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Characterisation and design methods of solar cookers

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Abstract

The use of solar cookers is much needed in many regions with good solar radiation intensity throughout the world. The reasons are economical, as the price of fuel for cooking is no longer affordable by many families; ecological, as in many regions deforestation is also associated with the use of wood as an energy source; and social, as the money used to buy fuel could be used to buy food, medications and other needs to improve the quality of life. Because of the variety of solar cookers that has been presented in the literature, a general procedure to compare these cookers with one another is very complex. This article presents the general types of solar cookers, theirs basic characteristics, and experimental procedures to test the different types of solar cookers. The variables measured in these procedures are necessary to calculate parameters, which are used to compare the thermal performance of the solar cookers. In addition to these experimental procedures, a simplified analytical model is presented to design simple cooking systems. For more complex systems, results are shown and references are indicated in the text.

Keywords: Solar cooker; Solar cooker design; Cooker testing procedures; Solar cooker characterization

1. Introduction

Developing countries have to deal with the lack of appropriate energy supply. Solutions used in industrialized countries are often not applicable, because the differences in the structure of the energy consumption are very big. In industrialized countries, the major part of the total consumption is supplied by fossil fuels, while in some developing nations firewood is the most common energy source and it is mostly used in household applications. In Africa, for instance, house or family consumption can reach 90% of the energy supply (BMWi, 1995), and a detailed look shows that firewood is mainly used for the preparation of food. In Sahel and in the Sudan-region, the consumption of firewood exceeds the growth-rate of the forests. The regions loose about 5% of their forests every year.

In areas with a high population density (urban regions), the supply of firewood is a problem. According to Mainguet (1994) the distance for the transport of wood is 120 km in Bamako (Mali) and 200 km in Khartoum (Sudan). In Ouagadougou (Burkina Faso), the distance is about 150 km. In addition to the ecological problems, firewood became expensive in these regions. Families spend up to 1/3 of their monthly income for firewood and there is not other alternative.

Solar energy can be part of the solution to this problem, if the solar systems can be used to prepare food. The systems have to be fully functional, reliable, and well adapted to the local needs.

2. Approach

To characterize solar cooker and their performance is a complex task due to the various types of cookers available and their operation. The following sections present

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Nomenclature

A	collector area (m^2)
c	specific heat capacity ($J\ kg^{-1}\ K^{-1}$)
h_{fg}	latent heat ($J\ kg^{-1}\ K^{-1}$)
I	incident solar flux on the collector plane ($W\ m^{-2}$)
K_1, K_2	constant
m	mass (kg)
$\dot{m}$	mass rate (kg/s)
$\dot{Q}$	heat power (W)
t	time (s)
U	heat transfer coefficient ($J\ s^{-1}\ K^{-1}$)

Greek symbols

Δ	difference
η	efficiency
η_o	average optical efficiency
θ	temperature difference (K)
∞	ambient

Subscripts

dir	direct
ev	evaporation
glb	global
max	maximum
o	optical
p	pressure
stag	stagnation
w	water

Superscript

c	concentrating

analytical an experimental suggestions that can be used to compare solar collectors.

2.1. Classification of solar cookers

The classification of the solar cookers is based on the type of the collector and the place of the cooking. Four types of solar cookers are presented in Fig. 1 and they are defined as

(a) Flat plate collector with direct use – type A
(b) Flat plate collector with indirect use – type B
(c) Parabolic reflector with direct use – type C
(d) Parabolic reflector with indirect use – type D

In the case of a direct system with a flat plate collector (type A), the cooking pot is placed directly in the collector. In the indirect system (type B), the energy is transported from the collector to the cooking place by a heat-transfer medium. In type C, a parabolic reflector concentrates the sunlight on the cooking pot. Similarly to type B, type D uses a heat-transfer medium, as shown in Fig. 1.

The parabolic reflector works correctly only when it is tracks the sun rays, whereas a flat plate collector may be installed in a fixed position. Indirect systems can use large surface to collect the solar energy efficiently and they do not have any principle limitations of the size. The use of a thermal storage and integration of the cooking place in a house are possible.

