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

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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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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$_{ag}$	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

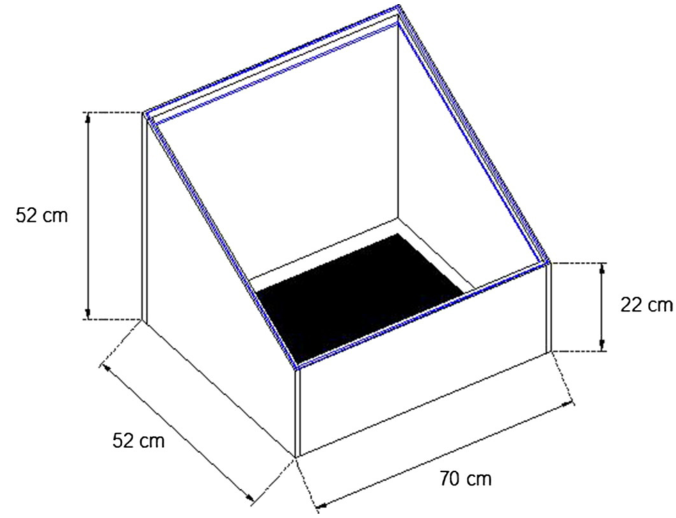

Fig. 1. Schematic of the solar cooker.

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).

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):

$$m_{ap}C_{ap}\frac{dT_{ap}}{dt} = I\tau^2\alpha A_g - h_p A_{ap}(T_{ap}-T_{ia}) - \frac{k_{ap}A_{ap}}{th_{ap}}(T_{ap}-T_c) \tag{1}$$

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:

$$m_{ia}C_{Pa}\frac{dT_{ia}}{dt} = h_p A_{ap}(T_{ap}-T_{ia}) - h_i\left[(A_c - A_{ap})\cdot(T_{ia}-T_c) + A_g(T_{ia}-T_g)\right] \tag{2}$$

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

Table 1
Physical properties of the different components of the solar cooker.

	m [kg]	C [J/kg K]	A [m^2]	th [m]	K [W/m K]
Absorber plate (ap)	5.6	445	0.24	0.003	50
Interior air (ia)	0.13	1000	–	–	0.03
Cork (c)	0.91	1800	1.27	0.004	0.04
Wood (w)	10.2	1250	1.27	0.015	0.15
Glass (g)	1.66	750	0.37	0.003	1.4

cooker are considered:

$$m_c C_c \frac{dT_c}{dt} = h_i (A_c - A_{ap}) \cdot (T_{ia} - T_c) + \frac{k_{ap} A_{ap}}{th_{ap}} (T_{ap} - T_c) - \frac{k_c A_c}{th_c} (T_c - T_w) \quad (3)$$

In the case of the wooden walls, the heat balance (Eq. (4)) considers heat transfer from the cork to the external air. The heat transfer from the internal surface of the wood to the external air is composed of a conduction heat transfer term through the wood and a convective heat transfer term from the external surface of the wood to the atmosphere:

$$m_w C_w \frac{dT_w}{dt} = \frac{k_c A_c}{th_c} (T_c - T_w) - \frac{A_w}{\frac{th_w}{k_w} + \frac{1}{h_e}} (T_w - T_e) \quad (4)$$

Finally, the double-glazing window transfers heat from the interior air of the cooker to the atmosphere. The heat released to the external air is composed of the conduction heat transfer through the double-glazed window and the air in the cavity and the convective heat transfer from the external surface to the atmosphere. The measurement of the cavity (th_{ag}) was fixed to 1 cm so that the Rayleigh number is under 10^3, preventing the confined air to move inside the cavity. Thus, the main heat transfer mechanism in this confined air is conduction (Saxena et al., 2011; Eckert et al., 1996; Duffie and Beckman, 2006). The heat balance for the double-glazed window is shown in Eq. (5):

$$m_g C_g \frac{dT_g}{dt} = h_i A_g (T_{ia} - T_g) - \frac{A_g}{2\frac{th_g}{k_g} + \frac{th_{ag}}{k_{ag}} + \frac{1}{h_e}} (T_g - T_e) \quad (5)$$

The inputs of the heat transfer model are the solar radiation (I) and the external air temperature (T_e), whereas the unknown parameters are the temperature of each component (T_{ap}, T_{ia}, T_c, T_w and T_g). The values employed for the mass (m), specific heat (C), area (A), thickness (th) and thermal conductivity (k) of each component can be found in Table 1.

