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Article *in* Solar Energy · May 2018

DOI: 10.1016/j.solener.2018.03.040

Solar Energy 166 (2018) 21–27

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

Review

Figures of merit and their relevance in the context of a standard testing and performance comparison methods for solar box – Cookers

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ARTICLE INFO

Keywords:
Solar box cooker
Standards for testing solar cookers
Figures of merit

ABSTRACT

Solar cookers, in particular solar box cookers, are becoming more popular and widespread. New ideas, manufacturing techniques and higher performance designs are being proposed. As usual, a good testing standard is an important tool for the market and for cooker acceptance from the users. In the past, testing procedures and figures of merit have been proposed [1–5] for cooker characterization. These have several limitations that can be eliminated with a deeper analysis of solar box cooker optical a thermal behavior. This paper proposes a revision of these procedures yielding more meaningful and useful Figures of Merit. This work can be a first step towards a future and more precise testing standard. This revision is formulated keeping an important characteristic of the existing proposals: simple and available instrumentation allowing these tests to be carried anywhere in the World, with a minimum of investment and/or lab conditions.

1. Introduction

In Mullick et al. (1987, 1996) the authors proposed a way towards the testing of solar cookers and extracted from the testing results two figures of merit, F_1 and F_2, to help in the comparison of different cookers performance.

F_1 is a figure of merit related with the fact that for proper cooking, the cooker must provide temperatures above the boiling point of water and F_2 is related to the way the cooker handles the sensible heating of the load. Other important definitions for cooker characterization and comparison are power delivered, cooker efficiency, etc. (Funk, 1999; Funk, 1998).

These figures of merit have become a part of the standard for testing of Box Cookers, proposed by BIS. These definitions should take into account that there are many different box type cooker geometries, with and without performance augmenting reflecting lids.

However, in BIS, the proposed standard demands that all augmenting mirrors be covered by a black cloth during testing and thus, in fact, the tests are carried out over the box only! Their usefulness is thus very limited and the proposed application of the resulting F_1 and F_2 for the calculation of a parameter like time to reach boiling is rather meaningless, since the cooker will normally operate with its augmenting mirrors and that time will certainly be shorter. Even the text of the standard acknowledges that. In fact, the authors in Mullick et al. (1987) were well aware (and even comment about it) that their definition was set as if augmenting mirrors did not exist.

Later, other authors in De Castell et al. (1999) discussed and extended the ideas of the first proposals for these figures of merit in an attempt at refining/correcting at least some of the shortcomings of the first definitions, by recognizing the presence of augmenting mirrors and different possible geometries, with and without concentration. However, their proposal does still not take fully advantage of a more accurate way for taking into account the cooker's characteristics.

In any case, the present situation is disturbing since not only researchers are using different definitions but also these are not really as precise as they could be. That hinders their application either to fully characterize any box cooker (Geddam et al., 2014), predict boiling time, determine optimal cooking loads (Mahavar et al., 2015), determine heat loss and optical efficiency (as for instance in Mullick et al. (1991)).

This paper proposes new definitions for F_1 and F_2 which go a step further from the proposals in De Castell et al. (1999), by taking into account the optical behavior of the lid augmenting mirror without requiring irradiation measurements other than on the horizontal plane.

In fact, a true merit of the very first proposals (Mullick et al., 1987; Mullick et al., 1996; BIS) is that only simple measurements are required for the characterization being sought, in contrast with a possible list of more demanding ones, which would perhaps better characterize each individual box-cooker, but might be quite difficult to transform into a procedure to be used everywhere in the same way and with good but

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https://doi.org/10.1016/j.solener.2018.03.040
Received 7 December 2017; Received in revised form 13 March 2018; Accepted 14 March 2018
Available online 20 March 2018

Nomenclature

Acronyms

BIS	Bureau of Indian Standards
CPC	Compound Parabolic Concentrator

Greek symbols

δ	solar declination
η_0	optical efficiency
Θ	zenith angle
λ	local latitude
ρ	mirror reflectivity
τ	time between T_{w1} and T_{w2}
τ_0	water boiling time
τ_{0new}	new water boil time
ω_t	solar time angle

