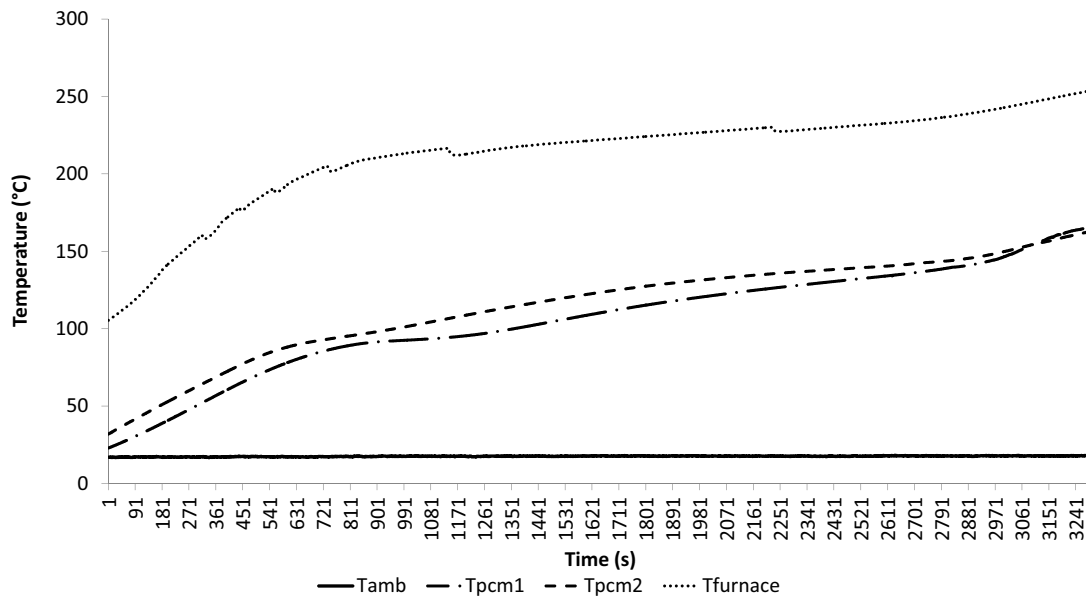


Figure 4. Solar salt temperature curve: melting.

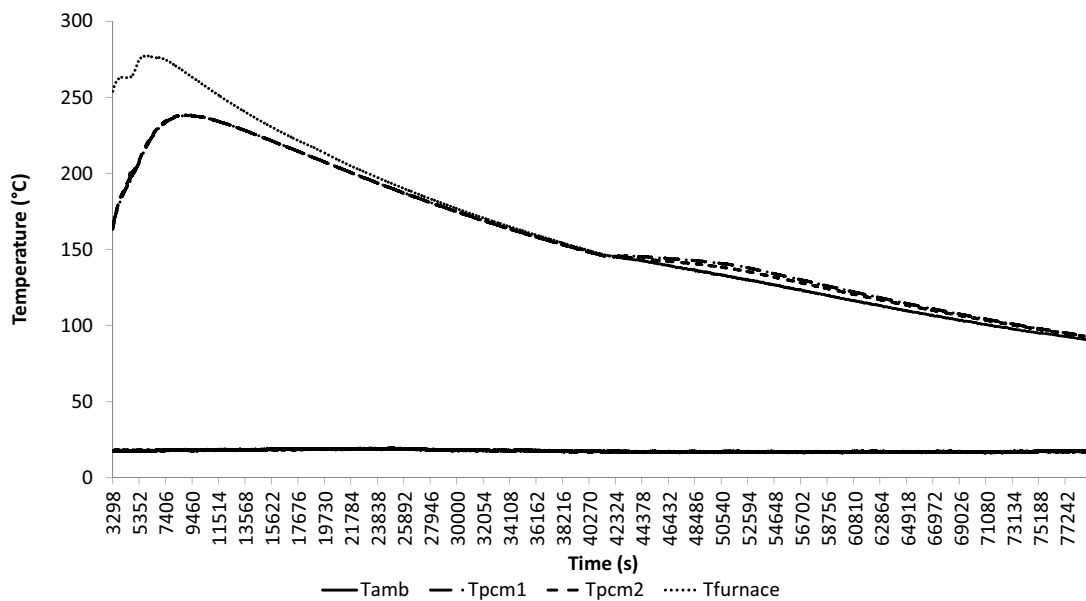


Figure 5. Solar salt temperature curve: solidification.

the results obtained by [12]. The furnace was turned off when the solar salt reached a temperature of approximately 240 °C (Figure 5). The cooling curve shows that solidification took place in the same melting temperature range.

