Solar cooking figures of merit. Extension to heat storage

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Solar cooking has been established as a resource to alleviate energy poverty and deforestation caused by wood burning in dwellings, especially in developing countries e. g. [1] and [2]. A large population is under risk because of wood and dung burning indoors for cooking. Not only there are a large number of premature deaths caused by inhalation and/or exposure to fumes, but also there is risk of destructive fires and skin burns [3] and [4].

Current technology of solar cookers is briefly described and their capabilities for including heat storage are commented with emphasis on the direct type. Several phase change material candidates for heat storage are presented. Solar cookers typically operate only during sunny hours, thus difficulting its implementation. Heat storage would allow dinner and breakfast cooking. There are standards for characterizing the performances of current solar cookers, but up to now they do not consider heat storage. In the paper a mathematical modelling is offered in order to explain the conventional figures of merit of common use to characterize the performances of solar cookers and the different alternatives are discussed. They can be extended to the ones that store heat. Some proposals are discussed.

**Keywords**: Solar cooking; heat storage; figures of merit; standards; Phase Change Materials; PCM; solar thermal energy; appropriate technology.

1. Introduction

In solar cookers solar radiation is directed to a cooking utensil, either directly or through a thermal fluid that transports heat (indirect cookers) [5]. Elevation of temperature is pursued so that the food is conveniently sterilized; some chemical transformations happen, hydration can happen also and the food softens, so that it becomes easily eaten and digested. A temperature above ambient is often desired when serving so that organoleptic properties are enhanced and some perception of thermal comfort is obtained. Generally a temperature above 70 ºC is required inside the food so that sterilization for immediate use is attained. The maximum solar irradiance for heating the food is \( G = 1.000 \text{ W/m}^2 \) and only a fraction of it can be collected, what makes it much lower than the heat flux obtained using a fire for cooking.

The non-mutually excluding alternatives for increasing the heat flux are: a) solar optical concentration, and b) greenhouse effect by a transparent cover. Reflective or refractive optical concentration can approach the thermal flux of fire cooking as the optical concentration can be higher than 10. The greenhouse effect is a thermo-optic diode effect that some materials have, like glass; they are transparent to most of the solar radiation but are opaque to the IR thermal radiation coming out of the heated body, thus keeping it warm. This is combined with trapping the hot gases formed by convection around the heated body, thus performing heat retention. Thermal losses to the ambience can also be reduced if some kind of thermal insulation is applied to the non-transparent parts of the cooker body.

With no optical concentration it is difficult to boil water and even more to fry, what happens at \( T > 100 \text{ ºC} \). This does not preclude cooking, but reaching the desired temperature, typically \( 70 \text{ ºC} \), takes a long time, in the order of 1 to several hours. Optical concentration can be in the order of 10 to 100, so that cooking in minutes is possible, including frying.

When reaching the boiling temperature water evaporation increases the latent heat losses so that they can be dominant in comparison with radiation and convection losses, limiting the temperature while boiling. This defines two consecutive and overlapping regimes: heating and temperature keeping. Heating is a non-steady process where the heat capacity of the body [food \(( f \) ) + containing walls \(( w \) ) + utensil \(( u \) )] of mass \( M = \Sigma M_i \) would be \( C = \Sigma c_i M_i \) if at an homogeneous temperature where \( c_i \) is the specific heat of component \( i \). It constitutes the thermal inertia. During the temperature keeping regime the food chemical transformations can be considered negligible in terms of heat in front of heat losses.

Finally, when the body is taken in the shade indoors there is a cooling regime. For immediate consumption fast cooling is desired, but for keeping the food warm some thermal insulation can prolong it for hours [6]. Some residual cooking is performed during this regime. It can be desirable or not.

Solar energy is irregular, so that a cloudy interval can ruin cooking. Some extra thermal inertia can help reducing the undesirable temperature drop. This brings the convenience of thermal storage. If there is some storing mass \( M_f \) heated together with the food, it will reduce the temperature time variations, but it will slow heating the food. Two circumstances avoid this drawback. First, \( M_f \) can be heated in advance to cooking, typically during the morning, so that the stored heat is available for accelerating the food heat up if transferring heat in parallel to direct solar heating. Second, if \( M_f \) is between the sun absorbing surface and the food, its temperature will be higher than the food temperature, thus storing more heat, but now the heat transfer rate from the PCM to the food controls its heating rate.
The amount of stored heat in common materials is limited if only the sensible heat is used \( Q = cM(T - 70^\circ C) \). Water has one of the highest values of sensible specific heat \( c = 4.19 \text{ kJ/(kg K)} \) but its evaporation and high vapour pressure above 100 °C precludes its use.