The transmissivity of the glazing, τ, was considered to be 0.9, and the absorptivity of the absorber plate, α, was 0.8. The convective coefficients between the absorber and the interior air (h_p), from the interior air to the cork or the glazing (h_i) and between the wood or the glazing and the external air (h_e) were obtained fitting the model results to the experimental measurements. The initial conditions needed to solve the equation system (Eqs. (1)–(5)) consist of equalling the temperature of all the components to the external air temperature at $t = 0$ s.

Results and discussion

The convective coefficients required for the heat transfer model were obtained by minimizing the differences between the experimental temperatures and those predicted by the model. This minimization of the discrepancies between the heat transfer model and the experimental data was carried out on a sunny day. Fig. 2 shows the solar radiation (a) and the external temperature (b) on the sunny day selected, June 23.

The solar radiation and the external temperature plotted in Fig. 2 were employed as inputs for the model, obtaining the temperature of each component of the solar cooker. The temperatures of the absorber plate, the interior air and the interior surface of the wood estimated using the heat transfer model were compared to the experimental measurements. The convective coefficients presented in the equations of the model were estimated minimizing the differences between the experimental and simulated values of these temperatures. The optimal values of the convective coefficients were 12 W/m^2 K for the coefficient from the absorber plate to the interior air (h_p), 3 W/m^2 K for the value between the interior air and the interior wall surfaces (h_i) and 4.5 W/m^2 K for the external heat transfer from the walls and the glazed cover to the environment (h_e). The higher value obtained for the absorber plate might be attributed to the effect of the radiation heat exchanged since the absorber plate temperature is the highest temperature of the solar cooker. The low value obtained for the convective coefficient between the interior walls and the air inside the cooker is characteristic of air confined in a cavity, whereas the external coefficient is typical for processes of natural convection. This is in accordance with the experimental procedure, when the incidence of wind over the solar cooker was avoided.

The values obtained for the heat transfer coefficients are in accordance with those obtained by several authors (Thulasi Das et al., 1994; Channiwala and Doshi, 1989; Harmin et al., 2012; Terres et al., 2014). These authors employed the correlation of Churchil and Chu (1975), shown in Eq. (6), to determine the Nusselt number for the natural convection between the external wall of the solar cooker and the atmosphere. In this case, the external heat transfer coefficient obtained using the correlation of Churchil and Chu (1975) is 4.23 W/m^2 K, a similar value to the optimal external coefficient obtained in this work ($h_e =$

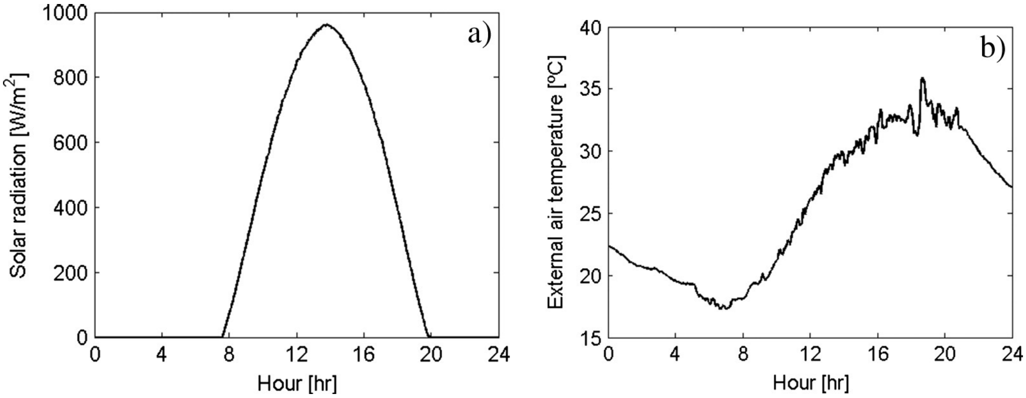

Fig. 2. (a) Solar radiation and (b) external temperature on a sunny day (June 23).