3. Experimental Tests and Results

Two outdoor tests were carried out in March 2017 on the DIISM roof (latitude 43.5867 N, longitude 13.5150 E) to characterize the PCM-based solar box cooker. Silicone oil (Rhodorsil Oil 47 V 100) was used as testing fluid to find the prototype most relevant thermodynamical parameters. This fluid was chosen for its high stability and good thermal conductivity.

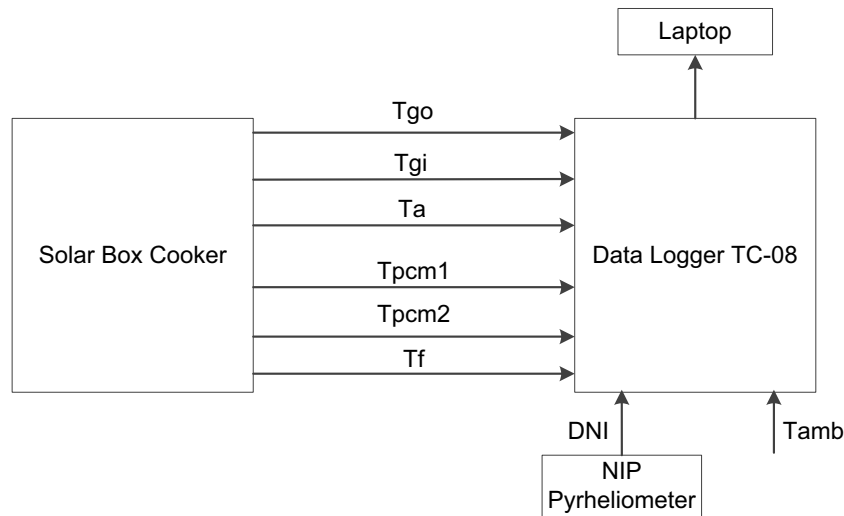


Figure 6. Solar box cooker test bench.

3.1. Test Bench

The solar box cooker was characterized adopting the test bench reported in Figure 6.

K-type thermocouples were used to measure temperature of ambient air (T_{amb}) and in different points of the cooker: outer (T_{go}) and inner glass cover (T_{gi}), absorber (T_a), PCM (two opposite points, $T_{PCM,1}$ and $T_{PCM,2}$), testing fluid (T_f). The thermocouple measuring T_{go} was positioned on the external side of the outer glass, near the wooden frame, and it was shielded by solar radiation. Instead, the sensor measuring T_{gi} was attached on the internal side of the inner glass, near the wooden frame (the thermocouple was not allowed to “see” solar radiation). The absorber temperature (T_a) was measured with a thermocouple fixed on the bottom of the cooking chamber.

The direct normal irradiance, DNI , was measured through a first-class normal-incidence pyrheliometer (NIP) mounted on a solar tracker. The pyrheliometer has a 1 second time response, a temperature dependence of $\pm 1\%$ in the range from -20 to 40°C , and shows a linear relationship of $\pm 0.5\%$ in the range 0 – 1400 W/m^2 . Only direct solar radiation was measured since the solar box prototype considered in this work has a high concentration ratio and hence it is not able to exploit diffuse solar energy [9].

The signals provided by the K-type thermocouples and the pyrheliometer were acquired by a Pico Technology TC-08 data logger.

3.2. Load Tests

The first load test, carried out on March 14, 2017, started at 10:32 and ended at 17:14. The average direct normal irradiance was 462.48 W/m^2 and the average ambient temperature was 12.73°C . The internal cylinder of the TSU was filled with 2.9 kg of silicone oil.