Higher storage mass density can be reached with suitable Phase Change Materials (PCMs). For the temperatures involved, their melting latent heat range is \( L = 100-350 \text{ kJ/kg} \) and \( c \sim 1.5 \text{ to 2.5 kJ/(kg K)} \) \([7]\) and \([8]\). This makes an equivalent sensible temperature increase \( \Delta T_{\text{eq}} = L/c \sim 50 \text{ to 200 °C} \) during melting, what is highly advantageous. These PCMs must be of low vapour pressure for temperatures up to 150 °C, non-toxic and even edible, long lasting, non-corrosive, low cost, recyclable and easily available. Paraffins are suitable and have melting temperatures up to \( T_m = 105 \text{ °C} \) and their density is near that of water \([8]\). Some sugar alcohols, such as erythritol, offer even higher melting temperatures, \( T_m = 118 \text{ °C} \). They exhibit higher \( L \) than paraffins and higher specific weight \( \rho \), but they show some supercooling effect \([9]\). They are used as sweetening agents in food industry. These melting temperatures are reachable with concentrating solar cookers, even in winter sunny days \([6]\) and thus these PCMs offer a high enough temperature above 70 °C to quickly transfer heat to the food, which is the only effective for cooking, thus lower melting temperatures than 70 °C are ineffective and even dangerous as sterilization cannot be guaranteed. The heat conductivity of paraffins is quite low, in the range of \( k = 0.2 \text{ to 0.65 W/(K m)} \). This limits the solar charging and discharging heat rate. In order to compensate this disadvantage it has been much proposed mixing them with structured high conductivity materials, such as fins, fibres, chips or powders. Inorganic salts and organic substances are better in this respect. Among them erythritol show higher \( L \) and \( \rho \) in addition to a much higher \( k \approx 2 \text{ W/(K m)} \), still low in comparison with metals used for utensils that show \( k \approx 15 \text{ to 200 W/(K m)} \). This raises the question of whether the PCMs and the container design for storing them could deliver heat to the food fast enough \([6]\).

This paper addresses the performances measurement of storing heat in a PCM and delivering it to the food in direct solar cookers of the individual or family size, such as those shown in Fig. 1. On the basis of simplified mathematical modelling, testing procedures are proposed for evaluating what are in reality complex processes. They include convection, radiation, phase change and mass transfer in a non-steady process with 3D geometry. The output of a possible performances standard should be a short set of figures of merit so that the relevant performances of heat storage solar cookers could be compared in a straightforward way.

![Fig. 1](http://en.wikipedia.org/wiki/Solar_cooker)  
**Fig. 1** Direct solar cookers. (a) Experimental parabolic concentrating cooker with a heat storing utensil containing a PCM between the external pot and the coaxial internal one, which incorporates food. (b) Commercial box cooker [http://en.wikipedia.org/wiki/Solar_cooker](http://en.wikipedia.org/wiki/Solar_cooker). Author: [http://commons.wikimedia.org/wiki/User:Xuaxo](http://commons.wikimedia.org/wiki/User:Xuaxo) accessed April the 28th 2013. A heat insulated box receives solar energy through a top aperture using a double layered glass. The sun radiation is boosted by external mirrors.

In Section 3.1 the theoretical basis is established. The conventional figures of merit for solar cookers of the non-storing type are presented and explained in section 3.2. The heating test is the basis for them. The possibility of taking into account the heat storage is considered so that their extension is explored. In Section 3.3 new figures of merit for complementing the previous ones are introduced and their purpose and limitations commented.