A combination of types C and D is a fix-focus parabolic collector (Fig. 2). It is a direct system, although the cooking place can be located inside of a building. The reflector is tracked around one axis during the day with the help of a mechanical clockwork or a small electrical motor powered by photovoltaic cells. The focus is situated on this axis so it does not move. Every month the position of the concentrator has to be fixed again due to seasonal variations.

2.2. Power and efficiency of solar cookers

In order to compare the different types of solar cookers, characteristic values need to be defined. The first two of these values are expressions of power and efficiency.

The average heating-power of a solar cooker is calculated as

$$\dot{Q}_{heat} = \frac{m_W \cdot c_p \cdot \Delta T_{\infty-95}}{\Delta t} \tag{1}$$

where m_w is the mass of water in kg, c_p is the specific heat capacity at constant pressure in J/(kg K), ΔT is the temperature difference in K, Δt is the duration of the measurement in s and the subscript ∞ denotes ambient. Usually this power is measured from ambient temperature up to 95 °C, to avoid uncertainty of the exact boiling-point.

The evaporation-power, $\dot{Q}_{ev}$, is determined during the evaporation of water at boiling point. The heat capacity of the cooker has less influence on the performance, because the system is working at constant temperature. This power is calculated from the measured rate of evaporated mass of water, $\dot{m}_{ev}$ in kg/s, multiplied by the latent heat of evaporation h_{fg} in J/kg,

$$\dot{Q}_{ev} = \dot{m}_{ev} \cdot h_{fg} \tag{2}$$

Efficiency is the power-output divided by the incoming power. The incoming power is the solar radiation I in W/m^2 multiplied by the collector surface A in m^2. For flat plate collectors, the solar radiation is the global radiation on the surface. For parabolic concentrators, it is the direct solar radiation on the aperture surface,

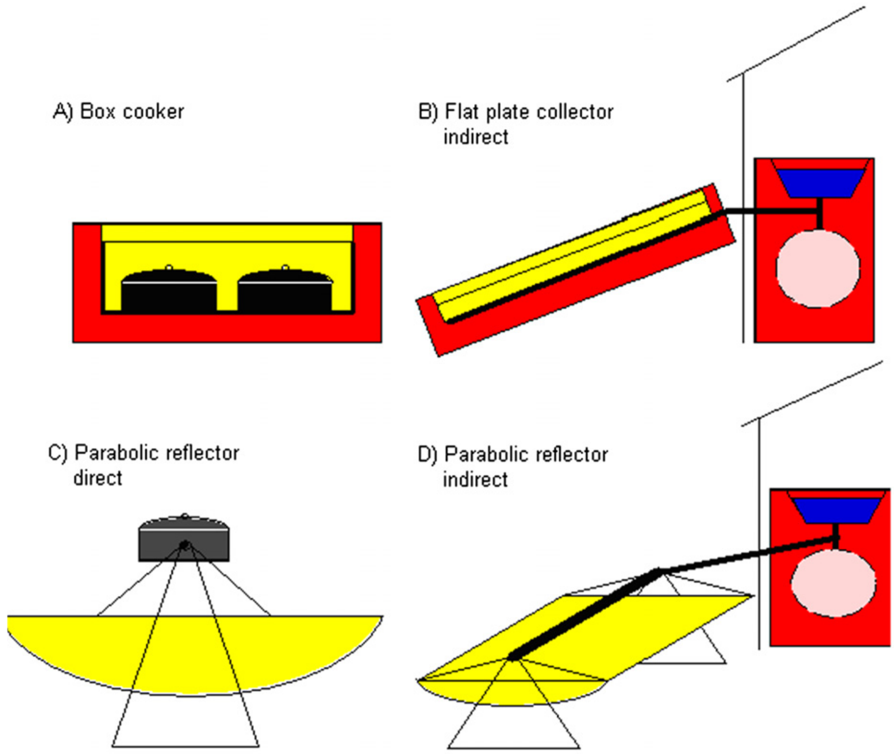

Fig. 1. General types of solar cookers.