Roman symbols

A_c	horizontal transparent cover area
A_n	normal area to incoming beam irradiation
A_p	plate area
A_H	projected area by the lid on the horizontal plane of the cover
F_1	figure of merit 1
F_{1new}	new figure of merit 1
F_2	figure of merit 2
F_{2new}	new figure of merit 2
I_c	collected solar irradiance
I_h	solar irradiance on horizontal plane
$(MC)_w$	product between mass of water and specific heat capacity of water
$(MC)'_w$	product between mass of water and specific heat capacity of all system (water, pot and cooker interiors)
P	power
T_{air}	ambient temperature
T_p	absorber (plate) temperature
T_{ps}	absorber (plate) temperature at stagnation
T_{w1}	initial water temperature
T_{w2}	final water temperature
U_L	heat loss coefficient

not expensive instrumentation.

A future standard will certainly benefit from these more precise definitions but must still be very careful at defining testing conditions that will resolve ambiguities in the results as consequence, for instance, of the time of the year of the testing, the load to be used, the extent and use of pre-heating, etc. This discussion is not the objective of this paper.

This paper derives and proposes adjustments to the definitions of the existing figures of merit, with the goal of contributing to a future standard testing procedure and performance comparison method for solar box – cookers.

2. Basic definitions

2.1. The problem

Consider a box cooker, just as the one in Fig. 1.

The work described in Mullick et al. (1987) proposes two figures of merit, F_1 and F_2. For the sake of the discussion that follows, a brief derivation of these figures of merit is presented just as made in Mullick et al. (1987).

Considering A_c as the horizontal transparent cover area and I_h as the irradiance on the horizontal plane (in this case coincident with the irradiance on the horizontal transparent cover to the cooker).

F_1 is obtained from a thermal performance equation describing the empty cooker's performance, by stating that the power being delivered by the cooker (the reflecting lid, if it exists, is considered to be covered by a black cloth) is as in Eq. (1)

$$P = A_c \times I_h \times \eta_0 - A_c \times U_L \times (T_p - T_{air}) \quad (1)$$

where

U_L represents the cooker heat loss factor referred to the cover area A_c;
η_0 the optical efficiency of the cooker;
T_p the absorber (plate) temperature of the empty cooker and T_{air} the ambient temperature.

At stagnation T_p becomes T_{ps} (maximum absorber temperature) and the power to be extracted is zero. Hence

$$A_c \times I_h \times \eta_0 = A_c \times U_L \times (T_{ps} - T_{air}) \quad (2)$$

And F_1 appears defined as

$$F_1 = \frac{\eta_0}{U_L} = \frac{(T_{ps} - T_{air})}{I_h} \quad (3)$$

The problem with this definition is that the cover area (A_c) may not characterize the cooker by itself: usually there may be an augmenting lid (see Fig. 1), intercepting solar irradiation and changing the cooker's performance; an infinite variety of cookers could correspond to the same cover area (A_c). Besides, the cover may not be horizontal (see Fig. 2) and such a definition does not even take into account that specificity.

The other Figure of Merit, F_2, arises in the context of loading the cooker with a certain quantity of food (represented by a certain quantity of water for the sake of the testing) and measuring the heating time associated with it.

Let $(MC)_w$ be the mass times the specific heat of the water being heated by the cooker; τ is the time, in seconds, it takes the water (standing for a cooking load) to go from T_{w1} to T_{w2} and again T_{air} is the average ambient temperature during testing.

The equations leading into the definition of F_2 are the following:

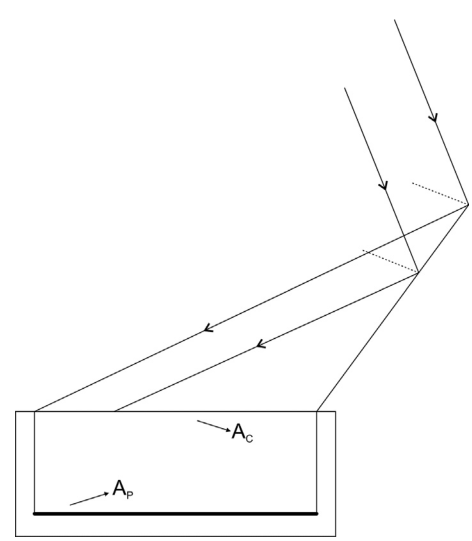

Fig. 1. A typical box cooker with a horizontal transparent cover and an augmenting lid.

