DESIGN, REALIZATION AND TEST OF A PORTABLE SOLAR BOX COOKER WITH BOOSTER MIRRORS

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Abstract: *Solar cooking is considered one of the most attractive ways to utilize solar energy. Thus, in this work a concentrating solar box cooker prototype was manufactured and tested. The cooker has a cooking chamber with a glass cover on the top and comprises a row of booster mirrors. The prototype can be manually oriented both along the azimuthal and the zenithal planes. In the cooking chamber, there is a rotating support able to rotate of 360°, in order to maintain vessels in balance when the zenith orientation changes. A test bench adopted to determine the thermal performance of the prototype is described. Two different experimental test were carried out: with and without load. Experimental tests without load were carried out to evaluate the maximum cooker temperature. Tests with load, instead, were conducted using an aluminum vessel filled with water, up to the fluid boiling. Results show that the cooker is able to cook food at high temperature, fast and with good efficiency.*

Keywords: Solar, thermal, experimental, concentrating

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 addition to the environmental issues, the firewood use also causes some serious health problems such as burns, eye disorders, and lung diseases [2].
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/m^2 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].
A solar box cooker prototype with a high concentration ratio (10.78) was designed, realized, and tested by 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.
The solar box cooker described in this work is the second prototype realized in DIISM (Department of Industrial Engineering and Mathematical Sciences). To test the cooker performance, we tried to follow and perform the most widespread and reliable quantitative procedures available in literature.

2. DESIGN, MATERIALS AND OPTICS

The proposed cooker, shown in Figure 1, is composed by a wooden box containing a zinc-coated steel frame with the function of cooking chamber (or absorber). The chamber was painted with a special selective coating (SOLKOTE HI/SORB-II) having a higher solar absorptance (0.90) than that of a common black paint. In the chamber, there is a vessel support able to rotate of 360°, in order to maintain the pots/food in balance. The cooking chamber walls were thermally insulated with glass wool to reduce heat losses and obtain higher cooking temperatures.

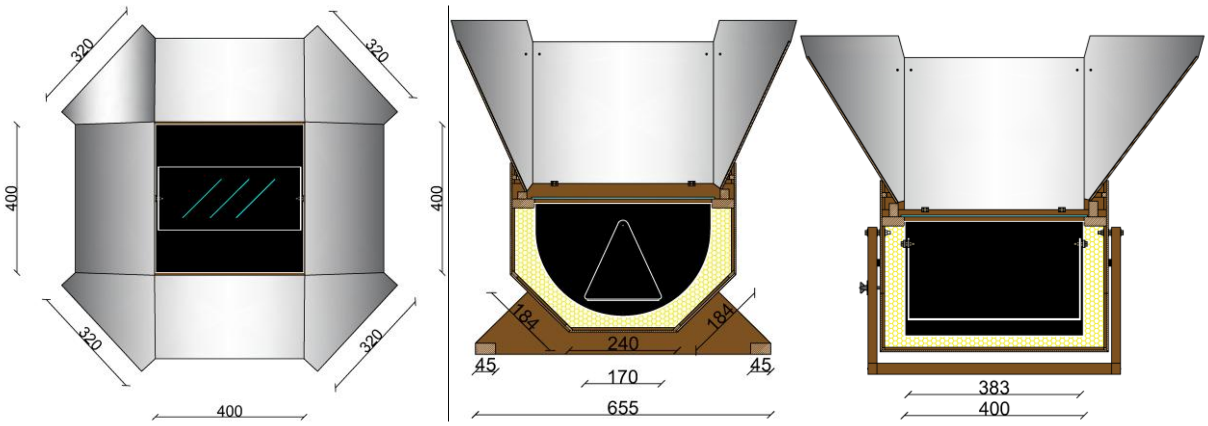

Figure 1. Views and cross-sections of the solar cooker prototype.

The box has a glass cover on the top, which allows solar radiation to be transmitted to the absorber.