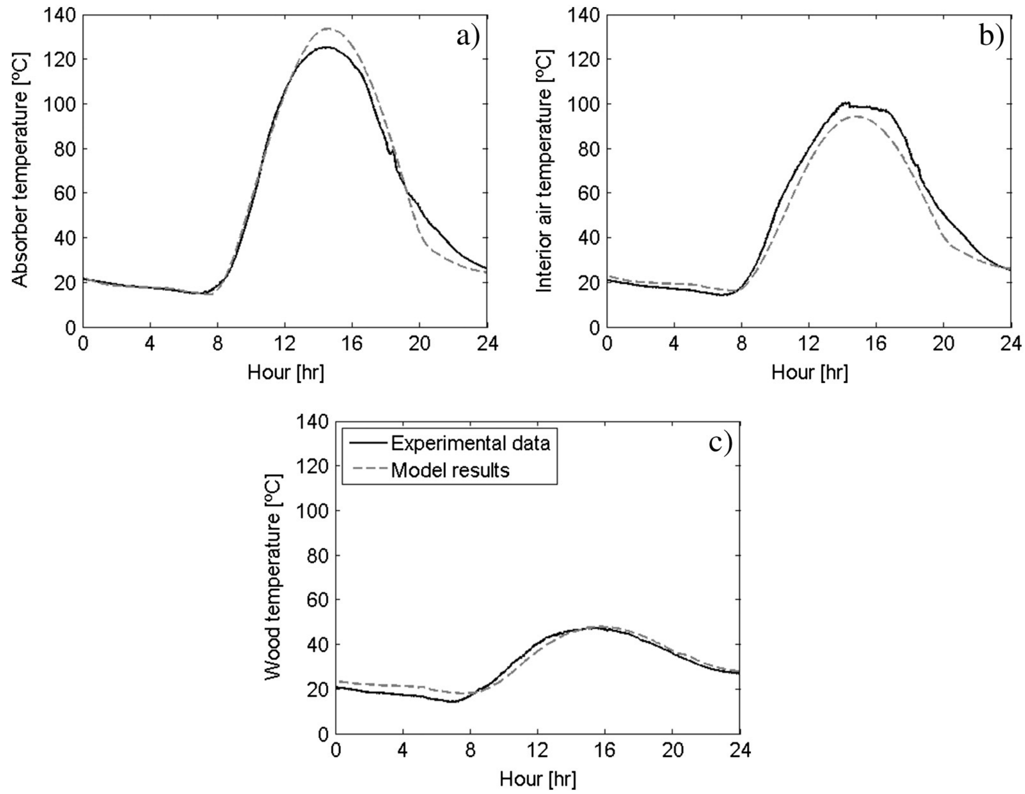

Fig. 3. Comparison between the experimental and simulated temperatures (a) absorber plate, (b) interior air and (c) wood (June 23).

4.5 W/m^2 K). Furthermore, Harmin et al. (2012) used the correlation of Churchil and Chu (1975) to determine the value of convective coefficients inside the solar cooker. The value of the interior convective coefficient obtained using Eq. (6) is 3.6 W/m^2 K, a value slightly higher than that obtained comparing the heat transfer model results and the experimental measurements ($h_i = 3$ W/m^2 K).

$$\mathrm{Nu} = \left[0.825 + \frac{0.387 Ra^{1/6}}{\left[1 + \left(\frac{0.492}{\mathrm{Pr}}\right)^{9/16}\right]^{8/27}}\right]^2 \quad (6)$$

Fig. 3 shows a comparison between the measured temperatures and the temperatures obtained from the heat transfer model. The experimental and simulated temperatures were found to be in good agreement. The values obtained for the temperature of the absorber plate, interior air and wood surface were in accordance with the values reported in the literature for different solar cookers (Harmin et al., 2010; Nahar, 1990; Mahavar et al., 2013; Sethi et al., 2014; El-Sebaii and Ibrahim, 2005; Purohit, 2010).