In Section 4 the cooling test is introduced for responding to the necessity of determining the overall heat transfer coefficient of the utensil and for characterizing the thermal insulating cover, like the one used in “hay baskets” for keeping the food warm. This insulating cover when combined with heat storage allows cooking overnight \([6]\).
2. Solar cooking characterization

2.1 Lumped capacity modelling

Although roasting, barbecuing and baking is possible in parabolic solar cookers [5] [8] meaning this a fairly dry process, solar cooking is performed typically in a fluid medium, using oil or most frequently an aqueous liquid. Immersed food solid pieces of volume $V_f$, having a contact surface with the liquid $A_{sp}$, specific heat $c_f$ and density $\rho_f$ evolve in time $t$ after the sudden immersion. When the product of the characteristic Biot and Fourier numbers $(BiFo)_f = \frac{hA_{sp}t}{\rho_f c_f V_f}$ >1, the temperature inside it is fairly homogeneous and close to the medium temperature [10]. $h$ is the characteristic convection heat transfer coefficient of the liquid cooking medium with food pieces and walls. If the cooking medium contains enough water or oil it is accurate enough to consider all the liquid at constant temperature. In practice the food temperature becomes close to the medium one because of the slow heating of most of the solar cookers and because the food pieces characteristic length $(V_f/A_{sp})$ is small and the pieces are mixed with the fluid medium before being heated together. Thus homogeneous temperature for the pot contents is a good simplifying hypothesis.

Because most foods are highly water containing it is current practice to perform testing and modelling of solar cooker using just water as a reasonable thermal representation of food for performance evaluation and if temperatures are too high, edible oil is used instead. The conductivity of the utensil and rest of the cooker materials is typically high and heat interchange between them is generally also high. This makes that assuming a lumped capacity (zero dimensional) model for the heated body is accurate enough, excepting the insulating material whose heat capacity is typically low. If for the moment we assume that the storage material $(s)$ reaches the same temperature, the heating and cooling time evolution of the overall temperature $T$ could be described by the differential equation:

$$\frac{dT}{dt} = F' \left[ G \eta \frac{A_{a}}{Q_{o}} \left( T - T_{st} \right) - U A \frac{T}{T_{st}} \right]$$

(1)

- $F'$ is a correction coefficient to take into account that the external temperature could be non-uniform, and also it is higher than that of the food when heating $(s)$ and lower that the one of food when cooling $(s)$ in the shade, $G = 0$. In addition to that, $F' \to 1$ when approaching the ambience temperature $T \to T_a$.
- $A_a$ is the aperture area where the tilted solar irradiance $G$ is impacting on.
- $\eta_b < 1$ is the optical efficiency because of light reflection, transmission, absorption and stray ray losses.
- $A$ is the reference area for both sensible and latent heat losses, typically the external area of the body.
- The equivalent overall convection and radiation heat transfer coefficient is dependent on temperature, $U\langle T \rangle$, for losses to ambience of temperature $T_{st}$, it is referred to $A$.

2.2 Standardized figures of merit

2.2.1 First figure of merit

The first experimental figure of merit $F_i$ comes in the Indian standard [9] and [10]. It requires a stagnation heating test which means $dT/ dt = 0$ in Eq. (1) when $T = T_{st}$, maximum temperature. This means that solar input balances heat losses. This implies that $C dT/ dt \ll GA_\eta_b$, which can be taken as a quality criterion for the stagnation test.

$$F_i = \frac{\eta_b}{U \langle T_{st} \rangle} \to F_i = \frac{\eta_b}{A_{a}} \frac{\left( T_{st} - T_a \right)}{G}$$

(2)

For box cookers and parabolic cookers we find fairly close values $0,12 < F_i < 0,16$ m² K W⁻¹.

The homogenization of temperatures at the end of this test ensures $F_i \mid_{st} = 1$. An almost still atmosphere is required for this test as the wind speed increases $U$ and correspondingly reduces $T_{st}$.

$F_i$ is a figure of merit valid for characterizing heat storing cookers if the stagnation lasts enough along time for the presumably slower heating of PCM $(s)$ than sensible materials to reach the equilibrium temperature under a constant $G$.

This would require $(BiFo)_s > 1$ and $h$ is now for internal natural convection towards cooking medium $\sim 15$ W/(m² K) for typical stagnation temperatures or an equivalent amount of 1,500 W/m² because of the absorbed solar heat flux. Assuming a Nusselt number $Nu = 1$, thus with no natural convection internal to the PCM, for the worst case $Bi = h/\kappa \sim 0.2$ for raw PCM with some cm thickness $t$, thus $Fo_t = 5$ is required if the PCM were subjected to a temperature step, what implies about 75 min stabilization time. This is within the two hours around noon recommended for stagnation tests. This homogenization time is much reduced if the stagnation test is done in a prolonged test.
preheating the PCM under the sun in the morning. Still there is the question of whether the PCM will reach homogeneous temperatures in a prolonged stagnation test if its characteristic length for heat conduction $l$ is larger than some cm.