The cover is made of tempered glass, which is high resistant and suitable for solar thermal applications (transmittance of about 0.90) and can be easily removed to insert food/pots in the cooking chamber.
The higher part of the box is surrounded by 8 booster mirrors. 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 mirrors guarantee an overall reflection of about 0.94. The mirrors 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:

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

Additionally, the prototype has two border wooden hands that allow both its movement 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 has a maximum height of 0.753 m and a mass of about 20 kg. Its overall cost is around 300 EUR; the aluminum foils are the most expensive items. The overall time required by one specialized and two non-specialized workers to realize the whole prototype is about 50 hours.

3. TEST BENCH

The solar box cooker prototype was characterized adopting the test bench reported in Figure 2.

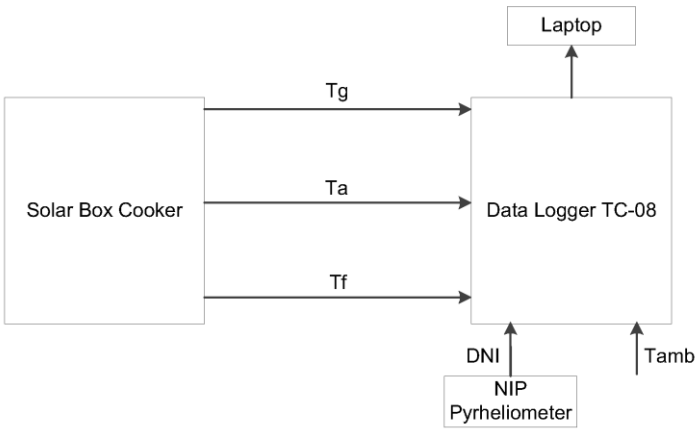

Figure 2. Solar box cooker test bench.

K-type thermocouples were used to measure temperature of ambient air (T_{amb}) and in two points of the cooker: the glass cover (T_g) and the absorber (T_a). The testing fluid temperature (T_f) was measured with a T-type thermocouple.
The direct normal irradiance, *DNI*, was measured through a first-class normal-incidence pyrheliometer (NIP) mounted on a solar tracker. Since the solar box prototype considered in this work has a quite high concentration ratio and, hence, it is not able to exploit diffuse solar energy [10], only direct solar radiation was measured.

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

4. EXPERIMENTAL TESTS AND RESULTS

Experimental tests were carried out on the DIISM roof (latitude 43.5867 N, longitude 13.5150 E). The cooker orientation was adjusted about every 5-10 minutes, to guarantee a correct alignment with the sun. Two kinds of experimental tests were conducted: with and without load. Tests without load allowed to evaluate the maximum temperature reachable by the solar box cooker.

Tests with load, instead, were accomplished inserting in the cooker 2 kg of water contained in a cylindrical aluminum vessel having 18 cm diameter and 12 cm height. The vessel included a lid with a small hole, used to let the insertion of a T-type thermocouple.

4.1. Tests without load

Three tests without load were carried out under different environmental conditions. A summary is provided in Table 1. The first figure of merit, F_1, is defined as [11]:

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

where $T_{a,max}$ is the maximum temperature reached by the absorber, while T_{amb} and DNI are, respectively, the corresponding ambient temperature and direct normal irradiance measured when the stagnation temperature is reached. For the solar cooker under study, the average F_1 was found to be equal to 0.19 °C/(W/m^2).

Table 1. Tests without load.

Day	T_{amb} (°C)	T_a (°C)	DNI (W/m^2)	F_1 (°C/(W/m^2))
23/05/2017	29.39	197.30	839.71	0.20
09/06/2017	23.39	187.42	971.75	0.17
13/06/2017	31.27	189.10	841.24	0.19
Mean				0.19

As an example, Figure 3 shows the temperatures and the solar radiation detected during the last test.

