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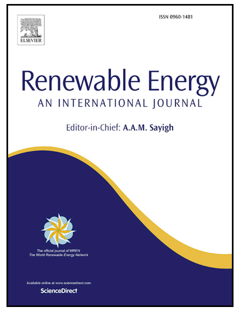

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Credit authorship contribution statement

Celestino Rodrigues Ruivo: Supervision, conceptualization, methodology, formal analysis, writing–reviewing and editing.

Gianluca Coccia: Investigation, editing and writing–reviewing.

Giovanni Di Nicola: Investigation, writing–reviewing and editing.

Antonio Carrillo-Andrés: Writing–reviewing and editing.

Xabier Apaolaza-Pagoaga: Investigation, data curation, visualization, writing–reviewing and editing.

Standardised power of solar cookers with a linear performance curve following the Hottel-Whillier-Bliss formulation

Celestino Rodrigues Ruivo[a,b,*], Gianluca Coccia[c], Giovanni Di Nicola[c], Antonio Carrillo-Andrés[d], Xabier Apaolaza-Pagoaga[d]

[a] *Department of Mechanical Engineering, Institute of Engineering, University of Algarve, Campus da Penha, 8005-139 Faro, Portugal*

[b] *ADAI - LAETA, Rua Pedro Hispano nº12, 3030-289, Coimbra, Portugal*

[c] *Marche Polytechnic University, Department of Industrial Engineering and Mathematical Sciences, Via Brecce Bianche 12, 60131 Ancona, Italy*

[d] *Energy Research Group. Department of Mechanical, Thermal and Fluids Engineering, University of Malaga. Calle Arquitecto Francisco Peñalosa, 6, 29071, Malaga, Spain*

Abstract

In the present work, an improvement of protocol widely used for reporting the thermal behaviour of solar cookers is communicated to the scientific community. The linear regression used to represent the standardised cooking power is based on the well-known Hottel-Whillier-Bliss equation written in dimensionless format. The authors' new formulation procedure for estimating the standardised power includes a correction for the difference between the load temperature and the ambient air temperature of the procedure of ASAE S580.1 Standard. It is derived from a simple theoretical deduction, similar to the ones usually applied to solar thermal flat collectors. The correction factor relates itself with the ratio between the measured solar irradiance and the solar irradiance chosen as a

* Corresponding author; e-mail: cruivo@ualg.pt

standard value. As one example, test results of a funnel cooker loaded with water are used to show the impact of the improvement of the procedure for reporting performance of a solar cooker. The procedure is valid only for solar cookers evidencing a clear linear performance curve.

Keywords: solar cookers; cooker power; linear regression; standardised power; consistent improvement.

Nomenclature

A_n	Normal area to the incoming solar radiation (m^2)
$A_{n,max}$	Maximum value of A_n (m^2)
A_s	System surface area (m^2)
a_0	Coefficient in Eq. (10) (W ºC^{-1})
a_0^*	Coefficient in Eq. (11) (W ºC^{-1})
a_1	Coefficient in Eq. (10) (W)
a_1^*	Coefficient in Eq. (11) (W)
$a_{S,0}$	Coefficient in Eq. (12) (W)
$a_{S,1}$	Coefficient in Eq. (12) (W ºC^{-1})
C	Concentration ratio
$c_{p,f}$	Specific heat of the load (J ºC^{-1}kg^{-1})
I_n	Global normal solar irradiance (W m^{-2})
$I_{n,exp,i}$	Global normal solar irradiance at time interval i (W m^{-2})
I_n^*	Global normal solar irradiance (W m^{-2})
$\dot{Q}$	Cooker power (W)

m_{f}	Mass of load (kg)
$\dot{Q}_i$	Cooker power at time interval *i* (W)
$\dot{Q}_{50}$	Cooker power for $\Delta T_{\mathrm{f,a}} = 50\,^{\circ}\mathrm{C}$, calculated with Eq. (10) (W)
$\dot{Q}^*$	Standardised power of the cooker (W)
$\dot{Q}_i^*$	Standardised power at time interval *i* (W)
$\dot{Q}_{50}^*$	Standardised power of the cooker for $\Delta T_{\mathrm{f,a}}^* = 50\,^{\circ}\mathrm{C}$, calculated with Eq. (11) (W)
$\dot{Q}_{\mathrm{rad}}$	Rate of solar radiation entering into the system (W)
$\dot{Q}_{\mathrm{S}}$	Standardised power to be used in Eq. (12) (W)
$\dot{Q}_{\mathrm{S},i}$	Standardised power at time interval *i* (W)
$\dot{Q}_{\mathrm{S,50}}$	Standardised power for $\Delta T_{\mathrm{f,a}} = 50\,^{\circ}\mathrm{C}$, calculated with Eq. (12) (W)
R	Thermal resistance ($\mathrm{m^2\,^{\circ}C\,W^{-1}}$)
T_{a}	Ambient temperature (ºC)
T_{f}	Load temperature (ºC)
t	Time (s)
U	Overall heat transfer coefficient ($\mathrm{Wm^{-2}\,^{\circ}C^{-1}}$).

Greek symbols

α_0	Coefficient of Eq. (7) (-)
α_1	Coefficient of Eq. (7) ($\mathrm{Wm^{-2}\,^{\circ}C^{-1}}$)
χ	Specific temperature difference ($\mathrm{m^2\,^{\circ}C\,W^{-1}}$)
χ_i	Specific temperature difference at time interval *i* ($\mathrm{m^2\,^{\circ}C\,W^{-1}}$)
$\delta\dot{Q}_{50,700}$	Ratio of $\Delta\dot{Q}_{50,700}$ to $\dot{Q}_{50}^*$ (W)

Δt_i	Time interval i (s)
$\Delta\dot{Q}_{50,700}$	Difference between $\dot{Q}_{S,50}$ and $\dot{Q}^{*}_{50}$ (W)
$\Delta T_{f,a}$	Difference between the load temperature and the ambient air temperature (ºC)
$\Delta T_{f,a,i}$	Difference between the load temperature and the ambient air temperature at time interval i (ºC)
$\Delta T_{f,i}$	Variation of load temperature in the time interval i (ºC)
$\Delta T^{*}_{f,a}$	Difference between the load temperature and the ambient air temperature (ºC)
$\Delta T^{*}_{f,a,i}$	Difference between the load temperature and the ambient air temperature at time interval i (ºC)
$\Delta T^{*}_{f,a,\dot{Q}S50}$	Correct value of difference between the load temperature and the ambient air temperature for the power value $\dot{Q}_{S,50}$ (ºC)
η	Instantaneous efficiency
η_i	Instantaneous efficiency at time interval i
η_o	Optical efficiency
η'_o	Corrected optical efficiency
Ω	Thermal capacitance of the load (J ºC^{-1})

1. Introduction

Most common solar cookers are single devices usually classified as tube cookers, box cookers, parabolic cookers and panel cookers. For panel cookers with a relatively small collecting area: i) a heat-trap is used with the cooking vessel as an important accessory to ensure that cooking succeeds and ii) the cooking process is not as fast as in common parabolic cookers of relatively high aperture area. The protocol of the ASAE 580.1

Standard [1] has been considered by testers to report the thermal behaviour of solar cookers with a standardised power value when the difference between the load temperature and the ambient air temperature is 50 ºC [2–4]. The linear regression produced by plotting power against the difference between the load temperature and the ambient air temperature, as required by the Standard [1], is influenced by the thermal resistance associated with the thermal losses from the load to the ambient [5].

Several designs of panel cookers, and in particular of funnel solar cookers, have been tested [4]. For instance, the portable Haines 1 and 2 solar cookers were found to have a standardised power of 41 W and 82 W, respectively, for a temperature difference of 50 °C [4]. Apaolaza et al. [6] have also analysed the Haines 2 cooker in a wide range of solar altitude angle and determined under most suitable conditions a standardised power value of 87.7 W. In the case of the Cookit solar cooker, having an aperture area similar to that of the Haines 2, a standardised power of 58 W was determined [4]. The HotPot is a small solar cooker comprising a foldable reflector made of aluminium and equipped with a black cooking vessel coupled with a glass enclosure to minimize thermal losses to the environment, but leakage of vapour through lid gaps was found to be the major cause of the thermal losses [7]. Based on the experimental results, a standardised power of only 25 W was determined for this small device, and about 6.9% of the mass of water contained in the HotPot evaporated at the end of the test [8]. It is worth noting that this small percentage causes a non-negligible error in the evaluation of the cooking power as reported in the ASAE S580.1 Standard.