The effect of thermal inertia is recognized so that an empty cooker is specified for the standard test and the temperature is measured at the basis plate for the pot in box cookers.

2.2.2 Second figure of merit

The other figure of merit considered in the Indian standard is $F_2$, which is an approximation to $\eta_o$:

$$F_2 = \frac{F_1 C_l}{A(t_2 - t_1)} \ln \left[ \frac{1 - \frac{A}{A_\text{g}} \frac{1}{G F_1} (T_1 - T_a)}{1 - \frac{A}{A_\text{g}} \frac{1}{G F_1} (T_2 - T_a)} \right] = \eta_o F'_{h\omega} C_R$$

$$\text{(3)}$$

This equation comes from integrating Eq. (1) when all its terms are assumed constant, excepting $T$ and $t$, between times $t_1$ and $t_2$ after starting, being $T_1$ and $T_2$ the respective temperatures reached.

$F'_{h\omega}$ is the value of $F'$ for the heating test.

This equation considers $U = U_{h\omega}$, because it includes $F_1$, so that temperatures $T_1$ and $T_2$ near stagnation values should be used to reduce error, for $U$ increases with the body temperature above ambient, thus $U = U (\bar{T})$.

Experimental determination of $F_2$ needs a heating process under a time-constant $G$. An average value is considered suitable in the test around noon.

The heat capacity ratio $C_R = C_l / C$ because heating is considered useful only for heating the liquid. This makes that the load heat capacity $C_l$ must be specified.

From the point of view of thermal inertia the wall heat capacity (and the storage heat capacity in due case) could be considered useful. In the inside of a heat insulation, such as the one in box cookers, Fig. 1b, temperature is fairly homogeneous, such that adding the heat capacities of all the components (mainly walls) could be considered accurate enough. But those parts that are thermal insulators exhibit a temperature distribution that goes from the inner part temperature to a temperature near ambient on their external surface. As the heating test is a non-steady process, a linear temperature distribution inside them can be non-representative. As a consequence, their effective heat capacity is not well known and can change along the test. This precaution seems not worthwhile when the insulation material is light as its heat capacity will be small.

In storing cookers $C_R$ is substantially less than 1.0 what could yield low values for $F_2$. This indicates that the liquid temperature will rise slowly unless $A_\text{g}$ is large enough. This is typical in concentrating cookers in comparison with box cookers.

Equation (3) considers that only the water heating is useful. But with heat storing cookers heating the accumulator is useful too. Thus, for a moment let’s suppose that in Eq. (3) $C_R = 1$ so that $C$ substitutes $C_l$ for $F_{2,\text{mod}}$.

One problem is the variation of $C$ because of the PCM melting, whose progression is unknown. As $F_{2,\text{mod}}$ in the modified Eq. (3) should be independent of the value of $C$, the only basic requirement is that during melting the same rate of melting is operating at $t_1$ and $t_2$, but this is difficult to determine in practice. The alternative of choosing $T_1$ and $T_2$ lower than the melting temperature still finds the problem of the PCM being at non-uniform temperature for the heating is too fast. Besides this, in this case $U < U_{h\omega}$ and this reduces accuracy.

One solution for both problems is to substitute the PCM with a suitable liquid, e. g. water or by a highly conducting material, so that a more homogeneous temperature distribution is attained, yielding $C'$ and still using $C_R = 1$ in Eq. (3).

Now $F'_{h\omega}$ can be slightly different. This $F_{2,\text{mod}}$ will put heat storing cookers under the same basis for evaluation than non-storing cookers.

2.2.3 Optical efficiency

The effect of $F'_{h\omega}$ could be eliminated measuring two external temperatures near $T_a$: $T_{e,1} = T_a + \Delta T$ at $t_1 = t_0 + \Delta t$ and $T_{e,2} = T_a + \Delta T$ at $t_2 = t_0 + 2\Delta t$; then on average $U = 0$ under natural convection and radiation at $t_0$. The resulting equation does not require $F_1$ [11] neither has the problem of varying $C$ if a liquid substitutes the PCM, as just above is proposed. The result is that $\eta_o$ can be determined with the following equation:

$$\eta_o = \frac{C' T_{e,2} - T_{e,1}}{A \bar{T} G 2\Delta t}$$

$$\text{(4)}$$

$\bar{T}$ is a spatially averaged external temperature. As $\eta_o$ is a purely optical parameter, changing $C$ to $C'$ by a material substitution does not incur in loss of accuracy, neither the value of $C'$ is of basic significance in the result, if the experiment is well designed under the metrological point of view. More relevant is the change in $\eta_o$ by the different elevation and azimuth of a solar tracking cooker or by the different solar ray incidence angle to the aperture surface for a stationary cooker along the day.
Another technique for alternatively determining $F_2$ around $T_o$ is described in [12], although it requires additional testing hardware.

