Energy for Sustainable Development 29 (2015) 65–71

Contents lists available at ScienceDirect

Energy for Sustainable Development

Experimental analysis and simulation of the performance of a box-type solar cooker

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ARTICLE INFO

Article history:
Received 1 April 2015
Revised 27 July 2015
Accepted 29 September 2015
Available online xxxx

Keywords:
Solar cooker
Box type
Heat transfer model
Experimental validation
Convective coefficient

ABSTRACT

A box-type solar cooker was tested and modelled during a long time period in Madrid (Spain). The experimental data were employed to obtain the convective coefficients of the heat transfer model proposed. The model was validated with experimental data, obtaining results with a relative error under 4% during a whole month of temperature measurements. The model was also employed to simulate the performance of the solar cooker for a year in several countries around the world, estimating the number of days per year in which the solar cooker can be operated in each location. The results obtained from the model informed of the high potential of solar cooking in developing countries.

Introduction

In developing countries, one of the major energy consuming sectors is cooking. The energy needed for cooking is mostly supplied by wood in rural areas, although dung, kerosene, liquefied petroleum gases (LPG) or biogas could also be employed in some locations (Reddy, 2003). Wood is usually burned in inefficient stoves. Bansal et al. (2013) presented data of several models of wood stoves, obtaining an average energy released during cooking of 1.22 kWh and an average efficiency of 25%, which is in accordance with Anozie et al. (2007). However, the use of wood as a primary fuel for cooking may cause serious environmental problems in these zones, such as deforestation (Cuce and Cuce, 2013). In rural zones, wood combustion produces smoke that pollutes the indoor air, causing a wide variety of respiratory diseases in this population. The World Health Organization (WHO) reported that 1.6 million deaths per year are attributed to indoor air pollution. Nevertheless, most of the developing countries and the highly populated countries in the world count on abundant solar radiation with an average daily solar energy in the range of 5–7 kWh/m^2 and more than 275 sunny days per year (Muthusivagami et al., 2010). Thus, solar energy may be employed as an alternative to wood for cooking in these areas. Solar cookers have various advantages like the use of clean energy, non-pollutant emissions, low running costs and high nutritional value of the food cooked (Lahkar and Samdarshi, 2010).

Solar cookers can be divided into three main groups: solar ovens (typically box-type), parabolic reflector cookers and indirect cookers. Indirect cookers are usually more expensive, and parabolic reflector cookers present some inherent defects: reorientation towards the sun is required every 10 min, cooking can only be done in the middle of the day and only in direct solar radiation, dust and wind have a great effect on the cooker's performance and a risk of burning for the operator of the cooker. Box-type solar ovens can reduce the risks and simplify the operational requirements of the parabolic reflector cookers (Nahar, 1990), being especially suitable for rural areas. Suharta et al. (1998) performed cooking experiments in a solar oven using a wide variety of foods, obtaining cooking times of around 1–2 h at temperatures of around 100 °C.

Several authors have analysed experimentally the performance of box-type solar cookers (Harmin et al., 2010; Nahar, 1990; Mahavar et al., 2013; Sethi et al., 2014; El-Sebaii and Ibrahim, 2005; Purohit, 2010), while other authors have focused on estimating the temperatures of the solar cookers through heat transfer models (Reedy and Rao, 2008; Binark and Türkmen, 1996). Nevertheless, both the experimental results and those obtained from the models reported in the literature consider a reduced time, typically between 1 and 4 h. In this study, a simple heat transfer model of a box-type solar cooker is proposed and validated by experiments carried out in Madrid (Spain), obtaining the convective coefficients required for the heat transfer model. The results obtained from the model are compared to experimental measurements taken during the whole month of August, obtaining a good agreement. Finally, once the model was validated by the experimental data, the model was employed to simulate the performance of the box-type solar cooker in different countries around the world, using the hourly solar radiation and external air temperature obtained from Energy Plus Weather Data for a whole year.

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http://dx.doi.org/10.1016/j.esd.2015.09.006
0973-0826/

Nomenclature

A	Area [m^2]
C	Specific heat [J/kg K]
E_{food}	Energy supplied to food [J]
h_{e}	Convective coefficient: external surface of the wall to ambient [J/m^2 K]
h_i	Convective coefficient: internal surface of the wall to interior air [J/m^2 K]
h_{p}	Convective coefficient: absorber plate to interior air [J/m^2 K]
I	Solar radiation [W/m^2]
k	Thermal conductivity [W/m K]
L_i	Lower heating value [J/kg]
L_o	Longitude [°]
m	Mass [kg]
m_{wood}	Mass of wood saved [kg]
N_{days}	Number of days with an absorber temperature over 100 °C [–]
Nu	Nusselt number [–]
Pr	Prandtl number [–]
Ra	Rayleigh number [–]
t	Time [s]
th	Thickness [m]
th$_{\text{ag}}$	Distance between the two glass covers [m]
T	Temperature [K]
Greek symbols	
α	Plate absorptivity [–]
ϕ	Latitude [°]
η_{stove}	Mean efficiency of wood stoves [%]
τ	Glass transmissivity [–]
Subscripts	
ia	Interior air
ap	Absorber plate
c	Cork
e	External air
g	Glass
w	Wood

Experimental procedure

A box-type solar cooker was built and tested. The solar cooker was made of wood, using cork in the interior as an insulator. The absorber employed was a black steel plate of 0.6 m in length and 0.4 m in width. Solar radiation can enter the cooker through a double-glazed window with a cavity of 1 cm. The glazed window was tilted 30° upwards from the horizontal plane. The interior surface of the cork was covered with an aluminium sheet to reflect solar radiation to the absorber plate. No external reflector was employed during the tests. A schematic of the solar cooker with the main dimensions is shown in Fig. 1.

Four different temperatures were monitored each minute using type k thermocouples and a data logger TESTO 177-T4: the absorber plate temperature (T_{ap}), the interior air temperature (T_{ia}), the temperature of the interior surface of the wood (T_{w}) and the external temperature (T_{e}). The solar radiation (I) was also measured using a pyranometer EKO Instruments MS-602 every minute. The uncertainty of the measurements was ± 2 W/m^2 for the solar radiation and ± 0.5 °C for the temperatures. The tests were carried out in Madrid (Spain), corresponding to a latitude $\phi = 40.31°$ and longitude $L_o = -3.75°$. The solar cooker was directed towards the south, and no reorientation was carried out during the tests. The measurement system, the accuracy of the different measurements (solar radiation and temperature) and the frequency of the data acquisition were selected to follow the requirements of the solar cooker testing standard described by Funk (2000).

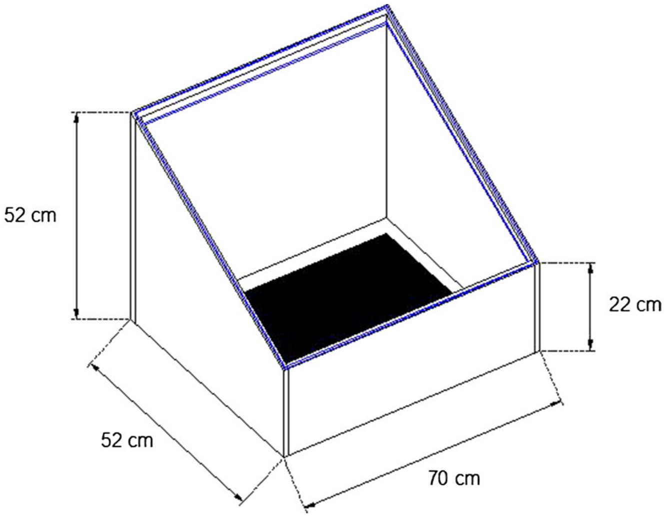

Fig. 1. Schematic of the solar cooker.

Theory

A heat transfer model is proposed to simulate the performance of the solar cooker based on the solar radiation and the external temperature. The theoretical process consists of heat balance relations of various components of the solar cooker, considering the thermal inertia of the components. The model intents to describe, in a simple way, the behaviour of the solar cooker under variable external conditions, i.e., solar radiation and external temperature. The heat exchange mechanisms considered in the model are conduction and convection, neglecting the radiation exchanges. Nevertheless, the convective coefficients were adjusted to match the experimental measurements; therefore, these coefficients would consider both the convective heat transfer and the possible radiation effect. Heat losses due to air interchanges between the interior of the cooker and the atmosphere are also neglected. These assumptions are in accordance with some models available in the literature, already proven to coincide with the experimental data (Reedy and Rao, 2008; Binark and Türkmen, 1996).

Since the interior walls of the solar cooker are covered with a reflecting aluminium sheet, the solar radiation that enters through the double-glazing reaches the absorber plate. The absorber plate releases heat to the air inside the cooker and to the cork located at the bottom of the bed. The heat balance of the absorber plate is shown in Eq. (1):

$$m_{\text{ap}} C_{\text{ap}} \frac{dT_{\text{ap}}}{dt} = I\tau^2 \alpha A_{\text{g}} - h_{\text{p}} A_{\text{ap}} (T_{\text{ap}} - T_{\text{ia}}) - \frac{k_{\text{ap}} A_{\text{ap}}}{\text{th}_{\text{ap}}} (T_{\text{ap}} - T_{\text{c}}) \tag{1}$$

The air inside the solar cooker transfers heat from the absorber plate, to the wall cork and the double-glazed window. Eq. (2) shows the heat balance of the air inside the cooker:

$$m_{\text{ia}} C_{\text{Pa}} \frac{dT_{\text{ia}}}{dt} = h_{\text{p}} A_{\text{ap}} (T_{\text{ap}} - T_{\text{ia}}) - h_i \left[(A_{\text{c}} - A_{\text{ap}}) \cdot (T_{\text{ia}} - T_{\text{c}}) + A_{\text{g}} (T_{\text{ia}} - T_{\text{g}}) \right] \tag{2}$$

In the heat balance of the cork (Eq. (3)), the heat fluxes from the interior air to the wood and from the absorber plate to the bottom of the