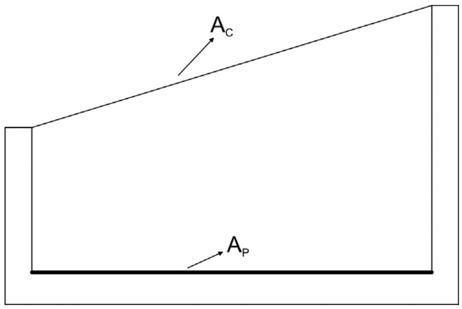

Fig. 2. Box cooker with a tilted transparent cover.

$$dQ = (MC)'dTw \tag{4}$$

where (MC)′ stands for the overall relevant cooker and utensils heat capacity, including the water load to be heated $(MC)_w$ (i.e. $(MC)' = (MC)_o + (MC)_w$)

but P, as in (1), is $P = \frac{dQ}{dt}$, hence

$$dt = \frac{(MC)'}{P} \times dT_w \tag{5}$$

Assuming that water is heated from a certain temperature T_{w1} at time t_1 to T_{w2} at a time t_2 ($\tau = t_2 - t_1$), while I_h and T_{air} remain constant, it is possible to obtain, integrating between t_1 and t_2, the boiling time as

$$\tau = -F_1\frac{(MC)'}{A_c\eta_0} \times \ln\left[\frac{I_h - \frac{1}{F_1}\left(\frac{T_{w2}-T_{air}}{I_h}\right)}{I_h - \frac{1}{F_1}\left(\frac{T_{w1}-T_{air}}{I_h}\right)}\right] \tag{6}$$

defining now $C_r = \frac{(MC)_w}{(MC)'}$

it is possible to write the second figure of merit (F_2) as

$$F_2 = \eta_0 \times C_r = F_1 \times \frac{(MC)_w}{A_c\tau}\ln\left[\frac{1-\frac{1}{F_1}\left(\frac{T_{w1}-T_{air}}{I_h}\right)}{1-\frac{1}{F_1}\left(\frac{T_{w2}-T_{air}}{I_h}\right)}\right] \tag{7}$$

This definition suffers from the same limitations as referred with respect to F_1 above. However, both have the merit of requiring very simple measurements to be obtained. The question is: how well do they really characterize the cooker?

There is a further and very important set of remarks:

(1) Testing must establish a standard way to choose $(MC)_w$, since F_2 depends on it;
(2) There is an ambiguity associated with the time of the year in which the testing is done.

To see how, consider Figs. 3 and 4 where the same cooker is tested in winter and in summer time.

In what follows the nomenclature A is used to refer all areas, however in the figures drawn it appears as a length. This is because the width of the box cooker (out of the plane of the paper and perpendicular to it) is a fixed multiplying value.

The angle of the lid in each situation is such that its edge reflects the maximum possible beam irradiation up to the cooker (edge of cover A). This defines an acceptance irradiation area (perpendicular to incident beam radiation), A_n, which is larger in summer than in winter. This means that ($T_{ps} - T_{air}$) will likely be higher in summer than in winter and thus both F_1 and F_2 are expected to be different.

2.2. Contribution to solving the problem

Consider A_n (see Figs. 3 and 4), on a plane perpendicular to the incoming beam irradiation, as the area corresponding to the irradiation being collected by the box cooker. Thus $A_n \times I_c$, where I_c is the sum of beam, diffuse and ground reflected irradiation on that plane, i.e. it is the irradiation that would be measured by a pyranometer placed on that plane.

Take A_H as the area projected by the lid on the horizontal plane, containing A_c (see Figs. 3 and 4) or its lowest point, in the case of it being tilted

In fact

$$A_n = A_H \times \cos\theta \tag{8}$$

where θ is the angle the incident beam radiation makes with the normal at the testing site at solar noon.