The validity of the heat transfer model was analysed by comparing the results obtained with experimental measurements on a sunny day with passing clouds. The solar radiation and external temperature on the sunny day with passing clouds (June 27) can be found in Fig. 4. As can be observed, the maximum value of the solar radiation on the day with passing clouds (Fig. 4) is similar to that on the sunny day (Fig. 2); nevertheless, there is a higher variability in this case as an effect of the passing clouds.

The solar radiation and the external temperature of the sunny day with passing clouds, plotted in Fig. 4, were used as inlet parameters in

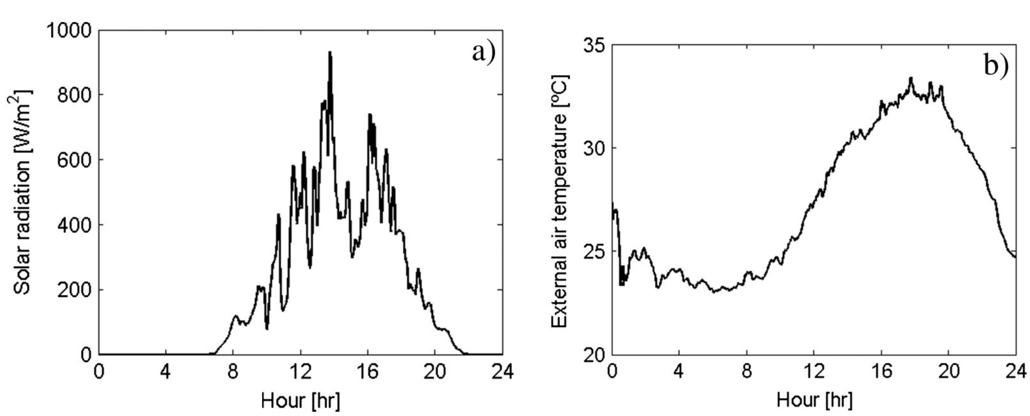

Fig. 4. (a) Solar radiation and (b) external temperature on a sunny day with passing clouds (June 27).