Typical values of $\eta_\infty$ range from 0.25 to 0.55 for both parabolic cookers and box cookers when they are properly aligned with the sun. Selective absorbing surfaces are not in use today in solar cookers excepting those that are based on evacuated tubes coming from commercial solar collectors for hot water production.

2.2.4 Useful heating power

A characteristic useful heating power, $\dot{Q}$ in Eq. (1) has been proposed as a figure of merit, quantifying the food heating capacity of the cooker under standard conditions of almost null wind speed and $G^* = 700 \text{ W/m}^2$, measured normal to sun rays with a pyranometer. As $\dot{Q}$ diminishes with the body temperature, Eq. (1), a characteristic value with an over-temperature of 50 ºC is specified by the ASAE S580 standard [15]:

$$\dot{Q}_{\text{stan,sun}} = \left(\dot{Q}_{\text{I}}\bigg|_{T_l-T_a = 50 \text{ ºC}}\right) \frac{G^*}{G_{|T_l-T_a = 50 \text{ ºC}}}$$

(5)

$T_l$ is the temperature of the liquid inside the utensil. The centred, second order accurate, finite differences algorithm for calculating $\dot{Q}$ at the discrete points $i$ of measurement is based on Eq. (1):

$$\dot{Q}_{i,i+1} = C_i \frac{T_{i,i+1} - T_{i,i-1}}{t_{i,i+1} - t_{i,i-1}}$$

(6)

$C_i$ is the nominal liquid contents heat capacity. Excluding the other heat capacities makes that only the useful heating power is being evaluated.

This procedure can be extended to heat storage cookers. With this kind of cookers two heating powers can be differentiated. One is the heating power of the PCM and the other is the heating power of the sun. When looking at the already existing standards that characterize only the solar heating power, a procedure establishing whether preheating of the PCM is performed or not is lacking. On this respect some possibilities can be envisaged.

1. A.- Heating the liquid load in the shade starting at $T_a$ with the PCM fully charged in a previous process under the sun. This circumstance can be both checked by assuring that the PCM has been fully melted at a specified heating above melting temperature. This test evaluates the capacity of heat transfer from PCM to the food. A variety of this test is to pre-charge the PCM with an electric heater indoors.

1. B.- Alternatively the PCM could be charged during a specific time, let’s say from sunrise to noon.

2. Simultaneously heating the PCM and the liquid under the sun. Both charging capacity and discharging in the liquid heating process are evaluated in this test.

Options 1.B and 2 would require that the obtained value is corrected for sun irradiation in a similar way as in Eq. (5) when looking at the already existing standards that characterize only the solar heating power, a procedure establishing whether preheating of the PCM is performed or not is lacking. On this respect some possibilities can be envisaged.

Still the PCM charging capacity and charging rate is not characterized. The next section addresses this issue.

2.3 Additional figures of merit for heat storing solar cookers

2.3.1 Nominal stored heat

The nominal heat stored in the utensil is $Q_s = M_s \left[ L + c_p (T_0 - 70 \text{ ºC}) \right] + M_p c_p (T_0 - 70 \text{ ºC}) + M_w c_w (T_0 - 70 \text{ ºC})$: for a temperature $T_0 > T_w > 70 \text{ ºC}$, considering the same specific heat in liquid than in solid state for the PCM, namely $c_p$, and respectively considering a heat capacity of pots $C_p = M_p c_p$ and walls $C_w = M_w c_w$. 70 ºC has been considered the minimum temperature for sterilization. This heat is available for increasing the temperature of the food above ambient and for temperature keeping against losses either I.- with no solar input (in the shade) or II.- under the sun, depending whether cooking lunch or either breakfast or dinner. The time for cooking is very dependent on the nature of the food, so that establishing a standard time for keeping the temperature is difficult. Moreover, the losses coefficient $U_{ls}$ has been already determined with $F_1$, Eq. (2) in combination with $\eta_\infty$, Eq. (4), so that ignoring this regime yields a figure of merit evaluating the theoretical heat storage capacity compared with the heat desired for cooking the nominal liquid mass load $M_{l,\text{nom}}$, whose specific heat is $c_l$. Choosing the worst case, just above named I, equating $Q_s$ to the heat required to increase the temperature of the nominal water load $M_{l,\text{nom}}$ to an equilibrium temperature $T_{eq}$, leads to the limit over-temperature that is the liquid temperature increase for the simplifying case indicated:

$$T_{eq} - T_a = M_s \left[ L + c_p (T_0 - T_w) \right] + M_p c_p (T_0 - T_w) + M_w c_w (T_0 - T_w)$$

(7)

In heat storing solar cookers generally $\Delta T_p, \Delta T_w < < \Delta T_l$ owing to the high melting heat $L$, $M_p \sim M_s$ and that generally $c_w > c_p > c_l$.

As with the stagnation test, if the resulting temperature is higher than 100 ºC, oil must be selected for the liquid or 100 ºC declared plus the quantity of boiled water. $\Delta T_l$ in Eq. (7) varies between $\approx 50 \text{ ºC}$ for paraffins up to $\approx 110 \text{ ºC}$ for...
erythritol, so that with no losses boiling is possible with a unity ratio of PCM mass to water mass, using the reported values.

2.3.2 Useful heat power

Equation (7) establishes the upper limit equilibrium temperature for a simple heating test that would determine both the real liquid heating with losses and the useful heating power. The procedure for determining the real value could be similar than the heating test used for determining \( F, \) Eq. (3), but with no insolation \( \dot{Q}_{\text{Solar}} = 0 \) and assuming a single spatially averaged temperature \( T_s \) for storage, pot and walls. Splitting the body in two sub-bodies: liquid (\( l \)) and the PCM (\( s \)) plus the corresponding part of the utensil, generally pots (\( p \)), at the same temperature \( T_s \), one obtains:

\[
\frac{dT}{dt} = M_c \frac{dT}{dt} + \left( M_c s + M_c p + M_c l \right) \frac{dT}{dt} = -F' \alpha AU \left( T_s \right) \left( T_s - T_a \right)
\]

Integration of this equation from the initial temperatures to the equilibrium temperature is not straightforward because the degree of solidification is not known. A procedure for this is described in the following. A simple model for an equivalent \( c_s \), valid for both solid (\( \text{s} \)) and liquid (\( \text{l} \)) PCM, can be built assuming a uniform step change during the melting temperature interval \( \Delta T \) [6]:

\[
\begin{align*}
T < T_s - \Delta T / 2 & \rightarrow c_{s, l} = c_{s, l, 0} \\
T - \Delta T / 2 \leq T_s \leq T + \Delta T / 2 & \rightarrow c_{s, l} = \frac{c_{s, l, 0} + c_{s, l, q}}{2} + \frac{L}{\Delta T} \\
T > T_s + \Delta T / 2 & \rightarrow c_{s, l} = c_{s, l, q}
\end{align*}
\]

The melting interval \( \Delta T \) is null for pure substances and \( \approx 10 \text{ to } 20 \degree C \) for mixtures, like technical paraffins. During this interval a mushy state has been reported. No supercooling has been considered in this model for simplicity, because of the many parameters influencing on this undesirable effect, although up to about 14 \degree C has been reported after some thermal cycling, e. g. [9]. Supercooling can be included modifying \( T_s \).

Eq. (9) plus the integration result of Eq. (8) allow a numerical estimation of \( T_{eq} \) if a known value of \( U \) is used. It could be the experimentally obtained constant value \( U \left( T_{eq} \right) \), obtained through Eqs. (2) and (3), albeit accepting some error as \( T_{eq} < T_s \). A better estimation can be obtained if a correction is applied, according to the theory of natural convection, accepting \( U \left( T \right) \propto \left( T - T_c \right)^{0.25 \text{ to } 0.4} \) [10]. This reference model assumes that natural convection is dominant. If the cooling test results (described in Section 4, case B) are available, better values of \( U \left( T \right) \) can be obtained.