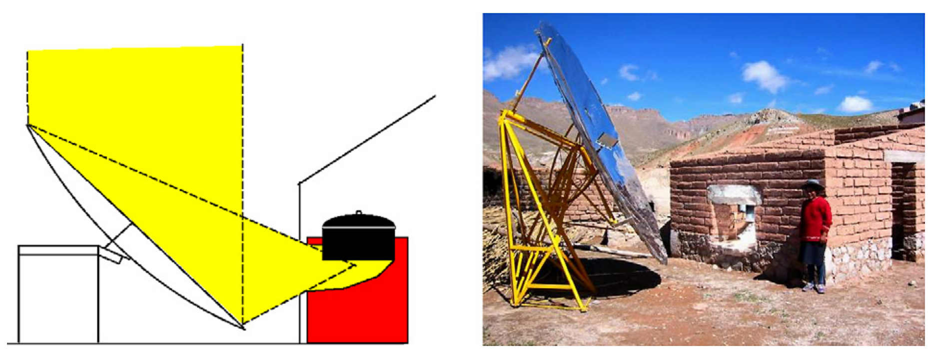

Fig. 2. Fix-focus parabolic collector, a combination of direct and indirect use (type C + D), for an Elementary School in the Altiplano, Argentina.

$$\eta = \frac{\dot{Q}}{I \cdot A} \tag{3}$$

The optical efficiency characterises a property of the system without any thermal losses and it is determined from the value of heating-power near ambient temperature.

The differences in the surface and in the tracking mechanism of different cookers imply that efficiencies are suitable for comparing cookers of the same type. To compare different types of cookers, other parameters, besides efficiency, are needed (ECSCR, 1994). These parameters are

- The *solar cooker tracking period* that indicates how often a solar cooker has to be tracked, or adjusted to the sun's position. To measure the tracking period, water is heated up in the pot until it reaches the boiling point, and the cooker is adjusted to the sun position. The solar cooker tracking period is the time for the temperature to drop below 95 °C.
- The *unattended cooking period* that indicates how long the cooker can work without any intervention of the user. To measure this period, water is heated up in the pot until it reaches the boiling point. The unattended cooking period is the time for the temperature in the pot to drop below 80 °C.
- The *heat losses without solar insolation* that indicates how quickly the solar cooker looses heat when there is no sun. To measure theses losses, the fluid in the pot is heated above 100 °C. The collector is covered by an

opaque screen, and the test starts when the oil reaches 100 °C. The test result is the time during which the temperature is kept above 80 °C. To avoid evaporative losses this test is done with oil.

- The *continuous cooking* that indicates the capacity of continuous cooking in a day. This capacity is measured as the amount of water that can be brought to boiling by a cooker during one day. The test starts in the morning with sunrise and with cold water in the pot. When the temperature reaches 95 °C, the heated water is replaced by cold water. This is continued until the evening. The result is the total amount of water heated.

2.3. Measurement guidelines

When measurements are to be made, it is suggested that the cooking-pots should be filled with 5 kg of water or oil per 1 m^2 of collector surface, and that the average solar radiation should be higher than 800 W/m^2.

For the determination of efficiency over the whole temperature-range, the evaporation-power is not sufficient. At least, power should be determined at two other fixed temperatures. These heating powers may be determined for small temperature rises, for instance 10 K. During this test, when the temperature of the water in the pot has reached its higher value, the water is removed and the pot filled with water at the lower temperature. Water should be stirred to avoid stratification. For temperatures above 100 °C, oil should be used instead of water, observing its self ignition temperature.

Another important value is the stagnation temperature of the collector. To measure this temperature, oil or a piece of metal is placed in the cooking pot and heated. When the temperature does not increase for a longer period of time, for example 10 min, the standstill temperature is reached. At this temperature, the losses of the collector are the same as the energy gain and the power output of the system is zero. The stagnation temperature may also be estimated by measuring the temperature in the pot after 130 min.

2.4. Design of solar cookers

Some basic equations are necessary to design solar cookers. Although this procedure is not sufficient for complex systems, it can be applied to most of the simple solar cookers (Types A and C). All needed parameters can be determined from the test results presented.