The funnel solar cooker tested recently in Malaga-Spain [2,3] can be classified as a panel cooker. The measured data, derived from a relatively large number of experiments carried out with this cooker, was taken into account to calculate the standardised value of power by following as much as possible the protocol procedure published in the ASAE 580.1

[1]. In the two published works [2,3], water was used as load but with a load ratio of 4 kg m^{-2}, i.e., a value smaller than the ratio required by the Standard [1]. In the case of the work of Ruivo et al. [2], funnel cookers were tested by using a massive glass enclosure and carrying out experiments under low-sun elevations. Authors found that using a glass lid over the black cooking pot allowed to obtain a power value 46% greater than that using a black opaque lid. Two funnel cookers having the same reflector were also tested at the same time using variable trivets to modify the position of the cooking set [3]. It was found that the height of the trivets slightly influences the cooking power, and the ASAE S580.1 Standard is not able to evaluate this small difference.

Four different configurations of the Copenhagen, another panel-type solar cooker, were characterized experimentally under the same weather conditions [9]. From the no-load results, the authors found that the performance of one configuration is more dependent on the solar altitude than the others. Also, the experimental observation points for plotting the curve of the cooker power of each configuration evidence that the linear trend of the standardised power is not universal and dependent on the solar altitude angle. This aspect suggests that the ASAE S580.1 Standard should be revised.

Sethi et al. [10] have experimentally tested one box-solar-cooker and reported its performance by using linear regression curves; however, a positive value for the slope of the fitting equation was found. The same result was obtained when the GoSun Sizzle cooker was tested [4]. In two recent papers by Ruivo et al. [11,12], it was clearly shown that the performance curve can contain two regions with different behaviours. A first region, where power or instantaneous efficiency increase from the beginning of the test up to an intermediate point during the test, and a subsequent region where both performance parameters decrease until the end of the transient load heating test. These two regions were investigated by using the test results of a funnel cooker, loaded with glycerine, and a box solar, loaded with peanut oil. In the authors' opinion, solar cooker designs showing this behaviour, with these two distinct regions, should be tested following a different protocol than the one recommended by the ASAE 580.1 Standard. The existence of these two regions was also observed in the test results of a box solar cooker with relatively high concentration ratio, investigated by Coccia et al. [13]. The first region is observed from the beginning of the experiment until the point where the difference between the load temperature and the ambient air temperature was approximately equal to 60 ºC. The second region with the linear trend, where power continuously decreases, was only observed after this intermediate point. A solution for reporting the performance of solar cookers, showing these two distinct regions in the performance curves, was investigated by Ruivo et al. [12] recently. The proposed regression is a nonlinear curve, which should be derived from a suitable exponential fitting of the measured load temperature values.

Even though the authors of the present paper have considerable experience of performing tests and reports on the solar cooker performance [2,3,6,9,11−16], it is only recently, when writing the recent published work [17], that they discovered that the ASAE 580.1 procedure to derive the linear standardised power performance curve, which is not scientifically correct in terms of dimensional analysis.

When reporting a cooker power for a standard condition that is different from the condition of the experimental test, the performance changes not only in terms of values of power but also in terms of the values of difference between the load temperature and the ambient air temperature. Thus, the single value of standardized power [1] obtained without taking into account the impact on the mentioned temperature difference is overestimated, being the overestimation directly related to the ratio of the solar irradiance of the test and the standard value. An updated procedure to report the single standardized power is therefore presented by following well-known established first principles of physics. As just one example, suitable experimental data obtained from testing a funnel cooker was chosen to illustrate the magnitude of the differences between the ASAE 580.1 procedure and the improved procedure supported by the best actual scientific knowledge. Moreover, all detailed measured experimental data of the chosen test is presented in Appendix A to be accessed by all research teams and testers.

2. Mathematical formulation

The coupled transfer phenomena occurring in solar cookers are usually analysed by assuming a set of simplifying assumptions. One commonly adopted assumption is that: the load and the cooking set are treated as one "lumped-capacitance-thermal" system. The incoming solar radiation collected at rate $\dot{Q}_{\mathrm{rad}}$ causes the heating of the load, but at the same time there are thermal losses from the system to the ambient air and to the surroundings, mainly due to convection and radiation phenomena, respectively. It is important to point out that in some cooker designs, a heat loss associated with thermal conduction and a mass loss associated with evaporation phenomena can also occur during the heating of the load. When testing solar cookers loaded with water, final temperatures are below boiling point. So, under this condition, there is no need to consider the energy loss associated with water boiling phenomena. Moreover, assuming that the phase change associated with evaporation is negligible, the power of the solar cooker $\dot{Q}$ depends on the rate of variation of the load temperature T_{f}, i.e., it corresponds to the rate of variation of sensible heat stored by the load, given by:

$$\dot{Q} = \Omega \frac{dT_{\mathrm{f}}}{dt} \tag{1}$$

It relates itself to the rates of thermal energy entering and leaving the thermodynamic system defined by the load, with a thermal capacitance Ω and surface area A_{s}, as:

$$\dot{Q} = \dot{Q}_{\mathrm{rad}} - UA_{\mathrm{s}}\left(T_{\mathrm{f}} - T_{\mathrm{a}}\right) \tag{2}$$

The coefficient U depends on the thermal resistances associated with all existing heat losses. Eq. (2) only applies when the mean radiant temperature of the surroundings is assumed to be close to the ambient temperature (T_{a}) as usually is considered when, for simplicity and convenience, a combined heat transfer coefficient approach is adopted in solving transfer problems where radiation and convection heat transfers being lost from a surface occur at the same time [18].

For a solar cooker with a collecting area perpendicular to incoming beam solar radiation A_{n}, $\dot{Q}_{\mathrm{rad}}$ can be estimated by:

$$\dot{Q}_{\mathrm{rad}} = \eta_{\mathrm{o}} I_{\mathrm{n}} A_{\mathrm{n}} \tag{3}$$

where I_{n} represents the normal solar irradiance and η_{o} the optical efficiency. When a solar cooker is used with an imperfect tracking, the collecting area of the system A_{n} is smaller than $A_{\mathrm{n,max}}$, the maximum value of A_{n} when perfect tracking is adopted. The optical efficiency usually depends on the tracking method and on the design of a particular cooker model.

Eq. (2) corresponds to the well-known Hottel-Whillier-Bliss (HWB) equation that has been widely used to support the performance report of solar collectors under steady-state conditions [19]. It can be demonstrated that Eq. (2) is also equivalent to:

$$\frac{\dot{Q}}{I_{\mathrm{n}} A_{\mathrm{n,max}}} = \eta'_{\mathrm{o}} - \frac{\eta'_{\mathrm{o}}}{R} \frac{\Delta T_{\mathrm{f,a}}}{I_{\mathrm{n}}} \tag{4}$$

where $\Delta T_{\mathrm{f,a}}$ represents the difference between the load temperature and the ambient air temperature. The term in the left member of Eq. (4) is here called instantaneous efficiency (η). It characterizes the conversion, at each instant, of the incoming solar radiation into the energy accumulated in the system. The ratio of this difference to the solar irradiance

I_n is here called specific temperature difference (χ), but it is also referred to as reduced temperature parameter by other authors [20]. Knowing that the concentration ratio C corresponds to the ratio of $A_{n,max}$. to A_s, R is defined as:

$$R = \eta_o' C / U \quad (5)$$

The corrected optical efficiency parameter, η_o', characterizing an imperfect tracking operation of the cooker is expressed by:

$$\eta_o' = \eta_o A_n / A_{n,max} \quad (6)$$

Eq. (4) can be written as a non-dimensional linear performance curve by:

$$\eta = \alpha_0 - \alpha_1 \chi \quad (7)$$

with assumed constant values of $\alpha_0 = \eta_o'$ and $\alpha_1 = \eta_o' / R$.