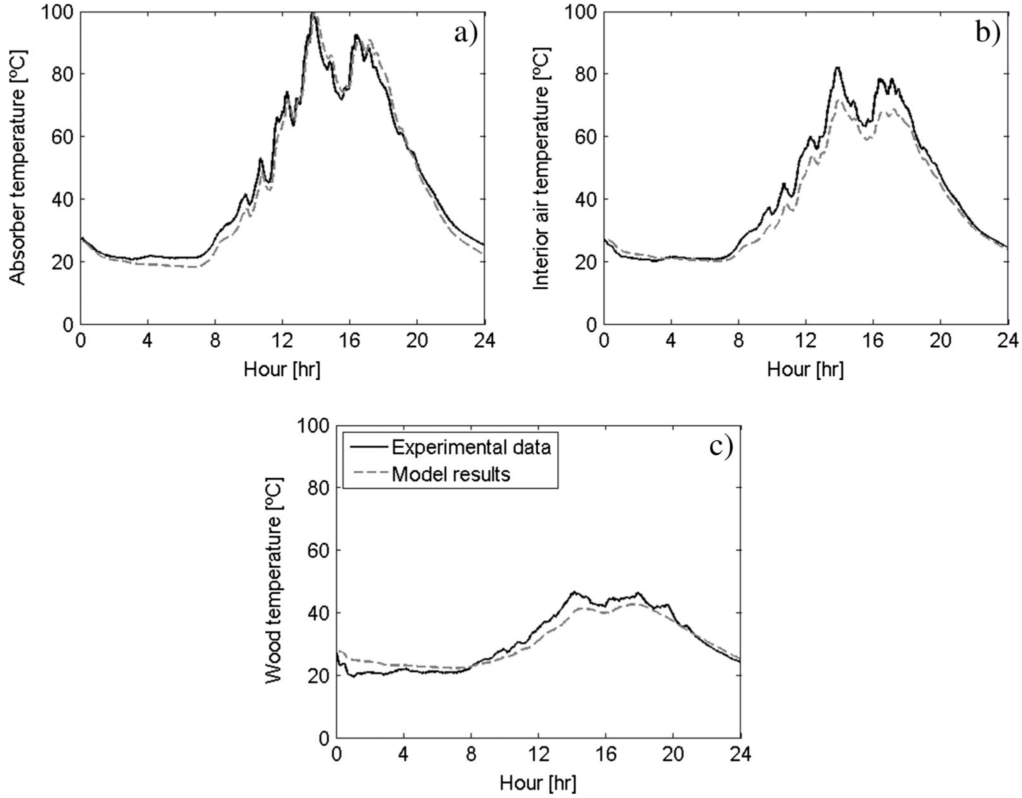

Fig. 5. Comparison between the experimental and simulated temperatures (a) absorber plate, (b) interior air and (c) wood (June 27).

the heat transfer model, calculating the temperature of each component of the solar cooker. The results obtained from the model were compared in Fig. 5 to the measured temperatures, showing a good match of the data. Therefore, the values obtained for the convective coefficients ($h_p = 12$ W/m^2 K, $h_i = 3$ W/m^2 K, $h_e = 4.5$ W/m^2 K) seem to be valid for a wide variety of environmental conditions.

The differences between the model and the experimental data were quantified by calculating the relative error. Fig. 6 shows the relative error for the absorber plate, interior air and wood temperatures for both the sunny day (a) and the sunny day with passing clouds (b). The relative error of the model is lower than 4% in all cases.

The solar cooker was tested during the whole month of August, and the solar radiation and external temperature of each day was employed in the heat transfer model. The maximum relative error of each temperature was computed daily and plotted in Fig. 7. The maximum relative error in the prediction of the absorber plate temperature ranged between 2% and 2.5%, while the maximum discrepancies found for the interior air and the wood temperature varied between 3% and 4%. Therefore, the model was found to be accurate for a wide variety of environmental conditions, i.e., solar radiation and external temperature.

Once the heat transfer model proposed was validated by the experimental measurements, the model was employed to describe the performance of the box-type solar cooker under different environmental conditions in several locations. Hourly values of solar radiation and external temperature, for a wide variety of countries around the world during one year, were obtained from the Energy Plus Weather Data files. This information was introduced as inlet data in the heat transfer model, simulating the operation of the solar cooker for one year in all these locations. The solar radiation coming through the double-glazing cover was considered to be the solar radiation on a horizontal plane, obtained directly from the Energy Plus Weather Database. Nevertheless, optimizing the double-glazing angle for each location, a slight increase in the solar radiation collected by the solar cooker could be obtained.