4.2. Load tests

Table 2 reports the results obtained through three load tests, while Figure 4 depicts the temperatures and the solar radiation detected on September 14, 2017.
In order to characterize the cooker performance under load, several parameters (provided in Table 2) were calculated based on the obtained experimental data. The first parameter was the time required to take the water temperature from T_1 to T_2, Δt. This parameter was used to derive the specific boiling time, t_s, defined as the time required for a cooker of aperture area A_a to take 1 kg of water from T_1 to T_2 [12]:

$$\Delta t_s = \frac{\Delta t * A_a}{m_f} \tag{3}$$

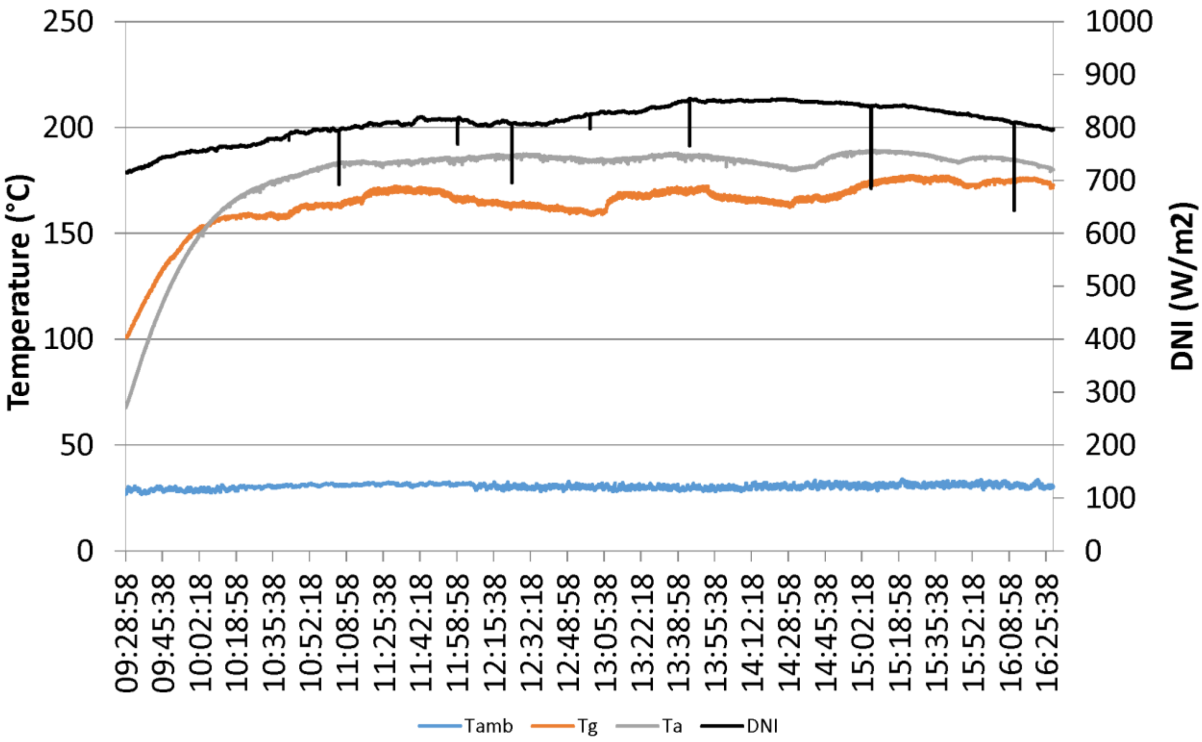

Figure 3. Test without load (13/06/2017).

Table 2. Tests with load.

Quantity	Test 01	Test 02	Test 03
Day	02/08/2017	14/09/2017	22/09/2017
$T_{amb,av}$ (°C)	36.59	25.00	22.42
DNI_{av} (W/m^2)	736.84	865.07	890.50
m_f (kg)	2	2	2
T_1 (°C)	40	40	53
T_2 (°C)	90	90	90
Δt (s)	5223	6063	5153
t_s (min m^2/kg)	29.64	34.41	29.24
t_c (min m^2/kg)	24.27	33.07	28.93
η_{av}	0.16	0.12	0.10
F_2	0.20	0.16	0.14