Similarly, Eq. (2) can be written as a linear regression in terms of cooker power:

$$\dot{Q} = a_0 - a_1 \Delta T_{f,a} \quad (8)$$

or in terms of standardised cooker power ($\dot{Q}^*$) for a global solar irradiance of I_n^* as:

$$\dot{Q}^* = a_0^* - a_1^* \Delta T_{f,a}^* \quad (9)$$

The linear regression expressed by Eq. (8) corresponds to the performance of the cooker for a particular value of global normal solar irradiance I_n and the linear regression represented by Eq. (9) corresponds to the correct performance curve of the cooker at a standard solar irradiance of I_n^*. Both Eqs. (9) and (10) are equivalent to the dimensionless regression expressed by Eq. (7). In the ASAE 580.1 Standard, the adopted linear regression for the standardised cooker power or adjusted cooker power ($\dot{Q}_S$) is:

$$\dot{Q}_S = a_{S,0} - a_{S,1} \Delta T_{f,a} \quad (10)$$

The same standardised cooker power values are used in this regression, but it is important to point out that Eq. (10) is not strictly equal to Eq. (9) as scientifically it should be, because the effect of the change in solar irradiance from the conditions of an experimental test to the standard solar irradiance is not considered in the value of the temperature difference $\Delta T_{\mathrm{f,a}}$, as it will be explained later.

Following the ASAE 580.1 procedure, the standardised power values ($\dot{Q}_{\mathrm{S},i}$) are calculated for a solar irradiance I_{n}^{*} as a finite difference:

$$\dot{Q}_{\mathrm{S},i} = \Omega \frac{\Delta T_{\mathrm{f,i}}}{\Delta t_{\mathrm{i}}} \frac{I_{\mathrm{n}}^{*}}{I_{\mathrm{n,exp},i}} \quad (11)$$

where $\Delta T_{\mathrm{f,i}}$ represents the load temperature variation in each time interval Δt_{i}, that in case of the Standard it is fixed at 600 s. Similarly, the solar irradiance $I_{\mathrm{n,exp},i}$ represents the average value of the global normal solar irradiance at time interval *i*. In order to plot the required number of points to derive the linear curve, the difference $\Delta T_{\mathrm{f,a},i}$ is calculated for each time interval as the difference between the average values of the load temperature and ambient air temperature. These two average temperature values are average values calculated with values measured at the respective time interval. In the non-standardised linear regression (Eq. (8)), the average value of the cooker power at time interval *i*, $\dot{Q}_i$, is calculated, without performing any solar irradiance correction, by:

$$\dot{Q}_i = \Omega \frac{\Delta T_{\mathrm{f,i}}}{\Delta t_{\mathrm{i}}} \quad (12)$$

In the case of the corrected standardised linear regression (Eq. (9)), the average value of the cooker power $\dot{Q}_i^{*}$ and the average value of the temperature difference $\Delta T_{\mathrm{f,a},i}^{*}$, at time interval *i*, are calculated, performing the solar irradiance correction, respectively, by:

$$\dot{Q}_i^{*} = \Omega \frac{\Delta T_{\mathrm{f,i}}}{\Delta t_{\mathrm{i}}} \frac{I_{\mathrm{n}}^{*}}{I_{\mathrm{n,exp},i}} \quad (13)$$

and

$$\Delta T^*_{\mathrm{f,a},i} = \Delta T_{\mathrm{f,a},i} \frac{I^*_{\mathrm{n}}}{I_{\mathrm{n,exp},i}} \quad (14)$$

Following the same procedure, the discrete values of efficiency η_i and specific temperature difference χ_i would be calculated in the same way to derive the linear regression represented by Eq. (7). The solar irradiance I^*_{n}=700 W m^{-2}, value recommended by the ASAE 580.1 Standard [1] is adopted in these calculations.

The main finding of the present work simply demonstrates that the standardised power reported by the Standard $\dot{Q}_{\mathrm{S},50}$, a value to be observed when the difference between the load temperature and the ambient air temperature is 50 ºC for I^*_{n}=700 W m^{-2}, has an associated difference. The magnitude of this difference ($\Delta\dot{Q}_{50,700}$) for a particular cooker depends on the slope of its linear regression curve. It is here evaluated by comparing $\dot{Q}_{\mathrm{S},50}$ predicted by Eq. (10) with $\Delta T_{\mathrm{f,a}} = 50$ ºC and $\dot{Q}^*_{50}$ predicted by Eq. (9) with $\Delta T^*_{\mathrm{f,a}}$ =50 ºC:

$$\Delta\dot{Q}_{50,700} = 50\left(a_{\mathrm{S},1} - a^*_1\right) \quad (15)$$

and the associated relative difference is defined as $\delta\dot{Q}_{50,700}$, i.e., the ratio of $\Delta\dot{Q}_{50,700}$ to $\dot{Q}^*_{50}$.

By using Eq. (9), the correct temperature difference ($\Delta T^*_{\mathrm{f,a,\dot{Q}S50}}$) associated with the power value can be estimated as:

$$\Delta T^*_{\mathrm{f,a,\dot{Q}S50}} = \frac{a^*_0 - \dot{Q}_{\mathrm{S},50}}{a^*_1} \quad (16)$$

One important finding by Ruivo et al. [11] is that considering the system thermal capacitance Ω equal only to the thermal capacitance value of the load or to the global thermal capacitance of the load and the cooking vessel has no impact on the calculated linear regression parameters. Thus, only the thermal capacitance of the load is here adopted, i.e., $\Omega = m_{\mathrm{f}} c_{\mathrm{p,f}}$ where m_{f} and $c_{\mathrm{p,f}}$ represent, respectively, the load mass and the load specific heat.

3. Calculation of the power of a tested funnel cooker

The funnel cooker shown in Fig. 1 has been used in several experiments for investigating the impact of cooker design changes in the performance of the system. Its maximum aperture area is 0.5 m^2 and its reflector is made of composite material. In the first set of experiments conducted by the authors [2], the cooker performance at low sun elevation angles was investigated. The black metal pot was loaded with water, and surrounded by a massive glass enclosure, as depicted in Fig. 1. In current work, only the results of a single test carried out by Ruivo et al. [2] were considered. The raw data from this experiment is presented in Appendix A. Such detailed data is rarely found in the public domain. Details of the experimental setup and data of cooking vessel and reflector of the funnel cooker can be found in the previous work of Ruivo et al. [2]. The test was carried out with 2 kg of water, which corresponds to a ratio of 4.0 kg m^{-2}. In the calculations, the specific heat of water was assumed to be constant and equal to 4180 J kg^{-1} $^{o}C^{-1}$. Fig. 2 depicts the plots of the global normal solar irradiance and the plots of temperature for the ambient and water during experiment no. E64 performed on 11th February 2020. This experiment started at 12h 05min. (before solar noon) and ended at 13h 31min. (after solar noon).

Fig. 1. Experimental setup used for testing solar cookers.