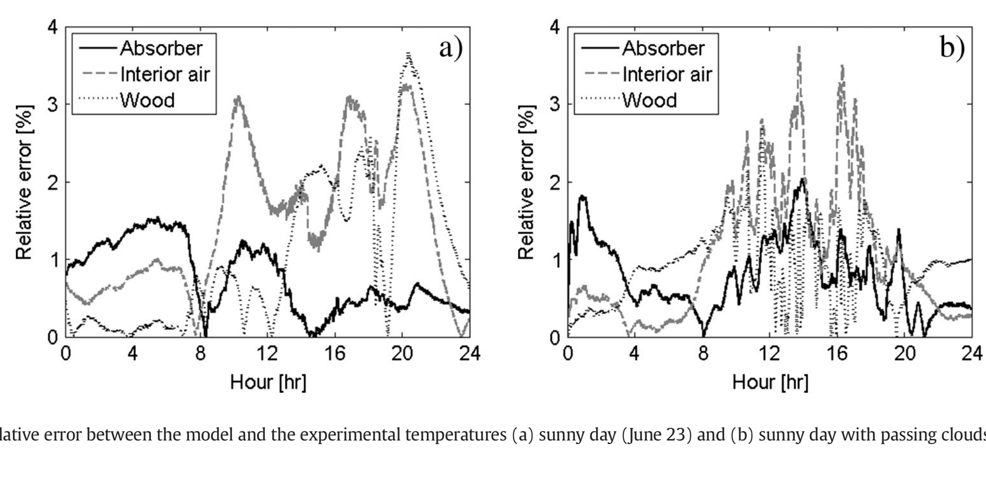

Fig. 6. Relative error between the model and the experimental temperatures (a) sunny day (June 23) and (b) sunny day with passing clouds (June 27).

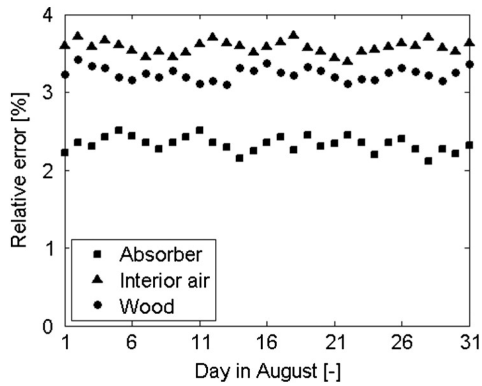

Fig. 7. Maximum relative error between the model and the experimental temperatures measured daily during August.

In order to analyse and compare the performance of the solar cooker in different locations, the number of days in one year in which the absorber plate temperature exceeded 100 °C was calculated, considering this as a condition to be able to cook with the solar cooker since reaching a temperature of 100 °C guarantees that the temperature is over 70 °C for more than 4 h, which is a proper combination of temperature and time to cook several different types of food. Considering solar energy as an alternative of burning wood in stoves for cooking, the mass of wood saved when using the solar cooker in each location can be estimated using Eq. (6). Bansal et al. (2013) studied different models of wood stoves, reporting their efficiency and the energy supplied to the food. The average efficiency of the stoves (η_{stove}), obtained by Bansal et al. (2013) was 25%, which is in accordance with Anozie et al. (2007), and the average energy supplied to the food (E_{food}) was 1.22 kWh. Therefore, these were the values employed in Eq. (7), together with a lower heating value (L_i) for the wood of 12 MJ/kg, to obtain the mass of wood saved in each location. If the solar cooker were to be used as an alternative to a stove using a different fuel, the mass of fuel saved could be determined using Eq. (7), provided that the lower heating value of the fuel (L_i) and the efficiency of the stove (η_{stove}) are known.

$$m_{wood} = \frac{N_{days} E_{food}}{\eta_{stove} L_i} \quad (7)$$

The values of the number of days per year in which the absorber plate temperature is higher than 100 °C (N_{days}) and the mass of wood saved (m_{wood}) in different countries can be found in Tables 2–5. The values were obtained introducing in the heat transfer model the hourly weather data (solar radiation and external temperature) of the capital city of each country, available in the Energy Plus Weather Data files. The results obtained show that the solar cooker can be employed during a large number of days in developing countries, where the problem to obtain an energy source for cooking is imperative.

Table 2
Simulation of the performance of the box-type solar cooker in different countries in Europe, using the weather data of each capital city.