When the PCM was completely melted (at about 14:15), the solar cooker was darkened to simulate absence of solar radiation and was left cooling down. Figure 7 shows the temperatures and the solar radiation detected during the test. It is possible to note that solar radiation was intermittent during the test, especially in the first hours; however, the presence of the thermal storage unit facilitated the temperature stability of the testing fluid respect to other cooker parts (note the 12:00–13:00 time period). In addition, it is evident that both the oil and the PCM temperature decrease slowly when solar radiation is no longer available, in contrast to the other cooker elements.

The second load test was conducted on March 16, 2017. It began at 09:46 and ended at 16:49.

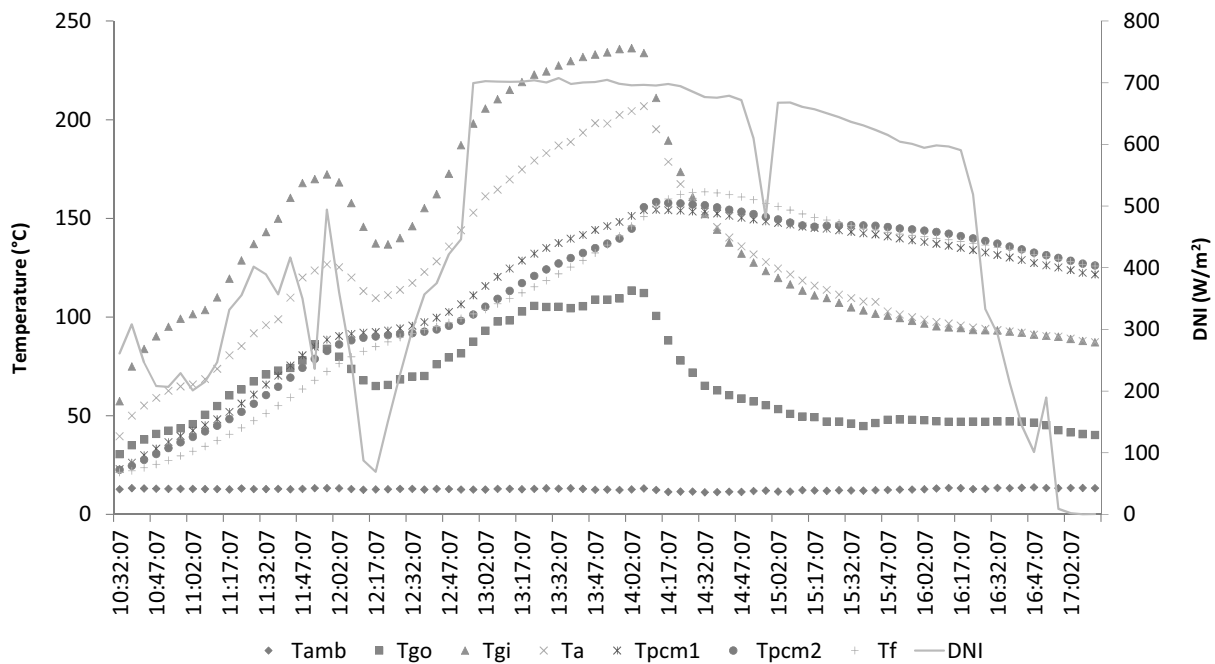


Figure 7. Test 1 (14/03/2017).

The average direct normal irradiance was 656.75 W/m^2 , while the average ambient temperature was 17.67°C . Again, the TSU was filled with 2.9 kg of silicone oil. The test results are reported in Figure 8. Thanks to a greater and constant solar radiation, in this second test the silicone oil was able to reach a temperature higher than the one obtained in the first test. In the same fashion of the previous experiment, the solar cooker prototype was obscured when the PCM reached melting ($12:00$); results show that the oil and the PCM temperatures are effectively stabilized during the cooling down period, respect to the other cooker elements.