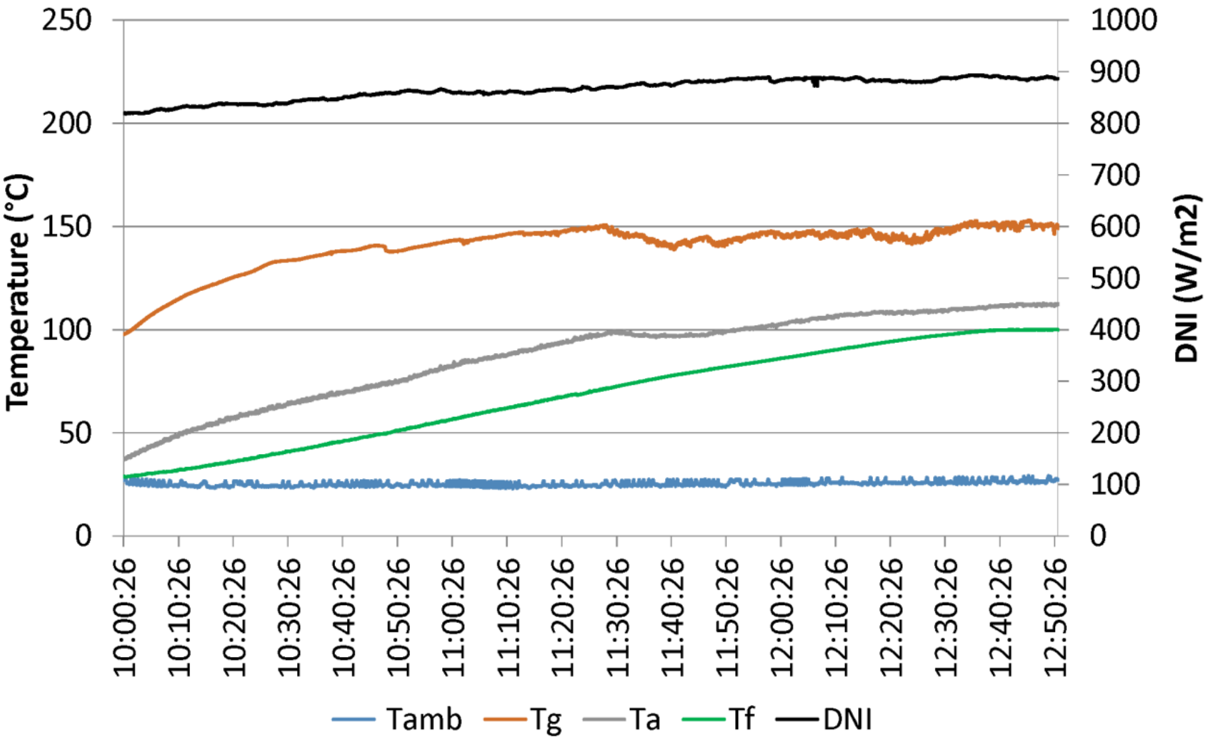

Figure 4. Test with load (14/09/2017).

where m_f is the mass of testing fluid. Another parameter is the characteristic boiling time, t_c, generally used for making comparisons between various solar cooker designs under different solar radiation levels [12]:

$$\Delta t_c = \frac{\Delta t_s * DNI_{av}}{DNI_{ref}} \tag{4}$$

where DNI_{av} is the average direct normal irradiance during the time interval Δt, while DNI_{ref} is a reference direct normal irradiance equal to 900 W/m^2.
The average overall solar cooker thermal efficiency is [12]:

$$\eta_{av} = \frac{m_f * c_f * (T_2 - T_1)}{DNI_{av} * A_a * \Delta t} \tag{5}$$

where c_f is the specific heat of water.

Finally, the 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 [11]:

$$F_2 = \frac{F_1 * m_f * c_f}{A_a * \Delta t} \ln\left[\frac{1 - \frac{1}{F_1}(T_1 - T_{amb,av}) / DNI_{av}}{1 - \frac{1}{F_1}(T_2 - T_{amb,av}) / DNI_{av}}\right] \tag{6}$$

As can be noted from Table 2, the cooker shows a good thermal performance, which is particularly influenced by the ambient temperature.

5. CONCLUSIONS

This work describes the design, manufacture and test of a prototype of solar box cooker with a concentration ratio of 4.08. The main findings of the work are as follows.

- The cooker is portable and can be manually oriented both in the azimuthal and zenithal planes.
- Experimental tests without load show that the cooker is able to reach a maximum temperature of about 200 °C.
- Tests with load (water) indicate that the prototype has a good thermal performance, being potentially able to cook food fast and at high temperature.

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