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Design, manufacturing, and test of a high concentration ratio solar box cooker with multiple reflectors

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ABSTRACT

Solar cooking is considered one of the most attractive ways to utilize solar energy. Therefore, in this work a high concentration ratio (11.12) solar box cooker prototype was manufactured and tested. The cooker has a cooking chamber with a glass cover on the top and is composed by two rows of booster mirrors. The prototype allows both an azimuthal and zenithal manual orientation. A test bench used to characterize the cooker performance is then described. Experimental tests without load were carried out to evaluate the maximum cooker temperature. Tests with load, conducted using aluminum vessels containing a certain amount of water, were accomplished with both standard vessels and black ones, and with one or two vessels. Additional tests were carried out with peanut oil. Using this fluid, temperatures higher than the water ones were achieved (>200 °C). Results show that the cooker is able to cook at high temperature with good optical efficiency and thermal insulation.

1. Introduction

Solar energy is the most abundant permanent energy resource on earth. Among the applications of solar thermal energy, solar cooking is considered as one of the simplest and attractive ways of the utilization of solar energy (Cuce and Cuce, 2013). Energy for cooking is one of the fundamental uses in developing countries. Wood is still the primary energy source in most of those countries because of its cheapness; this situation is responsible for some serious ecological problems, especially deforestation. 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 (Pohekar et al., 2005).

However, considering that in most of the developing countries of the world there is abundance of solar radiation (a mean daily solar radiation of 5–7 kW h/m^2 and more than 275 sunny days in a year have been estimated (Nahar, 2003)), it is clear that solar cookers represent in such countries a possibility to meet the energy demand in the domestic sector. Unfortunately, the large-scale dissemination of solar cookers still remains limited; these devices are diffused all over the world, but most of them are intended for research purposes only (Yettou et al., 2014). 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 (Muthusivagami et al., 2010).

In the last decades, solar box cookers demonstrated to be commercially successful and showed considerable developments in terms of design and performance (Cuce and Cuce, 2013). A solar box cooker consists of 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 usually 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.

Technical literature regarding solar box cookers, and small solar box cookers in particular, is very ample. However, according to our knowledge, there are no box cooker prototypes with high concentration ratios tested at high temperatures (fluid temperature > 200 °C), as the one described in this paper. Thus, we decided to report here only literature works showing experimental methods and parameters generally used to characterize solar box cookers, together with some works reporting experimental data obtained according to those methods/parameters.

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Nomenclature

Latin symbols

A	area (m^2)
C	concentration ratio
COR	cooker opto-thermal ratio (°C/(W/m^2))
c	specific heat (J/(kg °C))
DNI	direct normal irradiance (W/m^2)
F'	heat exchange efficiency factor
F_1	first figure of merit (°C/(W/m^2))
F_2	second figure of merit
G	global solar radiation (W/m^2)
m	mass (kg)
P	cooking power (W)
R^2	coefficient of determination
T	temperature (°C)
t	time (s)
U_L	overall loss coefficient (W/(m^2 °C))

Greek symbols

Δ	delta difference
η	thermal efficiency
η_o	optical efficiency
θ	inclination angle (°)

Subscripts

a	absorber, aperture
air	air
amb	ambient
av	average
c	characteristic
cs	circular segment
dod	dodecagon
f	fluid
g	glass
i	inner
m	mirror
max	maximum
o	outer
ref	reference
s	specific, standard
x	stagnation

Acronyms

DIISM	Department of Industrial Engineering and Mathematical Sciences
EUR	Euro
HWB	Hottel-Whillier-Bliss
NIP	Normal Incidence Pyrheliometer
UNIVPM	Marche Polytechnic University
UV	Ultraviolet

The first and simplest parameter used to characterize a cooker performance is the time required to reach the fluid evaporation, Δt, also referred to as cooking time. This time was used to derive the specific boiling time, defined by Khalifa et al. (1985) as:

$$t_s = \frac{\Delta t A_a}{m} \tag{1}$$

where A_a is the aperture area of the cooker and m is the mass of fluid. Another parameter is the characteristic boiling time (Khalifa et al., 1985):

$$t_c = t_s \frac{G_{av}}{G_{ref}} \tag{2}$$

where G_{av} is the average solar radiation during the time interval Δt, while G_{ref} is a reference solar radiation equal to 900 W/m^2. The characteristic boiling time can be used as a parameter for making comparisons between various solar cooker designs under different solar radiation levels.

The average overall solar cooker thermal efficiency is (Khalifa et al., 1985):

$$\eta_{av} = \frac{m c \Delta T}{G_{av} A_a \Delta t} \tag{3}$$

where c is the fluid specific heat and ΔT is the temperature difference between the maximum cooking fluid temperature and the ambient temperature. In their work, Khalifa et al. (1985) designed and tested three different types of solar cookers: two point-focusing arrangements (called Reyadh and Arafa), two box types (Mina-1 and Mina-2), and one indirect heat pipe cooker (Mecca). All prototypes were tested with both water and olive oil, but unfortunately the above mentioned parameters were determined only for water. In particular: Reyadh was able to heat 6 kg of water with an overall efficiency of 0.152 and a t_c of 35.6 min m^2/kg; Arafa boiled 1 kg of water with an efficiency of 0.200 and a t_c of 23.5 min m^2/kg; Mina-1 and 2 were tested with 0.45 kg of water and revealed a η_{av} of 0.230/0.212 and a t_c of 22.7 min m^2/kg and 27.0 min.m^2/kg, respectively.

As regards indirect solar cookers, Esen (2004) proposed a cooking system using vacuum-tube collectors with heat pipes containing a refrigerant as heat transfer fluid. Experiments were conducted during clear days in Turkey. The maximum temperature obtained in a pot containing 7 l of edible oil was 175 °C, while the cooking processes were performed in 27–70 min time periods. According to the author, the proposed system is more expensive and complex than conventional concentrators and box cookers, however cooking can take place inside and there is no risk of being blinded by concentrated sunlight.

Mullick et al. (1987) introduced the first figure of merit, F_1, which is defined as:

$$F_1 = \frac{T_{a,max} - T_{amb}}{G} \tag{4}$$

where $T_{a,max}$ is the maximum temperature reached by the absorber, while T_{amb} and G are, respectively, the corresponding ambient temperature and solar radiation measured when the stagnation temperature is reached.

In addition to the first figure of merit, Mullick et al. (1987) introduced a second figure of merit, F_2, which involves the temperature increase measurement with time of a known amount of fluid placed in the cooker. It is defined as:

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

where Δt is the time interval during which the fluid temperature rises from T_1 to T_2, while G_{av} and $T_{amb,av}$ are, respectively, the average solar irradiance and the average ambient temperature over the time interval Δt. Mullick et al. (1987) found the experimental F_1 and F_2 of a solar box cooker with the outer wall made of teak wood and the inner wall of a thin aluminum sheet. The cooker has a glass