From Duffie and Beckman (1980),

$$\cos\theta = \cos\lambda \times \cos\delta \times \cos\omega t + \sin\delta \times \sin\lambda \tag{9}$$

where λ is the local latitude, δ is the solar declination for each testing day and ωt the angle corresponding to the solar time (ωt = 0 being the value at solar noon)

The next step will be to write Eq. (1) as to better reflect the behavior of the cooker, since with the definitions cited before it really does not.

Delivered power should really more accurately be written as

$$P = A_n \times I_c \times \eta_0 - A_p \times U_L \times (T_p - T_{air}) \tag{10}$$

A_p is now used, rather than A_c, with U_L now referred to the plate (absorber) area rather than to the cover area, for a more precise physical meaning, which is related to the extent solar irradiation is being concentrated.

The term $A_n \times I_c$ might be difficult to measure and thus we propose an approximation which is good enough and easy to measure

$$A_n \times I_c = \sim A_H \times I_h \tag{11}$$

The term η_0 can be made more explicit by considering irradiation incident on the cover, with and without reflection on the lid mirror. So, Eq. (10) can now be written again, acknowledging this explicit presence of an augmenting cover lid (note: side mirrors, can be ignored at this stage, since the cooker tends to be tested with the sun in (or very near) the cooker's symmetry plane).

$$P = I_c \times [A_c \times \cos\theta + (A_n/\cos\theta - A_c) \times \rho \times \cos\theta] \times \eta_0' - A_p \times U_L \times (T_p - T_{air}) \tag{12}$$

Using Eq. (12) one now has

$$P = I_h \times A' \times \eta_0' - A_p \times U_L \times (T_p - T_{air}) \tag{13}$$

where

$$A' = [A_c + (A_n/\cos\theta - A_c) \times \rho] \tag{14}$$

Hence it is now possible to define F_{1new} and F_{2new}, just like before

$$F_{1new} = \frac{\eta_0'}{U_L} = \frac{A_p}{A'}\frac{(T_{ps} - T_{air})}{I_h} \tag{15}$$

and

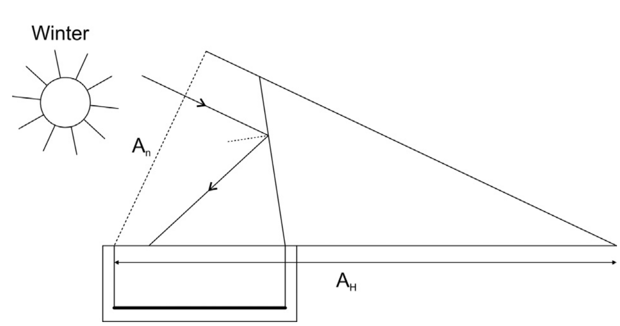

Fig. 3. Box cooker being tested in winter.

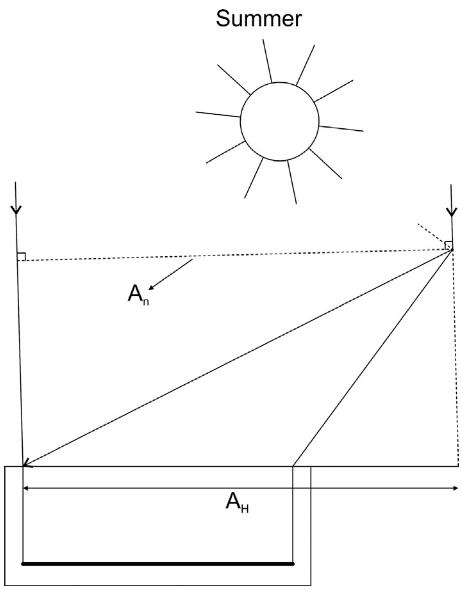

Fig. 4. Box cooker being tested in summer.

$$F_{2new} = \eta_0' \times C_r = F_1 \times \frac{(MC)_w}{A' \times \tau} \times \ln\left[\frac{\left(1-A_p \times \left(\frac{T_{w1}-T_{air}}{A' \times F_{1new} \times I_h}\right)\right)}{\left(1-A_p \times \left(\frac{T_{w2}-T_{air}}{A' \times F_{1new} \times I_h}\right)\right)}\right] \tag{16}$$

3. Application

3.1. Tests with the SUNCOOK

In Collares Pereira et al. (2003) the SUNCOOK was presented and discussed, a solar box-cooker with augmenting lid mirror and a box made with a double cover and inside mirrors of the asymmetric CPC type, a very favorable combination of concepts: ideal concentration (Winston, 2004) in a simple box type configuration.