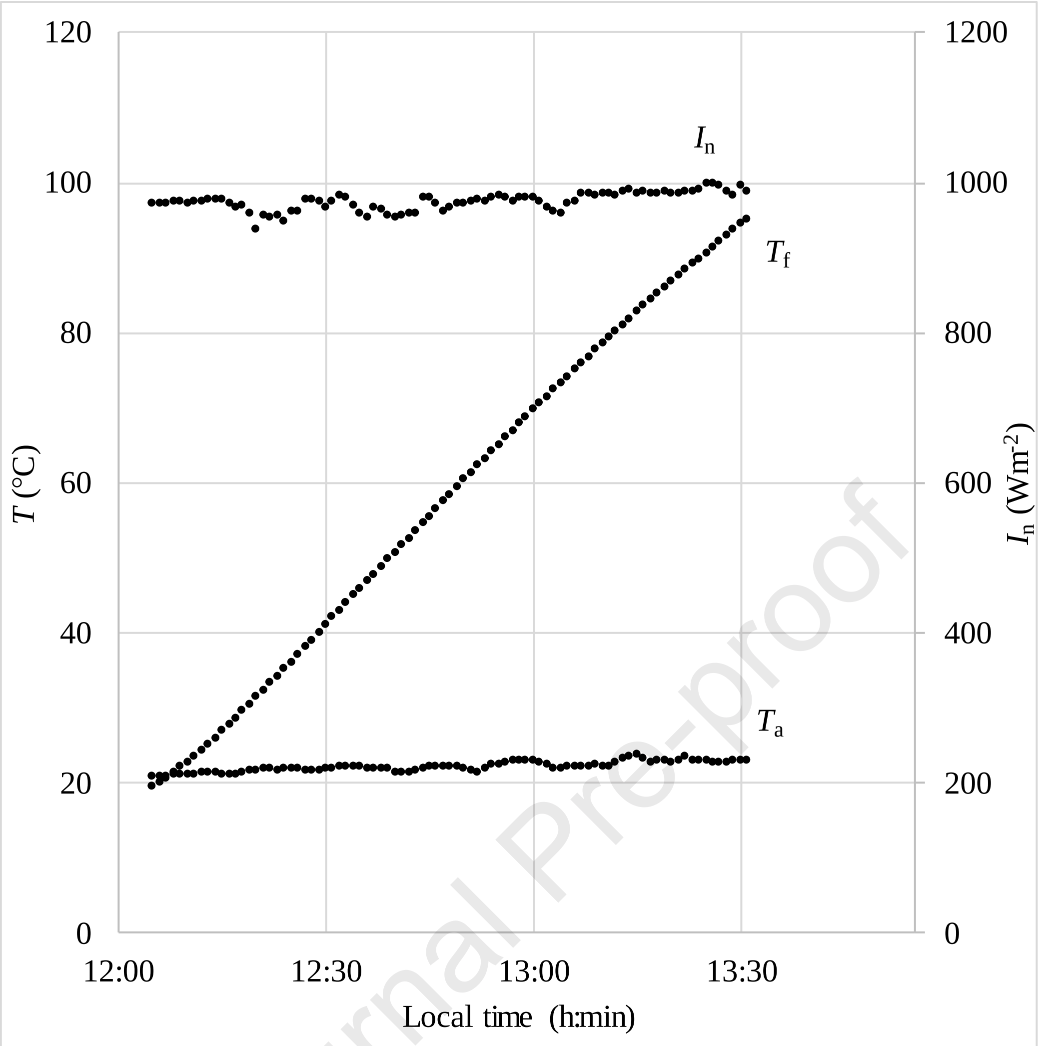
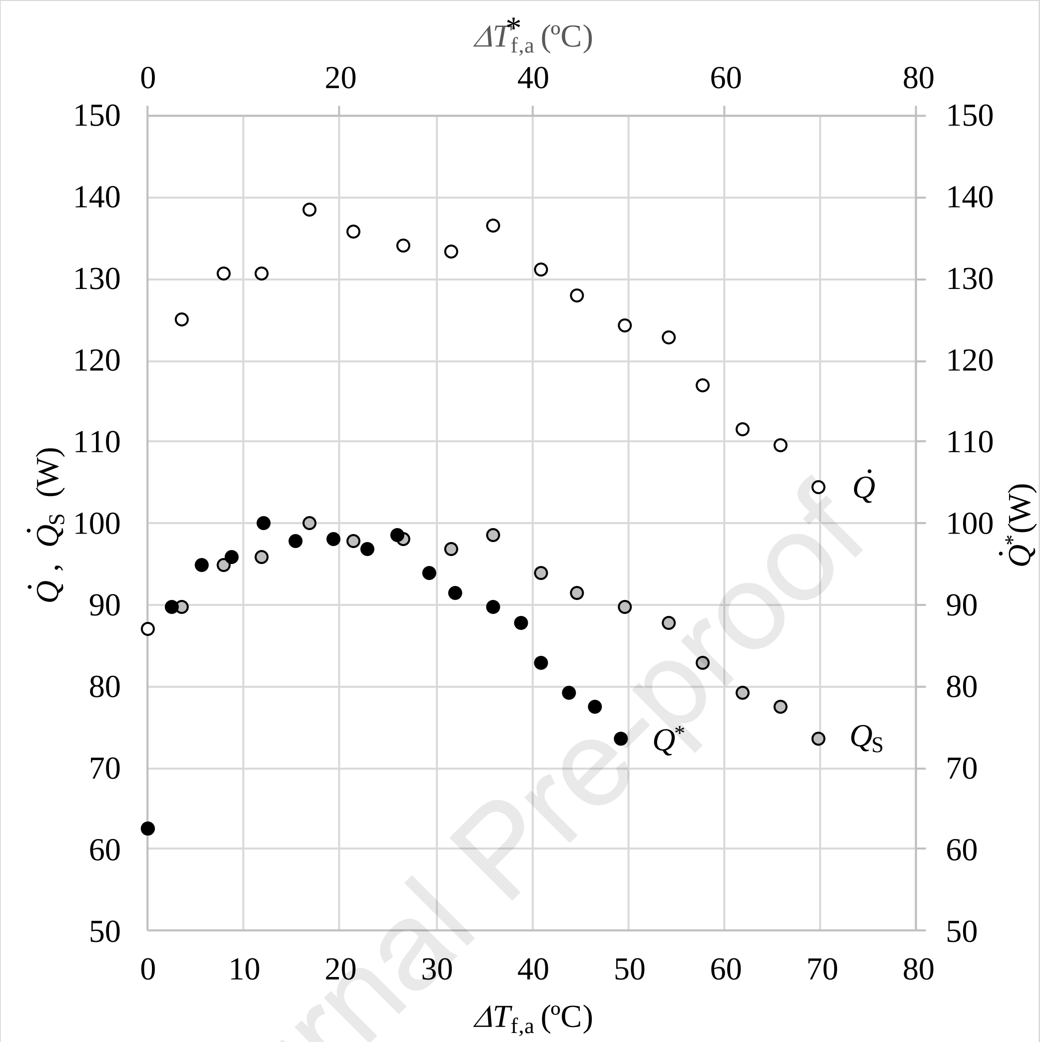


Fig. 2. Plots of the measured global normal solar irradiance, ambient and water temperature.

The load thermal capacitance is smaller than the value associated with the load ratio of 7 kg m^{-2} recommended by the ASAE 580.1 Standard [1]. A test conducted with 2 kg of water is faster than a test using a water load of 3.5 kg and, consequently, fewer valid observation points for the calculation of the discrete values of the cooker power are available when measured at 10-minute interval. Thus, due to this constraint and due to the fact that only data of one experiment is considered, a shorter time step of 5 minutes was used for the scope of the present work. Only observation points with load temperature below 95 ºC are considered as recommended by the Standard, i.e., points at the end of the experiment with a difference between the temperature of boiling water at sea level and the water temperature less than 5 ºC are not considered valid. The data of all valid and invalid observation points is listed in Table A4. Fig. 3 shows the plot of all observation points defining the three power curves, with a time interval of 5 minutes. Each plot shows that the power, when load heating begins, has not a linear decreasing dependence on the difference between the load temperature and the ambient air temperature, a behaviour that is difficult to detect when plotting points with a time step of 10 minutes. This shows that the linear regression should be used with some caution [11,12]. Because of this finding, only points with $\Delta T_{f,a,i}$ >25 ºC were selected for the calculation of the linear regressions. Fig. 4 shows the plots of the eleven observation points considered valid and the corresponding linear regressions.



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326 Fig. 3. Plots of observation points associated with the three cooker power curves.