The solar cooker is a storage-collector without any power transported out of the system. The energy balance in this system can be written as

$$m \cdot c_p \frac{d\theta}{dt} = \{\eta_0 \cdot I - U \cdot \theta\} \cdot A \tag{4}$$

where m is the mass in the pot in kg, c_p is the specific heat capacity at constant pressure in J/(kg K), θ is the temperature difference between the pot content and the ambient in K, η_o is the optical efficiency, I is the global solar radiation in W/m^2, U is the thermal loss coefficient in $W/(m^2\,K)$, and A is the collector aperture surface in m^2.

The optical efficiency is determined from the experimental tests presented. The thermal loss coefficient can be calculated from the data of the heat-loss test as

$$U = \frac{m \cdot c_p}{t_{end} - t_{start}} \ln \frac{\theta(t_{start})}{\theta(t_{end})} \tag{5}$$

where t is in seconds. It may also be calculated from the optical efficiency and the stagnation temperature as

$$U = \frac{\eta_o \cdot I}{T_{stag}} \tag{6}$$

In the last two equations, a constant solar radiation value is assumed. For simplicity, two constants are defined. For the flat plate collector with the global solar radiation I_{glb}, these are

$$K_1 = \frac{I_{glb} \cdot \eta_o \cdot A}{m \cdot c_p} \tag{7}$$

$$K_2 = \frac{k \cdot A}{m \cdot c_p} \tag{8}$$

For concentrating collectors, the direct solar radiation is used for K_1

$$K_1^C = \frac{I_{dir} \cdot \eta_o \cdot A}{m \cdot c_p} \tag{9}$$

whereas K_2 has the same expression. The solution of Eq. (4) is

$$\theta(t) = \frac{K_1}{K_2}(1 - e^{-K_2 \cdot t}) \tag{10}$$

The time that the cooker needs to heat an amount of water with a given temperature difference θ_{heat}, is then,

$$t_{heat} = -\frac{1}{K_2} \ln\left(1 - \frac{K_2}{K_1}\theta_{heat}\right) \tag{11}$$

2.5. Design of a complex system

As already mentioned, this simplified calculation is not suitable for complex systems especially when they are equipped with a storage tank. The equations help in the design, but they cannot replace a detailed analysis. A very comfortable way to do this analysis is to use a simulation model of the system. Such a model, computer program, has been developed for the Sunfire cookers and presented by Hafner (1999). The program permits the dynamic analysis of different heat sources and loads. It is based on TRNSYS but is also available for MATLAB-Simulink. A study for a community kitchen in a school in Tiger Kloof, in South-Africa, has been carried out by Dessel (1999). Different combinations of the components have been examined in a parameter study on the computer. In the analysis, it was shown that the configuration with a 20 m^2 flat plate collector, a pebble-bed-storage and a 250 l hot-water-storage has the lowest consumption in backup-energy. The size of the pebble bed storage influenced the system performance. A volume of 1000 l was an optimum size. In 2001, a large cooking system, following the principles of the Schwarzer cooker, was designed for 200 people and installed in an Elementary School Nicaragua. The system had three pots, one pan, and an additional 100 l hot water tank was connected to the system. This system is also used in baking.

3. Results and discussion

To exemplify the testing procedures presented, a solar cooker similar to those presented by Schwarzer and co-workers (Schwarzer and Silva, 2003; Hafner, 1999; Schwarzer and Krings, 1996) was tested (Fig. 3). The characteristics of this cooker are indirect heating which allows indoors or outdoors cooking, one 1.7 m^2 flat plate collector, two 8 l cooking pots and no storage tank. For the average values during the test period: global radiation 900 W/m^2, direct radiation 750 W/m^2 and 5 kg of water per 1 m^2 of collector surface, the period of time to heat up water from 20 °C to boiling was approximately 60 min. The continuous cooking test indicated that approximately 32 kg of water were brought to boiling in one day. If the system is hot, what normally occurs at daytime, the boiling time is about 15 min. The effect of the tracking can be seen in parabolic and fix-focus cookers, which uses the sun optimal from morning till evening whereas the simple parabolic cooker reflects some light on the pot-lid in morning- and evening-position (see Figs. 4–7).