In order to characterize the cooker performance, several parameters were calculated based on the obtained experimental data. The first parameter was the time required to take the oil temperature from 40°C to the PCM melting, Δt_1 (s). This parameter was used to derive the specific boiling time ($\text{min m}^2/\text{kg}$), defined in this work as the time required for a cooker of aperture A_a to take 1 kg of oil from 40°C to the PCM melting temperature [13]:

$$t_s = \frac{\Delta t_1 A_a}{m} \quad (1)$$

where A_a (m^2) is the cooker aperture area and m (kg) is the mass of testing fluid. Another parameter is the characteristic boiling time ($\text{min m}^2/\text{kg}$), generally used as a parameter for making comparisons between various solar cooker designs under different solar radiation levels [13]:

$$t_c = t_s \frac{DNI_{av}}{DNI_{ref}} \quad (2)$$

where DNI_{av} (W/m^2) is the average direct normal irradiance during the time interval Δt_1 , while DNI_{ref} is a reference direct normal irradiance equal to 900 W/m^2 .

The average overall solar cooker thermal efficiency is [13]:

$$\eta_{av} = \frac{m c \Delta T}{DNI_{av} A_a \Delta t_1} \quad (3)$$

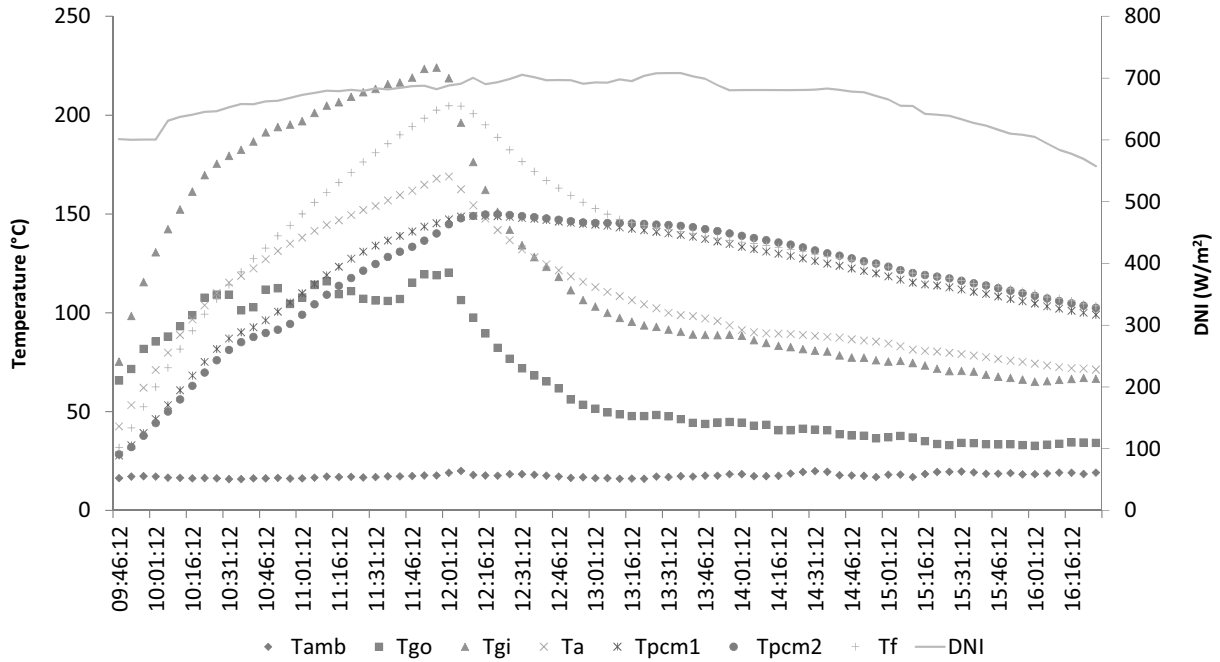


Figure 8. Test 2 (16/03/2017).

where c (J/(kg K)) is the oil specific heat and ΔT (°C) is the temperature difference between the maximum cooking fluid temperature and the ambient temperature.

In addition, [14] introduced the first figure of merit, F_1 (°C/(W/m²)), which is defined as:

$$F_1 = \frac{T_{a,\max} - T_{\text{amb}}}{DNI} \quad (4)$$

where $T_{a,\max}$ (°C) is the maximum temperature reached by the absorber, while T_{amb} (°C) and DNI (W/m²) are, respectively, the corresponding ambient temperature and direct normal irradiance measured when the stagnation temperature is reached. For the solar cooker under study, F_1 was determined to be equal to 0.39 °C/(W/m²) [6].