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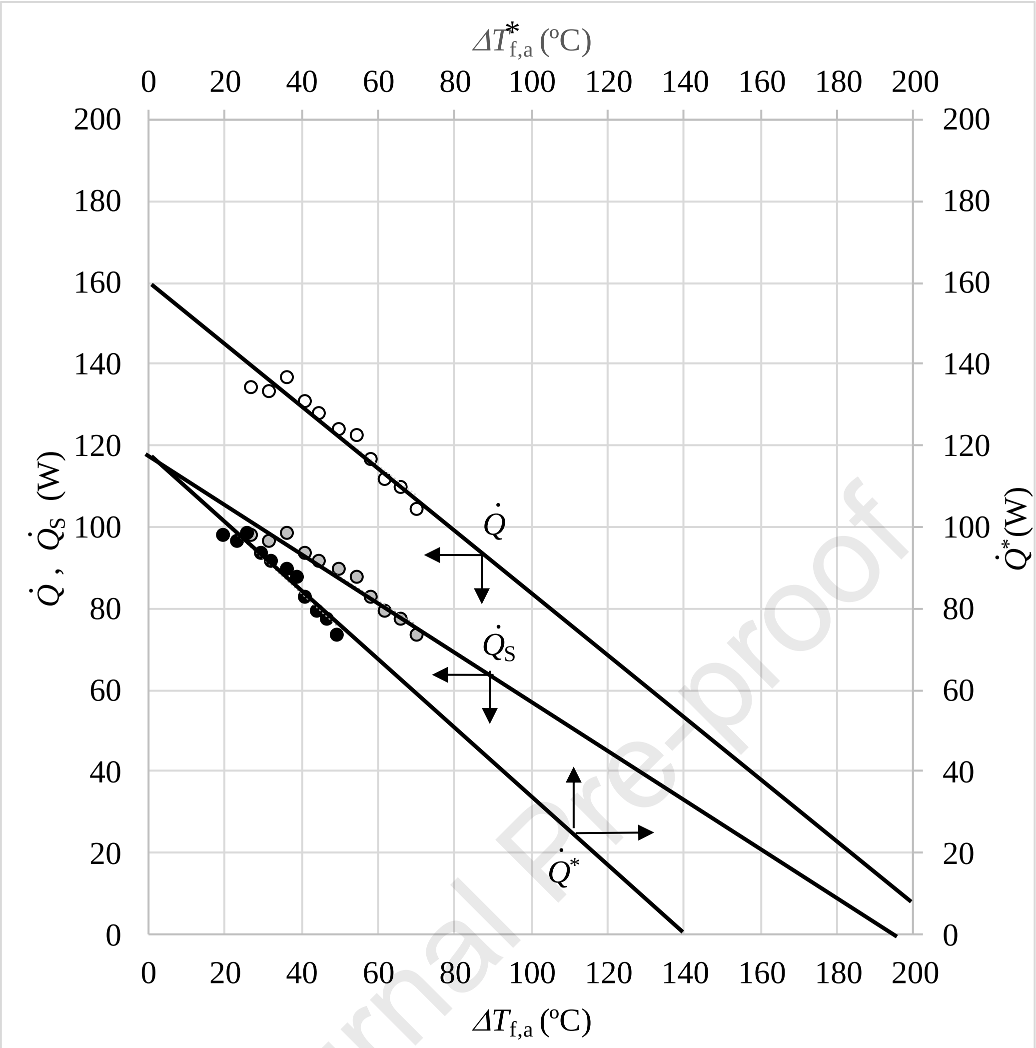

Fig. 4. Linear regression curves associated with power variables $\dot{Q}$, $\dot{Q}_S$ and $\dot{Q}^*$.

Table 1 summarizes the data from a single test, featured in a previous paper by Ruivo et al. [2]. The number of observation points measured in that experiment is about one third of the number of points recommended by the Standard. Ruivo et al. [2] adopted a time step of 10 minutes. But even if the R^2 values of the derived linear regressions, using data from more than one test, are acceptable, the determined power $\dot{Q}_{S,50}$ does not reflect the performance of the cooker at a standardised solar irradiance of 700 W m^{-2}. This means that the findings of Ruivo et al. [2] are not supported by the correct consistent plot of the observation points that should be used to derive the correct linear regression.

Table 2 summarizes the data of the obtained linear regressions. As mentioned before, the values of $\dot{Q}_{S,50}$ listed in Table 1 cannot be considered good estimates of the standardised power when irradiance is 700 W m^{-2} because, for a difference of 50 ºC between the load temperature and the ambient air temperature, the correct standardised value is greater. The correct value $\dot{Q}^{*}_{50}$ and the parameters of the correct standardised linear regression are listed at the end of Table 2. The error associated with $\dot{Q}_{S,50}$, indicated by $\Delta\dot{Q}_{50,700}$, is also provided in Table 2. The use of a regression similar to the ones recommended by the ASAE 580.1 Standard overestimates the standardised power of about 16.2% for a difference of 50 ºC between the load temperature and the ambient air temperature. In other words, the calculated value of $\dot{Q}_{S,50}$ =87.5 W corresponds to a temperature difference of 35.7 ºC and not to a difference of 50 ºC.

Table 1 - Data from the funnel solar cooker tested in the single experiment.

Load	Water
Mass of the load (kg)	2
Average ambient temperature (ºC)	20.3
Average global solar irradiance (W m^{-2})	960.9
Average value of solar altitude angle (º)	35.5
Average wind velocity (m s^{-1})	1.6

Table 2 – Data from the derived linear regression curves.

Linear regressions of cooker power					
Curve of $\dot{Q}$ (Eq. (8))		Curve of $\dot{Q}_S$ (Eq. (10))		Curve of $\dot{Q}^*$ (Eq. (9))	
a_0 (W)	159.04	$a_{S,0}$ (W)	117.03	a_0^* (W)	117.9
a_1 (WºC^{-1})	0.7367	$a_{S,1}$ (WºC^{-1})	0.5909	a_1^* (WºC^{-1})	0.8525
$\dot{Q}_{50}$ (W)	122.2	$\dot{Q}_{S,50}$ (W)	87.5	$\dot{Q}^*_{50}$ (W)	75.3
R^2	0.9235	R^2	0.9451	R^2	0.9414
Error indicators and standardised temperature difference					
$\Delta\dot{Q}_{50,700}$ (W)	12.2	$\delta\dot{Q}_{50,700}$ (%)	16.2	$\Delta T^*_{f,a,\dot{Q}S50}$ (ºC)	35.7

Fig. 4 shows the three linear regressions obtained from the test of the cooker. Both linear regressions associated with the power variables $\dot{Q}$ and $\dot{Q}^*$ would be strictly parallel if ambient temperature and solar irradiance were constant during the whole experiment. Both regressions are equivalent to the dimensionless linear regression expressed by Eq. (7) in terms of instantaneous efficiency. The linear regression associated with $\dot{Q}_S$ provides standardised values but without a clear physical meaning, with the exception of the point where $\Delta T_{f,a} = 0$. The maximum theoretical load temperature predicted by the linear regression $\dot{Q}_S$ for the standard value of solar irradiance 700 W m^{-2} is close to the maximum theoretical load temperature estimated using the linear regression $\dot{Q}$ valid for the conditions of the experiment. Unfortunately, this very misleading approach has been adopted in several published studies. Thus, the presented improvement should be incorporated in the ASAE 580.1 Standard. Furthermore, other improvements are necessary, such as testing a solar cooker with additional lower load ratios, and using a shorter time interval to determine the discrete power values used to obtain the linear performance curve in terms of power or instantaneous efficiency.

4. Discussion

The difference between the power calculated using the ASAE 580.1 Standard procedure and the procedure here presented is not negligible. It would be negligible, or almost negligible, if a value for the solar irradiance in the range 900 and 1000 W m^{-2} was adopted to normalize the power, instead of using the value of 700 W m^{-2}. The authors believe that the value of 700 W m^{-2} is too low. In addition, they think that ASAE 580.1 should use a value of clear sky solar irradiance of about 900 to 1000 W m^{-2}, which would be more meaningful to report the performance of a solar cooker. The occurrence of clouds, even for short periods, should invalidate a test. The estimation of performance of the cookers for other conditions should depart from the linear regression written in dimensionless form, i.e., by using Eq. (7). Only reporting the power value $\dot{Q}_{S,50}$ [1] or even the corrected value $\dot{Q}^{*}_{50}$ as a single performance parameter is not enough to assess a complete comparison of the performance of cookers with distinct designs. Thus, two independent parameters are needed to characterize the performance of a cooker. According to the recent work done by Ruivo et al. [7], those parameters may be the opto−thermal ratio and the time reference of the system for cookers showing a linear dependence of power against the difference between the load temperature and the ambient air temperature.

The procedure here proposed for calculation of the single standardised power of a cooker is considered scientifically correct because it is supported by Eq. (7), which is equivalent to the Hottel-Whillier-Bliss (HWB) equation expressed by Eq. (2). The procedure of ASAE S580.1 would be physical consistent if the heat losses to the surrounding environment were negligible. In fact, it does not happen for almost common cooker designs because heat losses to the environment are driven by $\Delta T_{\mathrm{f,a}}$.