This article presents the most common types of solar cookers that have been presented in the literature; experimental procedures to be used to calculate parameters, which determine the thermal performance of the solar cookers; and also a simplified procedure based on

Fig. 3. Photographs of the solar cooker with indirect heating made and tested in Northeast Brazil (1.7 m^2 solar collector, without storage tank, for outdoor use).

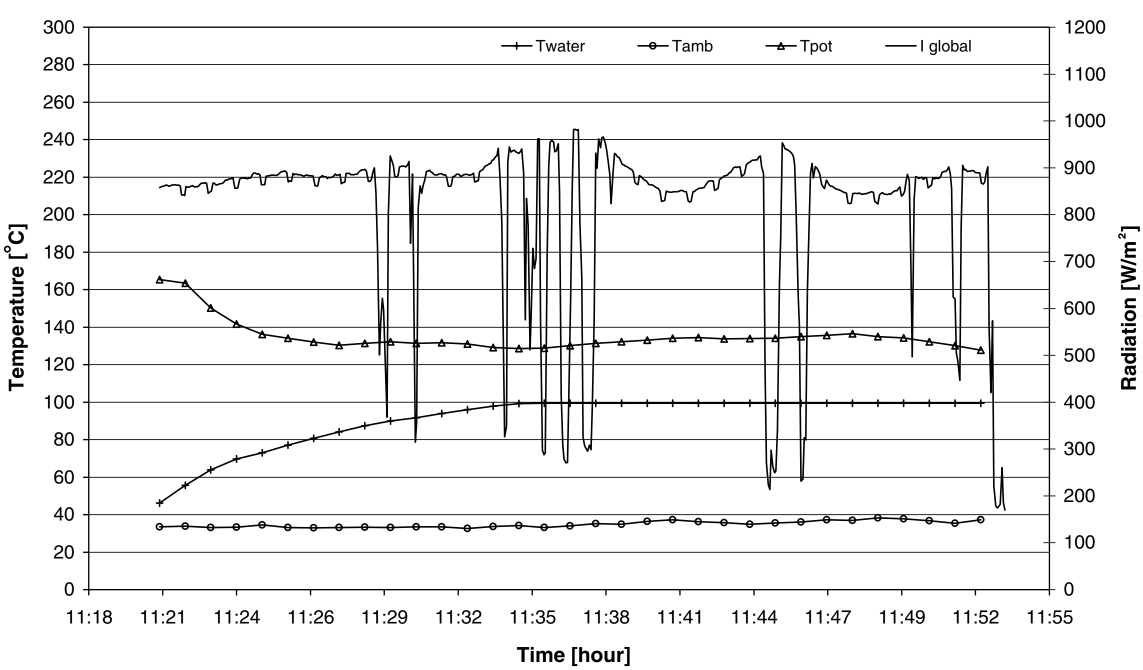

Fig. 4. Hot start field test for a solar cooker with indirect heating, for an average radiation of 837 W/m^2.