In Eq. (8) all the terms of \( \dot{Q} \) can be determined; with the algorithm of Eq. (6) and for an over-temperature of 50 \degree C. A standard heating power with PCM can be experimentally obtained:

\[
\dot{Q}_{\text{stand,PCM}} = \left. \dot{Q} \right|_{T_s - T_0 = 50 \degree C}
\]

This is a figure of merit that besides being easily determined gives understandable information to the user. It is a characteristic useful heating power between the maximum value when the cold food is put inside the utensil and the null value at \( T_{eq} \).

3. Cooling test

If in Eq. (1) the solar power is null, \( \dot{Q}_{\text{Solar}} = 0 \), the differential equation becomes representative of a cooling test (\( co \)), reducing to:

\[
\frac{dT}{dt} = \frac{T - T_s}{t_0} \ ; \ t_0 = \frac{C}{F' \alpha U}
\]

In the left hand equation \( t_s \left( T \right) \) is a characteristic cooling time that can in any case be determined in the processing of only temperature data resulting from a cooling test using the discretising algorithm in Eq. (6).

3.1 No cover

The bare utensil can be left in a room with stagnant air for a cooling test in the shade. Test inside a wind tunnel will determine the sensibility to air velocity.

A) In the case of a non-heat storing solar cooker \( C \) can be known with relative accuracy and it is constant neglecting water loss by evaporation. This test allows to determine \( \left( F' \alpha U \right) \left( T \right) \) which differs from \( U \) only in the factor \( F' \alpha U \) because \( T > T_s \). Integration assuming a constant value for \( F' \alpha U \) and an initial temperature \( T_0 \) leads to.
\[
\frac{T - T_a}{T_0 - T_a} = \exp\left( -\frac{t}{t_0} \right)
\]  

(12)

Minimum squares fit of this equation to the measured data with a free value of \( t_0 \) leads to an average \( t_0 \) that is a figure of merit for the whole cooling process. The typically longer time for cooling than for heating leads to: a relative homogenization of the spatial temperature distribution in the inner part of the body that improves the accuracy of this test results in comparison with the heating test, and also leads to approaching \( F \) to 1.0.

B) In the case of a heat storing cooker, because of the unknown value of \( C \) during solidification, it is not possible to determine \( \langle F \rangle \) unless a substitution of the PCM by a liquid or by a highly conducting solid with no phase change, thus with a known value of \( C \). Substitution of this information into Eq. (1) leads to the possibility of modelling a heating process under the sun with the inherent inaccuracy of being \( F \) eventually acceptable. The change of the heat storing material should not have a substantial influence on \( U \).

3.2 With insulating cover

Some solar cookers, either non-storing or storing, have the possibility of covering the utensil with insulating pieces of textile material, wood chips or hay after sun exposure. This increases the characteristic cooling time several times, thus either keeping the food warm or extending cooking in the afternoon. This concept can be extended such that a very insulating cover is devised for reaching efficient heat insulation, avoiding water vapour escaping and interrupting hot air leaks. Figure 2 shows a prototype developed for this task [6].

The result is an increase of \( t_0 \) up to 30 hours making possible to cook the dinner and even the breakfast next day. Artificial insulation material can be used, such as mineral wool or better than this, closed cell foam in order to reduce humidity absorption. Evaluating the insulating capacity of this device is relevant with the cooling test.

In Eq. (12) when \( t = t_0 \) the over-temperature is 36.8% the initial value. This figure of merit can be measured either with non-storing or storing solar cookers. Alternatively \( T = 70 \, ^\circ\text{C} \) or a suitable sterilizing temperature can be used as final temperature and the time for reaching it starting at a specified temperature given as a figure of merit. The meaning of either time is clear and its understanding simple.

4. Conclusions

The paper offers an extension of the accepted and standardized testing procedures for non-heat storing solar cookers of the direct type to those that incorporate heat storage, either of sensible or latent heat, such as PCMs. Similar testing is proposed to characterize their performances: under the sun heating test up to stagnation and cooling test in the shade, although some modifications must be accepted. The figures of merit are the same, but with a different interpretation.

- An extra test is needed to determine the heat transfer capacity of the heat storage to the testing fluid that represents the food.
- Another extra test is needed if a heat insulating cover is used to extend the heat storage time.

Both of them yield their respective figures of merit. Some issues are raised:

- Water evaporation must be kept under minimum unless including its effect is desired.
- The overall heat transfer coefficient \( U \) is temperature dependent.
- The optical efficiency is sensible to the sun-cooker geometry.
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