Fig. 5 shows an image of the SUNCOOK, box close and another of the SUNCOOK with the lid open and its booster mirror deployed.

Fig. 6 shows two cross sections of the box, with their respective asymmetric CPC walls (see Collares Pereira et al., 2003 for a full description).

Testing the SUNCOOK according with BIS grossly misrepresents the behavior of this cooker, as will be shown below.

Plate stagnation temperature was measured for a few days, from September to November. The results can be seen below, for several clear days. I_h is also presented in Table 1 below, on average, for the duration of the test. Measurements were made on the same cooker, with the lid and its booster mirror deployed properly and with the lid covered by a black cloth.

It can be seen that the results are quite different, with and without the mirror. In particular, even with the sun very low in the sky, with the lid properly tilted, the plate temperature is still quite high in mid-November (148 °C). However, with the cloth on, at the same time, it is no longer possible to boil water, since plate temperature is below 100 °C.

For the purpose of calculating F_1, F_2 and F_{1new}, F_{2new}, the results obtained around November 15 were used.

These results were obtained for this paper with a SUNCOOK, following all the recommendations in BIS in terms of cooker orientation and cooker pre-heating. However, the choice of $(MC)_w$ was done differently, rather following the recommendation in De Castell et al. (1999) as they refer to A_n and not to A_c. The higher value of 8 kg/m^2 proposed in BIS is referred to A_c cover area, smaller than A_n, and thus, on average, the difference is not so large.

Fig. 5. the SUNCOOK: (a) – closed box; (b) – lid open with booster mirror.

Fig. 7 shows specific data for November 16th, including that of solar radiation during the testing hours (no black cloth).

Fig. 8 shows the data obtained for an identical SUNCOOK with the black cloth covering the lid.

Table 2 shows the relevant data for the calculation of the coefficients of merit, for the testing day.

In Table 3 results are presented for F_1, F_2, F_{1new}, F_{2new}, according to Eqs. (3), (7), (15), and (16) respectively.

The test starts with the water at T_{W1} = 40 °C and T_{W2} = 80 °C is the temperature to be reached for the evaluation of F_2. The no cloth case is shown in Fig. 5 and the measurements with the cloth in Fig. 6.

It can be seen that covering the mirror with a cloth did not allow the water to reach 80 °C (in fact no more than 74 °C), therefore F_2 cannot even be determined.

It can also be observed that the testing with cloth did not even let the cooker reach the minimum admissible temperature as referred in Mullick et al. (1987), where F_1 values above 0.12 are indicated as desirable.

As derived for Eq. (6), it is possible to write (Eq. (17))

$$\tau = -F_{1new}\frac{(MC)'}{A'\eta_0'} \times \ln\left[\frac{\left(I_h-A_p \times \left(\frac{T_{w2}-T_{air}}{A' \times F_{1new} \times I_h}\right)\right)}{\left(I_h-A_p \times \left(\frac{T_{w1}-T_{air}}{A' \times F_{1new} \times I_h}\right)\right)}\right] \tag{17}$$

τ being the time it takes water to go from T_{w1} to T_{w2}.

This equation can be used to calculate the expected time for the cooker to reach boiling (i.e. to go from ambient temperature to near 100 °C) for different climatic conditions, i.e. pending only on I_h and T_{air}.

This can now be written as Eq. (18)[1]

$$\tau_{0new} = -\frac{F_{1new}}{F_{2new}} \times \frac{(MC)_w}{A'} \times \ln\left(1-\frac{A_p \times (99.2-T_{air})}{A' \times F_{1new} \times I_h}\right) \tag{18}$$

Fig. 9 corresponds to data obtained on November 20th with the SUNCOOK tested with water from ambient temperature to boiling with the proper $(MC)_w$ = 1917 kg × 4186 J/kg·K for that day.

The time to boiling was calculated according to eq. 18 and the result was τ_{0new} = 132 min.

This result compares very well with the result that can be obtained from Fig. 9, around 135 min.