A second figure of merit, F_2 , was introduced to involve the temperature increase measurement with time of a known amount of fluid placed in the cooker. It is defined as [14]:

$$F_2 = \frac{F_1 m c}{A_a \Delta t_1} \ln \left[\frac{1 - \frac{1}{F_1} (T_1 - T_{\text{amb,av}}) / DNI_{\text{av}}}{1 - \frac{1}{F_1} (T_2 - T_{\text{amb,av}}) / DNI_{\text{av}}} \right] \quad (5)$$

where Δt_1 is the time interval during which the fluid temperature rises from T_1 to T_2 , while DNI_{av} and $T_{\text{amb,av}}$ are, respectively, the average direct normal irradiance and the average ambient temperature over the time interval Δt_1 .

Table 1 reports a summary of the aforementioned parameters calculated during the oil heating period. It can be noted that, due to higher solar radiation and ambient temperature, test 2 allowed to reach better results respect to test 1. In particular, the results obtained during test 2 are only slightly worse than those obtained by the authors with a comparable test [6], where the testing fluid was peanut oil and the environmental conditions were more favorable. This seems to confirm that the solar salt thermal conductivity is good and that the chosen thermal storage mass does not penalize too much the fluid heating phase.

A summary of the cooling phase is reported in Table 2. The time required by the oil to drop its temperature from T_2 to 130 °C, Δt_2 (s), is similar for the two tests; however, it should be

Table 1. Heating test summary.

Quantity	Test 1	Test 2
Date	14/03/2017	16/03/2017
Start	11:19	09:53
End	14:34	12:03
A_a (m ²)	1.789	1.789
T_1 (°C)	40	40
T_2 (°C)	163.59	205.73
Δt_1 (s)	11 706	7782
$T_{amb,av}$ (°C)	12.77	16.79
DNI_{av} (W/m ²)	511.11	662.04
m (kg)	2.9	2.9
t_s (min m ² /kg)	120.36	80.01
t_c (min m ² /kg)	68.35	58.86
η_{av}	0.05	0.09
F_1 (°C/(W/m ²))	0.39	0.39
F_2	0.11	0.17

Table 2. Cooling test summary.

Quantity	Test 1	Test 2
Date	14/03/2017	16/03/2017
Start	14:34	12:03
End	16:58	14:30
$T_{amb,av}$ (°C)	12.50	17.59
Δt_2 (s)	8664	8788
$\Delta T_f / \Delta t_2$ (°C/min)	0.23	0.52

noted that T_2 was equal to 163.59 °C during the former test, while it was 205.73 °C during the latter. In other words, the silicone oil cooling down ratio, $\Delta T_f / \Delta t_2$ (°C/min), was worse for test 2. In this test, the temperature difference between the silicone oil and the PCM is due to the fact that no lid was used. In fact, thanks to a higher solar radiation, the oil was able to heat faster than the PCM. This behavior could be avoided if a lid was adopted, but in this case the heating phase would have been slower. Anyway, from Figure 8 it can be observed that, once the testing fluid and the PCM reach the same temperature, the TSU is able to stabilize the fluid temperature with good results.

4. Conclusions

This study concerns the thermodynamic characterization of a solar box cooker equipped with a thermal storage unit (TSU) based on a solar salt mixture PCM (53 wt% KNO₃, 40 wt% NaNO₂, 7 wt% NaNO₃). The mixture, having a melting point of about 142 °C, allowed to keep the testing fluid temperature stabilized in a near temperature range. Starting from the experimental results, the most relevant thermodynamic parameters were determined. It was found that the cooker performance during the heating phase is not significantly penalized. On the other hand, the presence of the TSU proved to stabilize and extend the utilization of a solar box cooker when solar radiation is absent or intermittent. Even though the reported results are promising, further tests are necessary to determine other cooker and TSU thermodynamic characteristics, e.g. their

behavior when a lid is used.

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