Country	N_{days} [−]	m_{wood} [kg]	Country	N_{days} [−]	m_{wood} [kg]
Austria	123	180.1	Lithuania	71	103.9
Belarus	60	87.8	Netherlands	103	151.0
Belgium	64	93.7	Norway	84	123.0
Bosnia	152	222.5	Poland	82	120.1
Bulgaria	101	147.9	Portugal	262	383.6
Cyprus	290	424.6	Romania	188	275.2
Czech Republic	64	93.7	Russia	79	115.7
Denmark	80	117.1	Serbia	177	259.1
Finland	79	115.7	Slovakia	137	200.6
France	99	144.9	Slovenia	107	156.6
Germany	102	149.3	Spain	235	344.0
Greece	238	348.4	Sweden	92	134.7
Hungary	122	178.6	Switzerland	133	194.7
Iceland	48	70.3	Turkey	163	238.6
Ireland	66	96.6	Ukraine	110	161.0
Italy	197	288.4	United Kingdom	107	156.6

Table 3
Simulation of the performance of the box-type solar cooker in different countries in America, using the weather data of each capital city.

Country	N_{days} [−]	m_{wood} [kg]	Country	N_{days} [−]	m_{wood} [kg]
Argentina	265	387.9	Guatemala	356	521.2
Belize	329	481.6	Honduras	325	475.8
Bolivia	208	304.5	Mexico	310	453.8
Brazil	246	360.1	Nicaragua	328	480.2
Canada	178	260.6	Paraguay	258	377.7
Chile	253	370.4	Peru	223	326.5
Colombia	212	310.4	Puerto Rico	337	493.4
Cuba	319	467.0	Uruguay	257	376.2
Ecuador	219	320.6	USA	200	292.8
El Salvador	341	499.2	Venezuela	340	497.8

Table 4
Simulation of the performance of the box-type solar cooker in different countries in Africa, using the weather data of each capital city.

Country	N_{days} [−]	m_{wood} [kg]	Country	N_{days} [−]	m_{wood} [kg]
Algeria	247	361.6	Madagascar	255	373.3
Egypt	282	412.8	Morocco	264	386.5
Ethiopia	327	478.7	Senegal	316	462.6
Ghana	351	513.8	South Africa	301	440.6
Kenya	283	414.3	Tunisia	256	374.8
Libyan	285	417.2	Zimbabwe	278	407.0

Conclusions

A heat transfer model was proposed to describe the performance of a box-type solar cooker based on the solar radiation and the external temperature. The convective coefficients of the heat transfer model were obtained from experimental measurements of the temperature in different components of the solar cooker, obtaining values of 12 W/m^2 K for the coefficient from the absorber plate to the interior air, 3 W/m^2 K for the convective coefficient between the interior air and the interior wall surfaces and 4.5 W/m^2 K for the external convection between the walls and the atmosphere. The values of the convective coefficients were found to be valid for a wide variety of solar radiation and external temperature. The temperature of different components of the solar cooker was monitored during a whole month, and the experimental

Table 5
Simulation of the performance of the box-type solar cooker in different countries in Oceania, using the weather data of each capital city.

Country	N_{days} [−]	m_{wood} [kg]	Country	N_{days} [−]	m_{wood} [kg]
Australia	252	369.0	Nepal	330	483.1
Bangladesh	324	474.3	New Zealand	232	339.6
China	207	303.1	North Korea	182	266.4
Fiji	304	445.1	Pakistan	299	437.7
Guam	324	474.3	Palau	280	409.9
India	328	480.2	Philippines	195	285.5
Iran	289	423.1	Saudi Arabia	334	489.0
Israel	306	448.0	South Korea	188	275.2
Japan	192	281.1	Sri Lanka	336	491.9
Kazakhstan	162	237.2	Syria	296	433.3
Kuwait	323	472.9	Taiwan	191	279.6
Malaysia	328	480.2	Thailand	278	407.0
Maldives	337	493.4	United Arab Emirates	345	505.1
Marshall Islands	319	467.0	Uzbekistan	236	345.5
Mongolia	161	235.7	Vietnam	232	339.6

values were compared to that predicted by the heat transfer model, obtaining relative errors of under 4% in all cases.

The model was employed to simulate the performance of the solar cooker for one year in several countries around the world, calculating the number of days in which the absorber plate temperature exceeded 100 °C and estimating the wood saved using the solar cooker. The results show the high potential of solar energy as an alternative to wood for cooking in developing countries.

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