3.2. Can these figures of merit be used in other times of the year?

It was mentioned above that it is important to address the issue of the usefulness of these figures of merit in connection with the moment

[1] 99.2°C is boiling water temperature at the measurement site (height above sea level – 253 m)

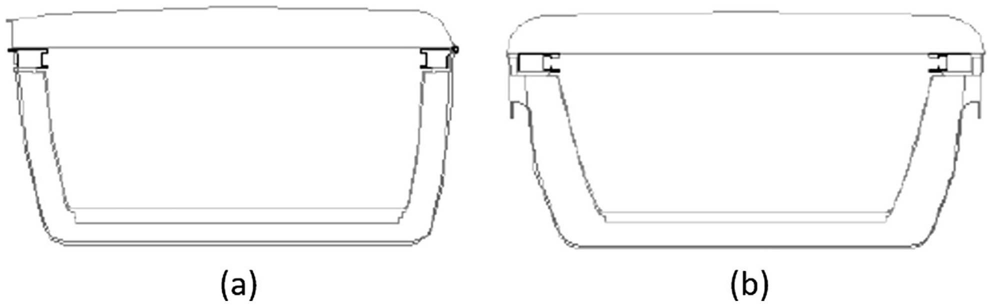

Fig. 6. (a) Front and back and (b) Left and right.

Table 1
Stagnation temperature measurements with the SUNCOOK, several different days.

SUNCOOK (lid and booster)	25/09/2017	26/09/2017	23/10/2017	15/11/2017
T_{ps} (°C)	171	174	160	148
I_h (W/m^2)	805	798	644	553
SUNCOOK with black cloth	02/10/2017	03/10/2017	04/10/2017	06/11/2017
T_{ps} (°C)	115	126	120	92
I_h (W/m^2)	750	739	759	598

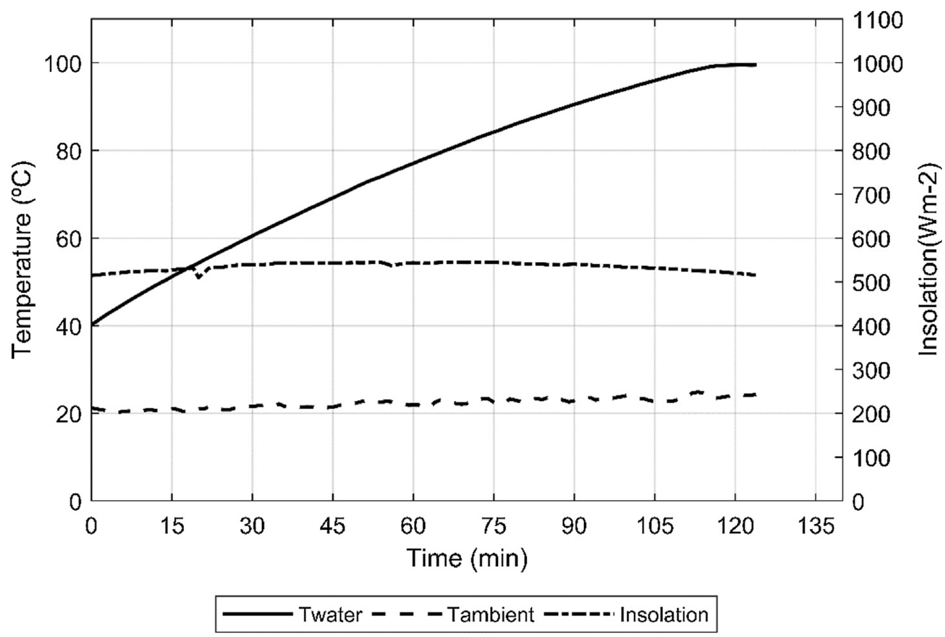

Fig. 7. Rise in water temperature with tracking (November 16th) every 15 min, with no cloth over the lid.

of the year (season) the measurements are made.

This is an interesting issue and will be the subject of another paper, with measurements made at different times of the year.

However, it is already possible to make an evaluation, since results were obtained from measurements of the same SUNCOOK and reported in Collares Pereira et al. (2003). These took place in May. Then the same time from ambient to boiling was measured to be 120 min, for the $(MC)_w$ of 2.5 kg and I_h = 943 W/m^2, A′ = 0.441 m^2.