As mentioned before, if experiments were conducted close to ideal conditions, constant values of solar irradiance and ambient temperature would be found, and the linear regressions represented, respectively, by Eqs. (9) and (10) would be parallel. Under this ideal scenario, the coefficients of the correct standardised power (Eq. (9)) relate to the coefficients of the linear regression written in terms of efficiency (Eq. (7)) as:

$$a_1^* = \alpha_1 A_{\mathrm{n,max}} \tag{17}$$

$$a_0^* = \alpha_0 A_{\mathrm{n,max}} I_{\mathrm{n}}^* \tag{18}$$

where I_{n}^* can be 700, 900 or 1100 W m^{-2}. In the opinion of the authors, cooker performance should be reported at three level of solar irradiance.

Fig. 5 depicts the plot of the same observation points used in Fig. 4, but using efficiency and specific temperature difference, variables used to derive the linear regression that corresponds to Eq. (7), whose obtained coefficients are listed in Table 3. Using the data from this linear regression, the coefficients expressed in Eq. (9) were estimated for the three levels of solar irradiance. Then, values of $\dot{Q}_{50}^*$ listed in Table 3 were estimated and the different performance linear curves were derived and represented in Fig. 6. This shows that, when solar irradiance increases from 700 to 1100 W m^{-2}, i.e., there is an increase of about 57 %, the power $\dot{Q}_{50}^*$ increases by about 90%.

In the authors' opinion, performance assessments of solar cookers should be based on the slope and intercept of cooking power and efficiency or on any equivalent data. These values, derived from testing different cookers, can be compared as long as testing conditions are within prescribed limits.

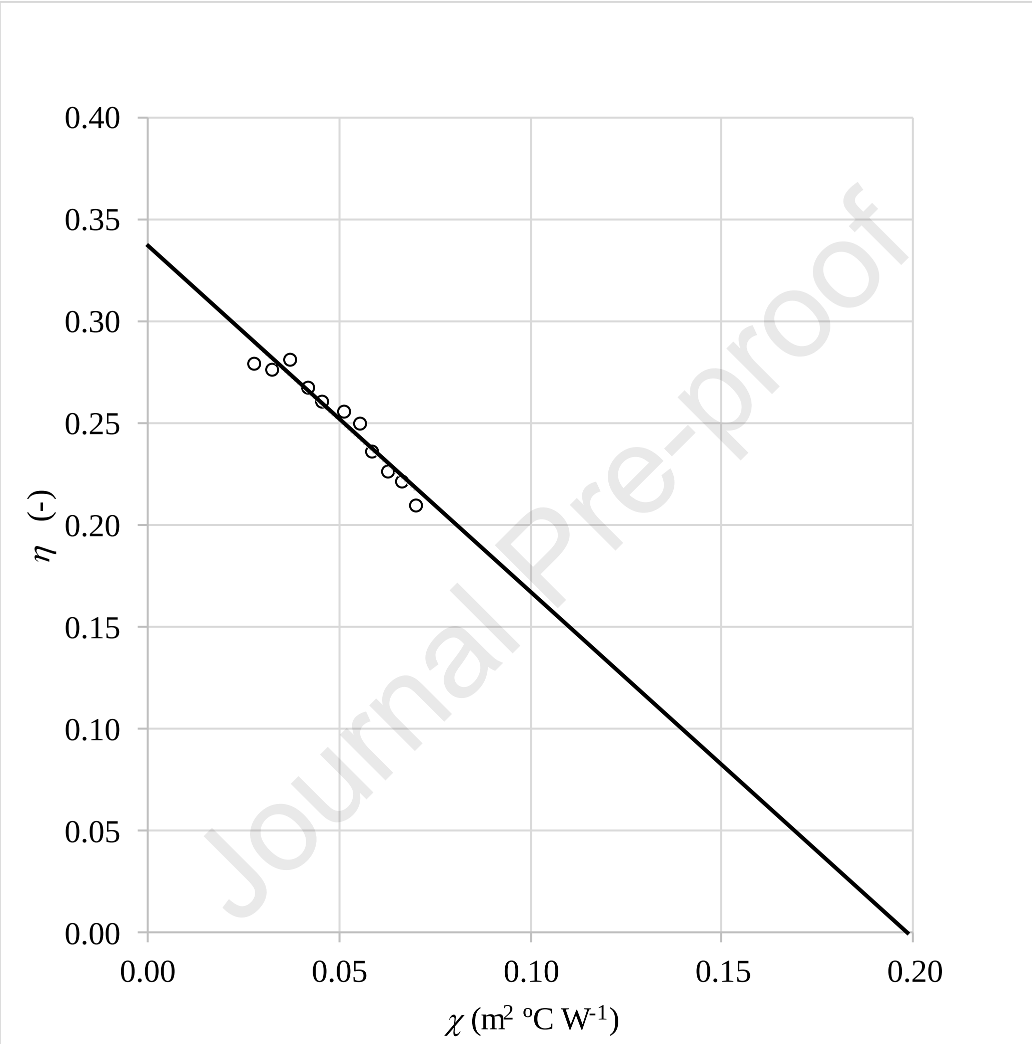

Fig. 5. Linear regression curve for the efficiency.

Table 3 – Data of the linear regression curves.

Linear regression expressed by Eq. (7)					
α_0 (-)	0.3369	α_1 (WºC^{-1} m^{-2})	1.7051	R^2	0.9414
Linear regression expressed by Eq. (11)					
I_n^* (W m^{-2})	700		900	1100	

a_0^* (W)	117.9	151.6	185.3
a_1^* (W°C^{-1})	0.8526	0.8526	0.8526
$\dot{Q}_{50}^*$ (W)	75.3	109.0	142.7

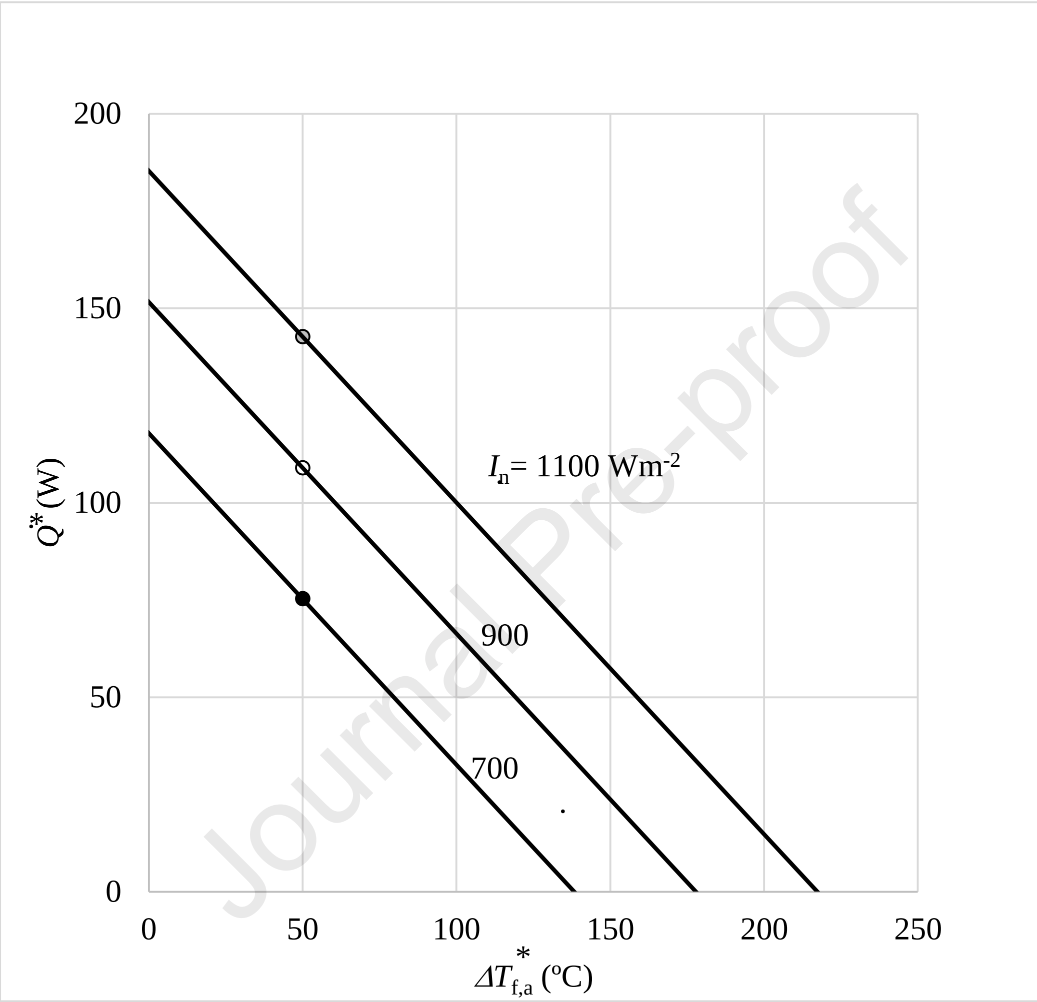

Fig. 6. Linear performance curves of power at global normal solar irradiance of 700, 900 and 1100 W m^{-2}.