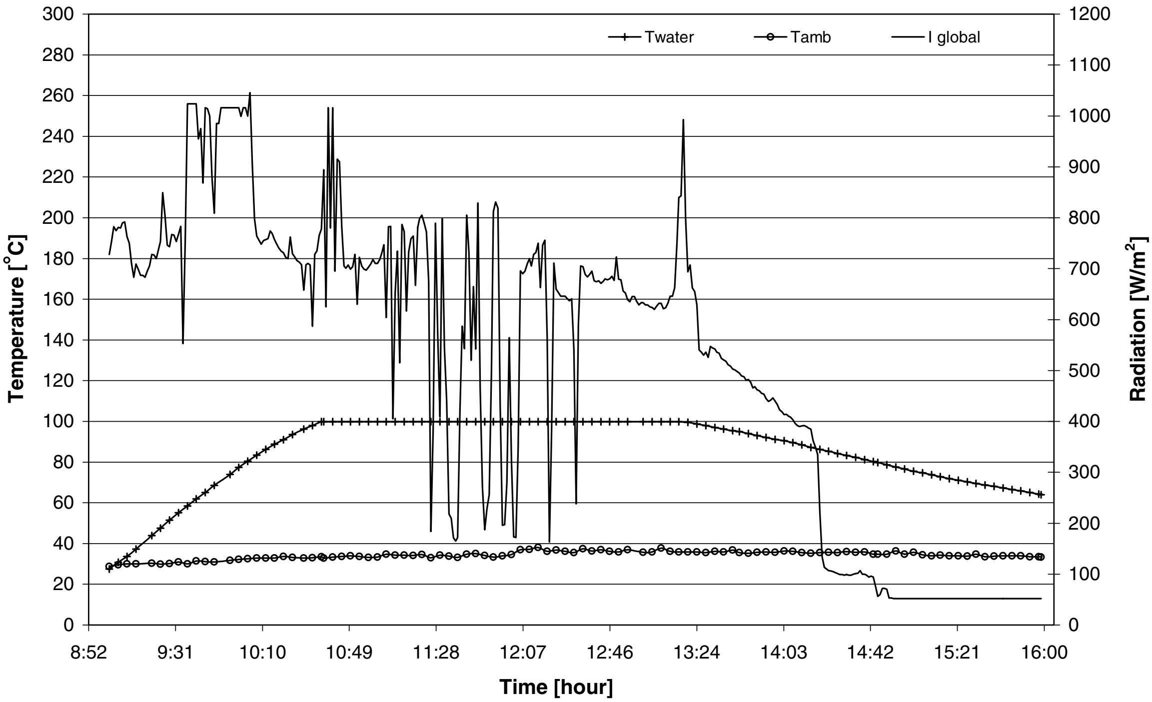

Fig. 5. Field test, with re-orientation of collector, for the solar cooker shown in Fig. 3, for an average radiation of about 700 W/m^2.

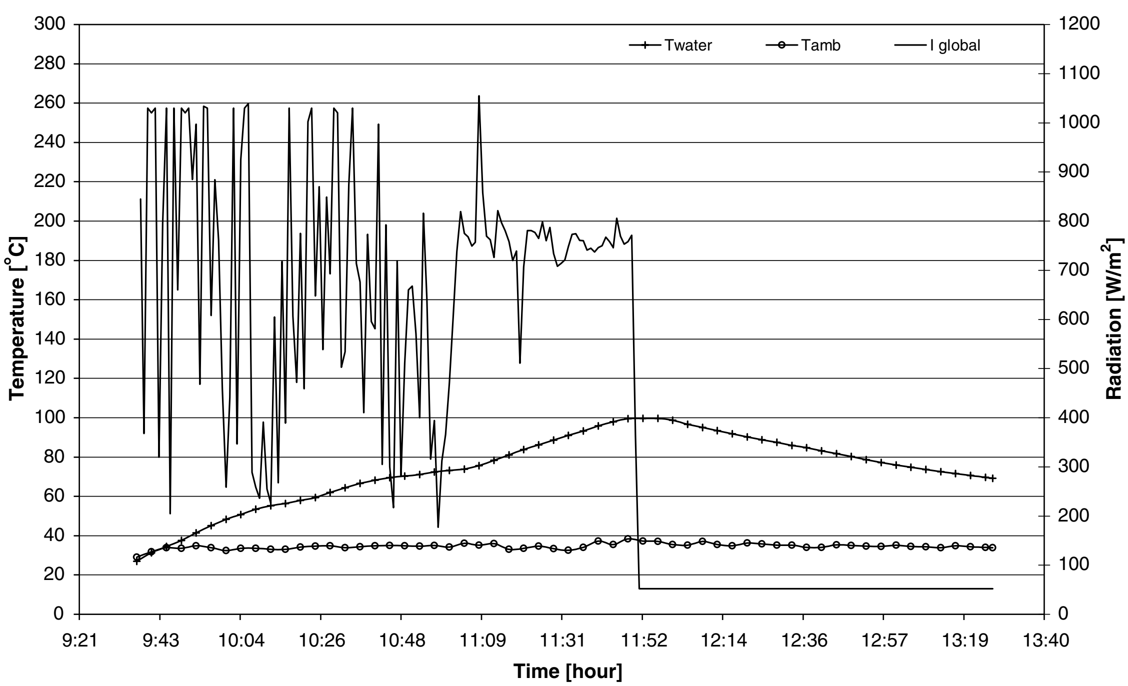

Fig. 6. Heat losses without insolation field test. At 11:50 h, the collector was covered (side reflectors were closed), allowing no radiation to reach the absorber plate.

energy balance equations to help design solar cookers. For more complex cooking systems, references are presented.

In order to have a more complete view of solar cookers, in addition to thermal tests, other friendliness and handling characteristics are necessary. These characteristics are safety of operation to avoid burning and other risks; easiness of transportation and assembly; tracking requirements and procedures; pot access and easiness of stirring; mechanical stability; robustness and life time. All these characteristics are to be considered when installing a cooker in community.

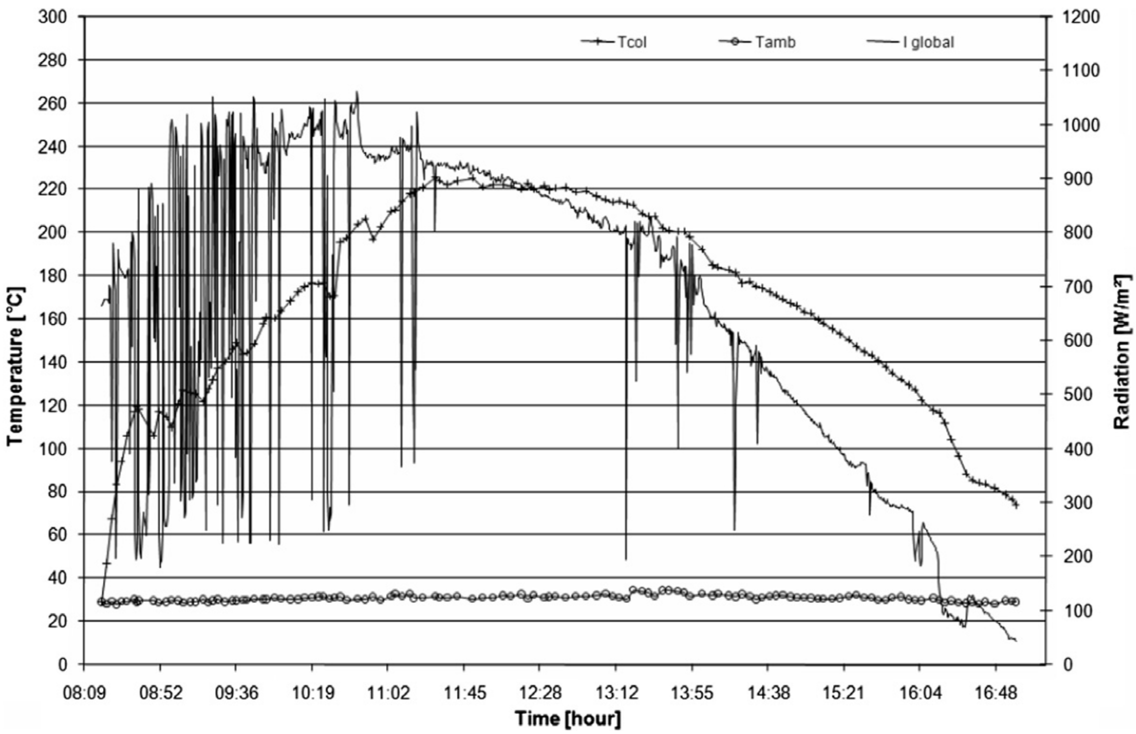

Fig. 7. Stagnation temperature field test (225 °C at 11:30 h) for the solar cooker.

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