Using F_{1new} and F_{2new} as reported in Table 2, Eq. (18) would yield 119 min, a very close estimate to the result in Collares Pereira et al. (2003), hinting at the possibility that if the values F_{1new} and F_{2new} are to be measured at the same time of the year and used together in these equations, they have a predictive power which is good enough for any time of the year.

In fact, for future standards, a new figure of merit allowing for meaningful solar box cooker comparisons, could well be “time to boiling” calculated with F_{1new} and F_{2new} measured as above, at whatever time of the year. This new figure of merit, $F_{time\ to\ boiling}$ would be calculated in some standard conditions according to Eq. (18). This possibility will be the objective of future study.

Obviously, this result and these conjectures could not be reached with F_1 and F_2 as defined in Mullick et al. (1987, 1996). In this case F_2 could not even be measured in November.

4. Conclusion

An internationally accepted standard testing of solar box cookers is quite important to allow for a fair comparison between cookers and a fair evaluation of performance vs cost, but it does not yet exist as such.

A standard procedure has been proposed in India (BIS) but it treats cookers in a simplified way (leaving out the performance induced by augmenting mirrors, like the reflecting lid, for instance, or the fact that the cooker might be a concentrator), therefore yielding inaccurate/ambiguous results at best, often unable to predict simple parameters like time between ambient temperature and boiling temperature.

However, it is recognized as being a very interesting feature that all measurements required are simple and use widely available instrumentation, a feature that it is important to preserve in any future standard, to allow for cooker testing anywhere in the World with reasonable costs and accuracy.

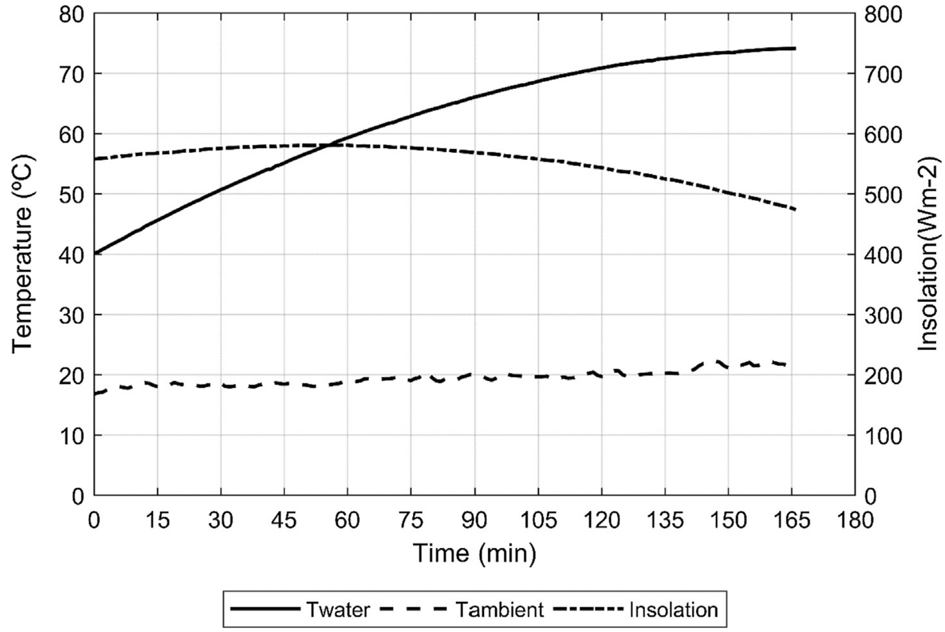

Fig. 8. Rise in water temperature with tracking (November 16th) every 15 min, with cloth over the lid.

Table 2
Relevant data for the calculation of the coefficients of merit, for the testing day.

Data	Θ (°)	Width (m)	Ac (m^2)	A_p (m^2)	A_n for the testing period (m^2)	$(MC)_w$ (J/K)
SUNCOOK (lid and booster)	57.72	0.455	0.455 × 0.460 = 0.21	0.350 × 0.410 = 0.1435	0.327	1.961[1] × 4186 = 8170

[1] From 6 kg/m^2 referred to A_n.

Table 3
F_1, F_2, F_{1new}, F_{2new} from measurements on November 16th.

Procedure	F_1, F_{1new}	F_2, F_{2new}
With cloth over lid mirror (as in BIS)	0.118	n.a. (80 °C not reached!)
New proposal	0.055	0.092

The BIS proposal rests, among others, on the calculation of two Figures of Merit, F_1 and F_2. F_1 is a figure of merit related with the fact that for proper cooking the cooker must provide temperatures above the boiling point of water and F_2 is related to the way the cooker handles the sensible heating of the load. A more precise proposal for these figures of merit was made in De Castell et al. (1999). There, the

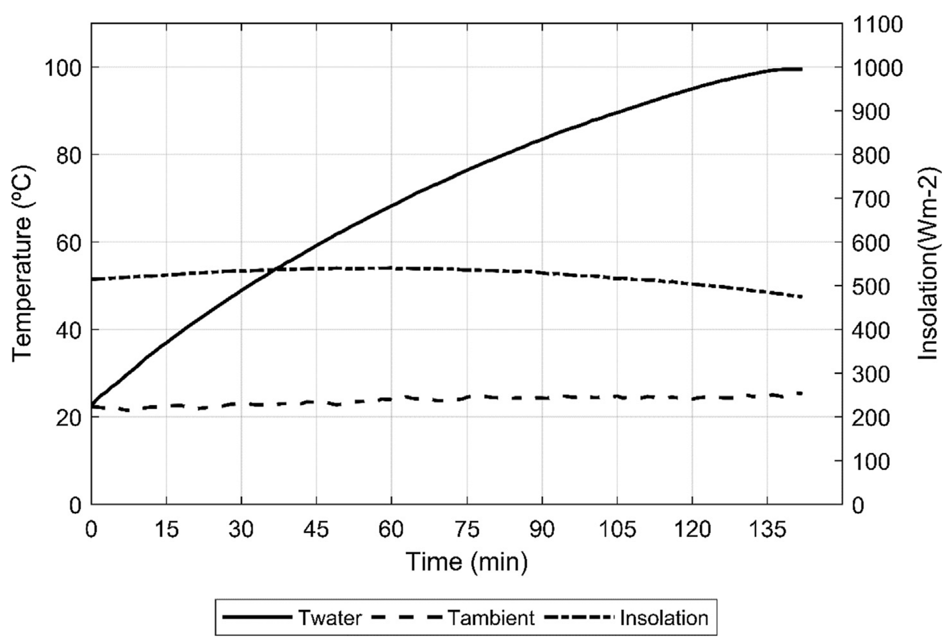

Fig. 9. rise in water temperature with tracking every 15 min and no cloth over the lid on November 20th.

authors already treat the solar box cooker complete with augmenting (lid) mirrors and their F_1 and F_2 figures of merit, keeping in line with the requirement of using the same simple measurements and widely available instrumentation. However, it is possible to go one step further in characterizing more precisely cooker behavior as shown in this paper.

The work presented in this paper explains the new proposal and compares it with the previous and simpler BIS proposal.

It then applies the results obtained to a particular cooker reported in Collares Pereira et al. (2003) and shows the capacity prediction of something like time to boiling. The results obtained with the new proposal made were shown to be well in line with the measurements made and even to be capable of reproducing this result measured at other times of the year. A proposal was made to consider, in future standards, the possibility of transforming "time to boiling" in a new figure of merit with real power to be meaningful in the comparison of several box cookers.

In view of the results obtained, the authors recommend that a future standard uses the figures of merit as defined here.

For a new standard to be fully developed, many specific circumstances must still be defined, as apparent in BIS and De Castell et al. (1999). The present work did not attempt at contributing to these definitions, a discussion which would certainly have to involve different experts in this area and also representatives of solar cooker manufacturing companies. In the meanwhile, the definitions and recommendations made here seem to be an adequate follow up from BIS and De Castell et al. (1999) and can integrate a useful and more precise future standard.

In the future the authors plan to contribute further to the definition of a revised testing procedure. Among other aspects they plan to address the broad question of time of the year influence in testing box cookers.

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