5. Conclusions

The well-known protocol, ASAE 580.1, used to report the standardised power of solar cookers, is based on a linear curve obtained from a series of experimental points, but it was found just recently by the authors that the associated formulation does not follow the well-known Hottel-Whillier-Bliss equation, i.e., it not supported by the dimensional analysis usually considered in the performance analysis of physical problems in several scientific domains, such as fluid mechanics or heat transfer. Thus, the reported power, based on the ASAE 580.1 procedure, is not scientifically correct, because the derived linear regression does not represent the behaviour of the cooker in terms of power for the adopted solar irradiance of 700 W m^{-2}. The reported power value does not correspond to the point where the difference between the load temperature and the ambient air temperature is 50 ºC. The reported power value is overestimated because it corresponds to a temperature difference smaller than 50 ºC, i.e., it corresponds to a point where the ratio between the correct temperature difference and the 50 ºC temperature difference is approximately equal to the ratio between the solar irradiance of 700 W m^{-2} and the average solar irradiance during testing. In this work, reliable test data, from a funnel solar cooker using 2 kg of water as load, under low sun elevation, was used to demonstrate the impact of the improvement of procedure based on Hottel-Whillier-Bliss equation. Even though only data from a single test was considered, the results clearly show that the ASAE 580.1 Standard should be improved. In the authors' opinion, highlighting the need of reporting the power with physically meaning and supported by the best scientific knowledge, represents an important scientific contribution.

Credit authorship contribution statement

Celestino Rodrigues Ruivo: Supervision, conceptualization, methodology, formal analysis, writing–reviewing and editing.

Gianluca Coccia: Investigation, editing and writing–reviewing.

Giovanni Di Nicola: Investigation, writing–reviewing and editing.

Antonio Carrillo-Andrés: Writing–reviewing and editing.

Xabier Apaolaza-Pagoaga: Investigation, data curation, visualization, writing−reviewing and editing.

Declaration of competing interest

no conflict of interest to declare.

References

[1] ASAE S580.1 NOV2013, Testing and reporting solar cooker performance, American Society of Agricultural Engineers, Michigan, USA, 2013.

[2] C. Ruivo, A. Carrillo-Andrés, X. Apaolaza-Pagoaga, Experimental determination of the standardised power of a solar funnel cooker for low sun elevations, Renew. Energy 170 (2021) 364–374, https://doi.org/10.1016/j.renene.2021.01.146.

[3] X. Apaolaza-Pagoaga, A. Carrillo-Andrés, C. Ruivo, New approach for analysing the effect of minor and major solar cooker design changes: Influence of height trivet on the power of a funnel cooker, Renew. Energy 179 (2021) 2071–2085, https://doi.org/10.1016/j.renene.2021.08.025.

[4] Solar Cookers International, https://www.solarcookers.org/resources/results (Accessed 22 April 2022)

[5] P.A. Funk, Evaluating the international standard procedure for testing solar cookers and reporting performance, Sol. Energy 68 (2000) 1–7, https://doi.org/10.1016/S0038-092X(99)00059-6.

[6] X. Apaolaza-Pagoaga, A. Carrillo-Andrés, C. Rodrigues Ruivo, Experimental characterization of the thermal performance of the Haines 2 solar cooker, Energy 257 (2022) 124730, https://doi.org/10.1016/j.energy.2022.124730.

[7] Solar Household Energy, https://www.she-inc.org/?page_id=2767 (Accessed 8 September 2022).

[8] S. M. Ebersviller, J- J. Jetter, Evaluation of performance of household solar cookers, Sol. Energy 208 (2020) 166–172, https://doi.org/10.1016/j.solener.2020.07.056.

[9] X. Apaolaza-Pagoaga, A. Carrillo-Andrés, C. Ruivo, Experimental thermal performance evaluation of different configurations of Copenhagen solar cooker, Renew. Energy 184 (2022) 604–618, https://doi.org/10.1016/j.renene.2021.11.105.

[10] V.P. Sethi, D.S. Pal, K. Sumathy, Performance evaluation and solar radiation capture of optimally inclined box type solar cooker with parallelepiped cooking vessel design, Energy Convers. Manage. 81 (2014) 231–241, https://doi.org/10.1016/j.enconman.2014.02.041.

[11] C. Ruivo, X. Apaolaza-Pagoaga, G. Di Nicola, A. Carrillo-Andrés, On the use of experimental measured data to derive the linear regression usually adopted for determining the performance parameters of a solar cooker, Renew. Energy 181 (2022) 105–115, https://doi.org/10.1016/j.renene.2021.09.047.

[12] C. Ruivo, X. Apaolaza-Pagoaga, A. Carrillo-Andrés, G. Coccia, Proposal of a non-linear curve for reporting the performance of solar cookers, Renew. Energy 191 (2022) 110–121, https://doi.org/10.1016/j.renene.2022.04.026.

[13] G. Coccia, G. Di Nicola, M. Pierantozzi, S. Tomassetti, A. Aquilanti, Design, manufacturing, and test of a high concentration ratio solar box cooker with multiple reflectors, Sol. Energy 155 (2017) 781–792, https://doi.org/10.1016/j.solener.2017.07.020.

[14] G. Coccia, A. Aquilanti, S. Tomassetti, A. Ishibashi, G. Di Nicola, Design, manufacture and test of a low-cost solar cooker with high-performance light concentrating lens, Sol. Energy 224 (2021) 1028–1039, https://doi.org/10.1016/j.solener.2021.06.025.

[15] G. Coccia, G. Di Nicola, S. Tomassetti, M. Pierantozzi, M. Chieruzzi, L. Torre, Experimental validation of a high-temperature solar box cooker with a solar salt-based thermal storage unit, Sol. Energy 170 (2018) 1016–1025, https://doi.org/10.1016/j.solener.2018.06.021.

[16] G. Coccia, A. Aquilanti, S. Tomassetti, G. Comodi, G. Di Nicola, Design, realization, and tests of a portable solar box cooker coupled with an erythritol-based PCM thermal energy storage, Sol. Energy 201 (2020) 530–540, https://doi.org/10.1016/j.solener.2020.03.031.

[17] C.R. Ruivo, A. Carrillo-Andrés, G. Coccia, X. Apaolaza-Pagoaga, Influence of the aperture area on the performance of a solar funnel cooker operating at high sun elevations using glycerine as load; Sustain. Energy Technol. Assess. 53 (2022) 102600, https://doi.org/10.1016/j.seta.2022.102600.

[18] Y. Çengel, Heat Transfer – A Practical Approach, McGraw-Hill, New York, 1998.

[19] J.A. Duffie, W.A. Beckman, Solar Engineering of Thermal Processes, fourth ed., Willey, 2013.

[20] D.E. Roberts, A. Forbes, An analytical expression for the instantaneous efficiency of a flat plate solar water heater and the influence of absorber plate absorptance and emittance, Sol. Energy 86 (2012) 1416–1427, https://doi.org/10.1016/j.solener.2012.01.032.

Appendix A- Experimental measured data and observations points

In this appendix, experimental data of just one experiment of testing a funnel solar cooker using 2 kg of water is provided. The experiment was carried out in an experimental set-up located in Malaga-Spain, at 36.9°N latitude, and 57 m above sea level. The experimental measured data, with a time interval of 1 min, is reported in Tables A1, A2 and A3. The details of the experimental set-up and how this experiment was performed can be found in [2].

Table A4 lists the values of variables of the several observation points calculated from the measured data listed in Tables A1 to A3 by adopting a time interval of 5 minutes.

Table A1. Experimental data of Expt. E64 for a testing period from 12:05 to 12:45.

Local time	Load temperature (°C)	Ambient temperature (°C)	Global normal solar irradiance (Wm^{-2})	Solar altitude angle (°)
12:05	19.55	20.84	971.50	35.11
12:06	20.10	20.89	972.39	35.20
12:07	20.63	20.92	972.53	35.28
12:08	21.26	21.01	974.23	35.37
12:09	22.00	21.10	975.32	35.46
12:10	22.67	21.10	973.51	35.54
12:11	23.47	21.19	975.78	35.62
12:12	24.30	21.26	975.79	35.71
12:13	25.13	21.39	977.09	35.79
12:14	25.98	21.33	976.99	35.87
12:15	26.86	21.13	977.51	35.95
12:16	27.72	21.19	972.45	36.03
12:17	28.62	21.20	967.85	36.11
12:18	29.51	21.28	970.24	36.18
12:19	30.44	21.50	958.84	36.26
12:20	31.35	21.62	938.92	36.33
12:21	32.27	21.84	955.77	36.41
12:22	33.19	21.74	954.66	36.48
12:23	34.09	21.68	957.33	36.56
12:24	35.07	21.86	949.38	36.63
12:25	36.03	21.88	960.94	36.70
12:26	37.02	21.83	962.77	36.77
12:27	38.04	21.71	977.80	36.84
12:28	39.01	21.71	978.83	36.90
12:29	39.99	21.69	974.84	36.97
12:30	41.01	21.87	968.20	37.04
12:31	41.99	21.93	974.83	37.10
12:32	42.97	22.07	982.74	37.17
12:33	43.95	22.17	980.77	37.23
12:34	44.92	22.24	969.01	37.29
12:35	45.88	22.01	958.05	37.35
12:36	46.89	21.89	952.79	37.41
12:37	47.82	21.77	965.58	37.47
12:38	48.77	21.89	963.46	37.53
12:39	49.74	21.89	956.83	37.59
12:40	50.70	21.38	953.71	37.64
12:41	51.65	21.28	955.73	37.70
12:42	52.62	21.38	960.14	37.75
12:43	53.55	21.57	959.30	37.81
12:44	54.50	21.86	979.10	37.86
12:45	55.48	22.17	979.43	37.91

568 Table A2. Experimental data of Expt. E64 for a testing period from 12:46 to 13:25.

Local time	Load temperature (°C)	Ambient temperature (°C)	Global normal solar irradiance (Wm^{-2})	Solar altitude angle (°)
12:46	56.49	22.21	972.80	37.96
12:47	57.48	22.08	961.79	38.01
12:48	58.47	22.26	967.81	38.06
12:49	59.41	22.07	971.60	38.10
12:50	60.39	21.76	972.89	38.15
12:51	61.35	21.68	975.81	38.19
12:52	62.32	21.46	978.06	38.24
12:53	63.24	21.77	976.04	38.28
12:54	64.17	22.29	980.35	38.32
12:55	65.09	22.36	983.34	38.36
12:56	66.04	22.59	979.38	38.40
12:57	66.96	22.93	975.32	38.44
12:58	67.88	23.03	979.67	38.48
12:59	68.78	23.06	980.82	38.52
13:00	69.69	22.84	979.36	38.55
13:01	70.61	22.59	975.90	38.59
13:02	71.51	22.38	966.49	38.62
13:03	72.36	21.96	962.29	38.65
13:04	73.26	21.88	960.01	38.68
13:05	74.15	22.03	971.65	38.71
13:06	75.10	22.20	974.88	38.74
13:07	75.94	22.06	984.65	38.77
13:08	76.82	22.07	984.77	38.80
13:09	77.69	22.27	983.55	38.82
13:10	78.55	22.18	984.35	38.85
13:11	79.41	22.19	986.29	38.87
13:12	80.23	22.74	984.11	38.89
13:13	81.10	23.16	989.05	38.92
13:14	81.88	23.56	989.74	38.94
13:15	82.75	23.79	985.60	38.96
13:16	83.55	23.14	988.71	38.97
13:17	84.36	22.71	985.27	38.99
13:18	85.16	22.94	985.73	39.01
13:19	85.98	22.80	987.10	39.02
13:20	86.75	22.67	984.79	39.04
13:21	87.56	23.03	985.10	39.05
13:22	88.37	23.35	988.34	39.06
13:23	89.14	22.87	988.80	39.07
13:24	89.89	23.02	989.53	39.08
13:25	90.69	22.93	997.95	39.09

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Table A3. Experimental data of Expt. E64 for a testing period from 13:26 to 13:31.

Local time	Load temperature (ºC)	Ambient temperature (ºC)	Global normal solar irradiance (Wm^{-2})	Solar altitude angle (º)
13:26	91.47	22.68	998.41	39.10
13:27	92.23	22.71	996.46	39.11
13:28	92.95	22.79	988.54	39.11
13:29	93.71	23.06	983.22	39.12
13:30	94.43	23.02	995.20	39.12
13:31	95.18	22.99	988.98	39.12

Table A4. Data of observation points spaced with a time interval of 5 minutes.

i	Time (min.)	$I_{n,exp,i}$ ($W\ m^{-2}$)	$T_{f,exp,i}$ (ºC)	$T_{a,exp,i}$ (ºC)	$\Delta T_{f,a,i}$ (ºC)	$\Delta T_{f,i}$ (ºC)	$\dot{Q}_i$ (W)	$\dot{Q}_{S,i}$ (W)	$\Delta T^*_{f,a,i}$ (ºC)	$\dot{Q}^*_i$ (W)	χ_i ($m^{2o}CW^{-2}$)	η_i
1	2.5	973.2	21.0	21.0	0.1	3.1	87.0	62.6	0.0	62.6	0.0001	0.179
2	5	976.1	24.7	21.2	3.5	4.5	125.1	89.7	2.5	89.7	0.0036	0.256
3	7.5	964.3	29.1	21.3	7.8	4.7	130.6	94.8	5.6	94.8	0.0081	0.271
4	10	952.8	33.7	21.8	11.9	4.7	130.6	96.0	8.7	96.0	0.0125	0.274
5	12.5	970.6	38.5	21.8	16.7	5.0	138.6	99.9	12.1	99.9	0.0172	0.286
6	15	972.3	43.5	22.0	21.4	4.9	135.9	97.8	15.4	97.8	0.0220	0.280
7	17.5	958.4	48.3	21.8	26.5	4.8	134.2	98.0	19.4	98.0	0.0276	0.280
8	20	964.6	53.1	21.6	31.5	4.8	133.4	96.8	22.8	96.8	0.0326	0.277
9	22.5	971.1	58.0	22.1	35.9	4.9	136.6	98.5	25.9	98.5	0.0369	0.281
10	25	977.7	62.8	21.9	40.9	4.7	131.1	93.9	29.3	93.9	0.0418	0.268
11	27.5	979.6	67.4	22.8	44.6	4.6	128.1	91.5	31.9	91.5	0.0455	0.261
12	30	969.3	71.9	22.3	49.7	4.5	124.3	89.8	35.9	89.8	0.0512	0.256
13	32.5	980.6	76.4	22.1	54.2	4.4	122.8	87.7	38.7	87.7	0.0553	0.250
14	35	986.5	80.7	22.9	57.7	4.2	116.9	82.9	41.0	82.9	0.0585	0.237
15	37.5	986.2	84.8	23.0	61.8	4.0	111.6	79.2	43.8	79.2	0.0626	0.226
16	40	989.1	88.7	23.0	65.8	3.9	109.6	77.6	46.5	77.6	0.0665	0.222
17	42.5	993.3	92.6	22.9	69.7	3.7	104.4	73.6	49.1	73.6	0.0702	0.210

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: