

SOLAR COOKING WITH HEAT STORAGE: EXPERIMENTS USING PCM AND FIGURES OF MERITS FOR SOLAR COOKERS

A. Lecuona-Neumann¹, J. I. Nogueira-Goriba¹, R. Ventas-Garzón

1: Grupo ITEA Departamento de Ingeniería Térmica y de Fluidos, Universidad Carlos III de Madrid
Avda. de la Universidad 30, 28911 Leganés, Madrid
lecuona@ing.uc3m.es, goriba@ing.uc3m.es web, rventas@ing.uc3m.es: <http://www.uc3m.es>

Abstract: *Solar cooking has been established as a resource to alleviate energy poverty and deforestation caused by wood burning in dwellings, especially in developing countries. It may also alleviate the several million premature deaths per year that are attributed to illnesses originated by smoke. In [1] –[4] diverse aspects on the topic can be found.*

A large population is under risk. Not only by inhalation and/or exposure to fumes, but also there is risk of destructive fires and skin burns.

Improved cookstoves are believed to alleviate this problem for a large fraction of humanity that cooks using firewood, but the health and environmental problems still remain.

Cooking with the sun energy offers eliminating both deforestation and fumes. Its implementation suffers several problems that can be addressed. Technological application and development can overcome them by offering appropriate technologies.

In this paper current technology of solar cookers is briefly described and their capabilities for including heat storage are commented with emphasis on those of the direct type. Several phase change material (PCM) are presented as candidates for heat storage.

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 performance of current solar cookers, especially the direct heating types, but up to now they do not consider any sort of 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. The different alternatives are discussed, as well as how they can be extended to the ones that store heat.

The paper offers results on a laboratory scale of a prototype of solar utensil. It is implemented in concentrating cookers of the parabolic dish variety that is nowadays widely commercialized. It allows cooking while heat storage is performed into it. After sun exposition, the utensil is stored in an insulating device indoors, allowing to cook and heat water at night, and even cook breakfast.

Keywords: Cooker, Oven, Solar, Thermal, Food processing, developing countries

1. INTRODUCTION

1.1 Solar cooker scenario

With direct solar cookers solar radiation is focused on a cooking utensil [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, in such a way that becomes easy to eat and digest. 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 °C is required inside the food attaining sterilization for immediate use. The maximum solar irradiance for heating the food is $G \approx 1 \text{ kW W/m}^2$. A fraction of it can be collected and optically concentrated, but the result is generally a lower number than the heat flux obtained using a fire for cooking.

The non-mutually excluding alternatives for increasing the heat flux are:

- Greenhouse effect by a selective transparent cover. The greenhouse effect is a thermo-optic diode that some materials offer, like ordinary glass. They are transparent to most of the interesting solar radiation (VIS (Visible) and NIR (Near Infra-Red) but are opaque to the FIR (Far Infra-Red) 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 and allowing a kind of oven effect. 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.
- Solar optical concentration to reduce the heat losses surface. Reflective or refractive optical concentration can approach the thermal flux of fire cooking as the optical concentration can be higher than 10. With no optical concentration it is difficult to boil water and even more to fry, what happens at $T > 100 \text{ °C}$. Absence of solar concentration does not preclude cooking, but reaching the desired temperature, typically $> 70 \text{ °C}$, would take a long time, in the order of one to several hours. Optical concentration factors 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 thermal radiation and convection losses, limiting the temperature while boiling. This defines three consecutive regimes when cooking:

- **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 . C constitutes the thermal inertia.
- **Temperature keeping** regime. The food experiences chemical and physical transformations that can be considered negligible in terms of heat in respect to heat losses. Pathogens killing is performed above around 70 °C.
- **Cooling** regime. The food is taken to the shade indoors for its final preparation and consumption. For immediate consumption fast cooling is desired, but for keeping the food warm some thermal insulation can prolong it for hours [6]. Residual cooking is performed during this regime. It can be desirable or not.

1.2 Simultaneous heat storage convenience and possibilities

Solar energy is irregular, so that a cloudy interval can ruin cooking. Some extra thermal inertia can help reducing the undesirable temperature drop. This highlights the convenience of thermal storage. If there is some storing mass m_s heated together with the food, it will reduce the temperature time variations, but it will slow the food heating. Two circumstances avoid this drawback.

- Firstly m_s can be heated in advance to cooking, typically during the morning, so that the stored heat is available for accelerating the food heat up. This could be performed allowing heat transfer to the food simultaneously to direct solar heating.
- Additionally, if m_s is located between the sun absorbing surface and the food, its temperature will be higher than the food temperature during heating, thus storing more heat, but now the heat transfer rate from the PCM to the food controls its heating rate.

The amount of useful stored heat in common materials is limited if only the sensible heat is used $Q = cm(T-70\text{ °C})$. Water has one of the highest values of sensible specific heat $c = 4.2\text{ kJ/(kg K)}$ but its evaporation and high vapour pressure above 100 °C precludes its use in simple and appropriate technology.

Higher thermal storage mass density can be reached with suitable Phase Change Materials (PCMs). For the temperatures involved, this paper proposes solutions with melting latent heat range in the order of $L = 100\text{-}350\text{ kJ/kg}$ and specific heat, $c_s \sim 1.5\text{ to }2.5\text{ kJ/(kg K)}$ [7] and [8]. This makes an equivalent sensible temperature increase $\Delta T_{equ} = L/c_s \sim 50\text{ to }200\text{ °C}$ 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 just for the case of leaking, long lasting, non-corrosive, low cost, recyclable and easily available. In addition to that, long term low degradation is a must.

- **Paraffins** are suitable and have melting temperatures up to $T_m \approx 105\text{ °C}$ and their density is near that of water [8]. A low heat conductivity $k_s \approx 0.2\text{ W/(K m)}$ limits the solar charging and discharging heat rate. A density $\rho_s \approx 8.8\text{ g/cm}^3$ limit their volume energy density, thus increasing bulk and lengths and as a result exacerbating the conduction and convection heat transfer rate.
- **Sugar alcohols**, such as erythritol, offer higher melting temperatures, $T_m \approx 118\text{ °C}$ and higher $k_{s,sol} = 0.73\text{ W/(K m)}$ and $k_{s,liq} = 0.33\text{ W/(K m)}$, facilitating heat transfer to food and a very favourable $L = 340\text{ kJ/kg}$, very similar that of ice melting, $c_{s,sol} = 1.38\text{ kJ kg}^{-1}\text{ K}^{-1}$, $c_{s,liq} = 2.76\text{ kJ kg}^{-1}\text{ K}^{-1}$. Another candidate, D-mannitol, offers a higher $T_m = 165\text{ °C}$, $k_{s,liq} = 0.28\text{ W/(K m)}$ and lower $L \approx 300\text{ kJ/kg}$; $c_{s,sol} = 1.32\text{ kJ kg}^{-1}\text{ K}^{-1}$, $c_{s,liq} = 1.9\text{ kJ kg}^{-1}\text{ K}^{-1}$. It shows a diversity of solid phases, reducing its heat storage performances. Sugar alcohols exhibit higher L and heat conductivity than paraffins and higher specific weight $\rho_s \approx 1.5\text{ g/cm}^3$, but they show some supercooling effect [9]. They are used as sweetening agents in food industry, so that availability and affordable price are assured.
- No other PCM for this range of temperatures and heat storage performances have been found up to now.

The mentioned 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. Above this temperature is the only effective heat for cooking, thus melting temperatures lower than about 100 °C are ineffective and even dangerous as sterilization cannot be guaranteed. Residual heat below 70 °C is still useful for preparing hot sanitary water.

Even the heat conductivity of sugar alcohols can be judged not high enough in comparison with metals used for utensils that show $k \approx 15\text{ to }200\text{ W/(K m)}$. 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, Fig. 3. This raises the question of whether the container design with PCM could deliver heat to the food fast enough [6]. This issue is also addressed in this paper.

After heat storage, the utensil containing the PCM is kept inside an insulating cover, so that heat losses are minimized, Fig. 2. It is also possible to introduce water inside this cover, helping the latent heat stored in the PCM, as can be appreciated in Fig. 3d.

1.3 Considered configurations

This paper addresses the performances measurement of storing heat in a pot type utensil with a form factor appropriate for its application in the third world as a usual pot. It contains erythritol as PCM and delivers it to water mimicking the real food. Its application is for direct type 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 energy intensive processes, not only in this precise type of solar cookers, but also in others. The output of a possible performances standard should be a small set of figures of merit so that the relevant performances of heat storage solar cookers could be compared in a direct way.



Figure 1 Direct solar cookers. (a) Commercial parabolic dish concentrating cooker using a heat storing utensil containing erythritol between the external pot and the coaxial internal one, which allocates the food, as developed by the ITEA group. (b) Commercial solar oven of the box type. Source: http://en.wikipedia.org/wiki/Solar_cooker. (Credit: <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 and heat insulating walls and floor. The sun radiation is boosted by moderate concentration external mirrors.

2. SOLAR COOKING FIGURES OF MERIT

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 liquid medium (i), using oil or most frequently an aqueous liquid. Immersed food solid pieces of mass m_f , having a contact surface with the liquid A_{if} , specific heat c_f , evolve in time t after the sudden immersion in a fluid of heat convection coefficient h . When the product of the characteristic Biot and Fourier numbers $(BiFo)_f = \frac{h_{if}A_{if}t}{m_f c_f} > 1$, the temperature inside it is reaching a fairly homogeneous and close to the medium temperature [10],

excepting for large chunks of food because of a Biot number $Bi_f = \frac{h_{lf}L_f}{k_f}$ larger than 1, what is not the usual case in solar cooking.

- In practice the food temperature becomes close to the fluid one because of the slow heating of most of the solar cookers and because the food pieces characteristic length (V_f/A_{lf}) 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.
- If the cooking fluid contains enough water or oil to allow free convection it is accurate enough to consider all the liquid at constant temperature. This is a consequence of fulfilling the same criterion by the liquid when heated by the pot walls: $(BiFo)_l = \frac{h_{lw}A_{lw}t}{m_l c_l} > 1$.
- It is evident that for the solid PCM $Bi_s \gg 1$, thus large temperature differences inside it are expected when applying solar irradiation to the PCM. But waiting large enough times to favour temperature homogenisation and full melting, will help. The distribution of the PCM proposed in this paper can be checked at Fig. 2.

Most foods are highly water containing, thus for performance evaluation it is current practice to perform testing and modelling of solar cooker using just a load of water as a reasonable thermal representation of food and cooking medium, thus $m_{lf} = m_l$. If temperatures are too high edible oil is used instead. The conductivity of the utensil and the remaining 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, but fortunately its heat capacity is low, so that neglecting its effect seems accurate enough. If for the moment we assume that the PCM reaches the same lump temperature, the heating and cooling time evolution of the overall temperature T could be described by the differential equation:

$$\underbrace{\underbrace{\underbrace{\dot{C}_{fl}}_{\dot{C}_f} + \underbrace{\dot{C}_l}_{\dot{C}_l} + \underbrace{\dot{C}_{p+b} + \dot{C}_s}_{\dot{C}_u}}_{\dot{C}}}_{\dot{Q}} \frac{dT}{dt} = F' \left[\underbrace{G_T A_a \eta_o}_{\dot{Q}_{Solar}} - \underbrace{UA(T - T_a)}_{\text{Over-temperature}} \right] - \dot{m}_b L_b + \dot{Q}_x \quad (1)$$

- F' is a correction coefficient to take into account that the inside temperatures could be not exactly uniform. Consequently the external temperature is higher than that of the liquid substituting the food when heating ($_{he}$) and lower when cooling ($_{coo}$) in the shade, where solar tilted irradiance $G_T = 0$, according to usual practice [17]. In addition to that, either $F' \rightarrow 1$ when approaching the ambience temperature $T \rightarrow T_a$ or approaching the stagnation temperature: $\frac{dT}{dt} = 0 \Rightarrow T = T_{st}$. In a progressive heating along the morning, one can expect that $F' \approx 1$ under some conditions. This issue is analysed below.
- A_a is the aperture area where the tilted solar irradiance G_T is impacting on.
- $\eta_o < 1$ is the optical efficiency because of light reflection, transmission, absorption and stray ray losses.
- A is the reference area for both sensible and evaporation latent heat losses, typically the external area of the heated body.
- The equivalent overall convection and radiation heat transfer coefficient is mainly dependent on temperature and wind speed v_a ; $U \langle T, v_a \rangle$, for losses to ambience of temperature T_a ; it is referred to A.

- \dot{m}_b is the evaporation or boiling mass flow. L_b is the latent heat of water evaporation.
- \dot{Q}_x is the auxiliary power applied, e. g. a submerged electrical resistance for performing a test.
- C_{p+b} refers to pot and solar oven box, if existent.

Figure 2 offers a view of a prototype developed at the research group ITEA of a pot based utensil with heat storage, devised for solar cooking, according to Fig. 1. In this utensil the sun heats the PCM directly, as it is located between an external large pot and an inner smaller one. The liquid and/or food is contained in the inner smaller pot.

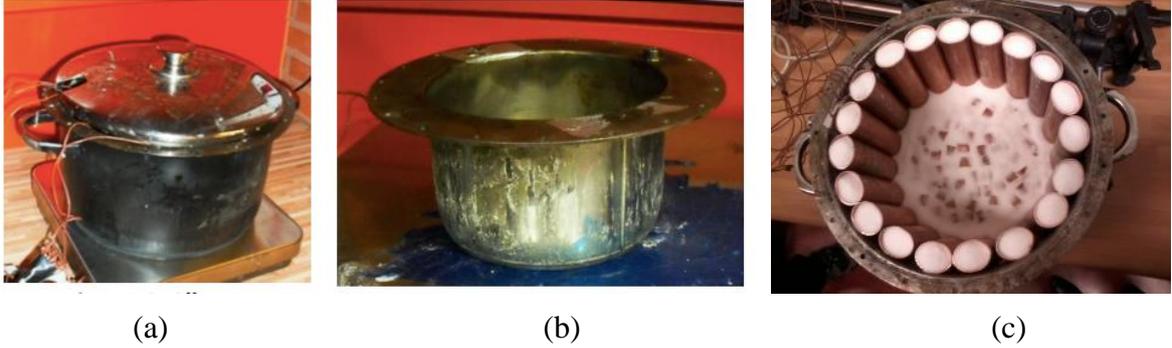


Figure 2 (a) Heat storing utensil formed by two coaxial pots, showing the thermocouple wires and being weighted for water evaporation evaluation. The flange for joining the inner and outer pots is evident, as well as the double walled top lid. (b) Inner pot with integral flange for cooking. It includes two wells for measuring temperature inside the PCM and an overpressure release valve. (c) External pot showing virgin erythritol powder filling copper tubes for enhancing the heat conduction [16].

2.2 Standardized figures of merit

2.2.1 First figure of merit F_1

F_1 comes in the Indian standard [9] and [10]. It requires a stagnation heating test which means $dT/dt = 0$ in Eq. (1) when reaching $T = T_{st}$, maximum temperature. It characterizes when heat losses counter-balance solar input. This implies that $CdT/dt \ll G_T A_a \eta_o$, which can be taken as a quality criterion for the stagnation test.

$$\left. \begin{array}{l} \text{Definition: } F_1 \doteq \eta_o / U \langle T_{st} \rangle \\ \text{Eq. (1) with } \frac{dT}{dt} = 0 \end{array} \right\} \rightarrow F_1 = \frac{A}{A_a} \frac{(T_{st} - T_a)}{G_T} \quad (2)$$

$$\doteq C_s^{-1}$$

For box solar ovens and parabolic dish cookers one can find fairly close values $0.12 < F_1 < 0.16 \text{ m}^2 \text{ K W}^{-1}$.

An almost still atmosphere is required for this test as the wind speed increases U and correspondingly reduces T_{st} .

- **Non storing cookers.** The requirements for an accurate experimental determination is included in the analysis below.
- **Storing cookers.** F_1 is a figure of merit that could be valid for characterizing heat storing cookers if the stagnation lasts enough for the presumably slower heating of PCM than sensible heat materials

to reach the equilibrium temperature for the PCM being completely melted and then perform the test under a constant G_T . This would require $(BiFo)_s > 1$ and for being conservative h is now the smaller between external, $h_a \sim 5 - 15 \text{ W}/(\text{m}^2 \text{ K})$ and internal natural convection towards cooking medium, $h_l \sim 500 - 1,500 \text{ W}/\text{m}^2$. As this is typically $< C_s G_T / (T_{st} - T_a)$ representing the heat input, the external h is limiting. Assuming a Nusselt number $Nu_s \approx 1$, thus neglecting natural convection inside the PCM, for the worst case $Bi_s = h_{min} l / k_s \sim 10^{-1} - 10^0$ for PCM with some cm thickness l , thus $Fo_s \approx 5$ 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 standard tests. This seems reasonable for such a design layout that charges the PCM before sun decline in the afternoon, but could be not the case for some other designs. 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, implying a high Bi_s . But this seems not to be the case if effective power to the food is searched for.

For such difficult cases, the original definition of F_1 can be used, Eq. (2) measuring U_{st} and η_o separately through alternative experiments. U_{st} could be measured using an instrumented auxiliary heating electrical resistance to stabilize a previously estimated T_{st} giving from Ec (1) with $G_T = 0$ and $\dot{m}_b = 0$:

$$\dot{Q}_x = F'_{st} U'_{st} A (T_{st} - T_a).$$

$F'_{st} U'_{st}$ will slightly differ from the real value U_{st} because the temperature distribution inside the utensil during this test does not coincide exactly with solar heating during the stagnation test. η_o measurement is described below.

Going back to the effect of thermal inertia C , it is recognized to difficult fulfilling $C dT / dt \ll G_T A_a \eta_o$ so that an empty cooker is specified for the standard test for non-storing cookers and the temperature is measured at the basis plate for the pot in box cookers. In a heat storage solar cooker this is especially difficult because of the large value of equivalent C_s , Eq. (10). Following the standard's philosophy, there is an additional alternative: the PCM content can be removed and the stagnation test performed, as F_1 evaluates parameters external to the PCM storing and delivering processes.

As a conclusion, there are at least three reasonable possibilities of determining F_1 for storing solar cookers.

2.2.2. Second figure of merit F_2

The other figure of merit considered in the Indian standard is F_2 , which is an approximation to η_o . From integration of Eq. (1) during a still air heating experiment ($_{he}$) between (t_1, T_1) and (t_2, T_2) , with $G_T = \text{const.}$, $\eta_o = \text{const.}$ and with F_1 considered applicable although originally it corresponds to stagnation:

$$F_2 = \frac{F_1 C_l}{A(t_2 - t_1)} \ln \left[\frac{1 - \frac{C_s (T_1 - T_a)}{G_T F_1}}{1 - \frac{C_s (T_2 - T_a)}{G_T F_1}} \right] \approx \eta_o F'_{he} C_R \quad (3)$$

F'_{he} is the value of F' for the heating test, slightly different to stagnation condition as there must be heating, $T_2 > T_1$.

This equation considers $U = U_{st}$ because it includes F_1 , so that temperatures T_1 and T_2 near stagnation values should be used to reduce error, because U increases with the body temperature above ambient. Experimental determination of F_2 needs a heating process under a time-constant G_T . An average value is considered suitable in the test around solar noon in a clear day.

The heat capacity ratio is $C_R = C_l/C \neq 1$ because the standard considers heating useful only for heating the liquid, what makes that the load heat capacity C_l must be specified. This seems reasonable by other reasons, determining the solar oven walls effective heat capacity C_b is difficult using simple resources, see Fig. 1.

- **Non-storing cookers:** From the point of view of thermal inertia the walls heat capacity is not considered useful. $C_R \approx 1$, so that assuming $C_R = 1$ is acceptable.
- **Storing cookers:** C_R is substantially less than 1.0 what could yield unfair low values for F_2 . This indicates that the liquid temperature will rise differently than the PCM temperature, unless heat capacity is low: $G_T A_a \gg C (T_{st} - T_a)$ simultaneously with a small PCM heat resistance, $Bi_s = \frac{h_s \{a\} l_s}{k_s} \ll 1$, which is typically not the case. Equation (3) considers that only the water heating is useful. But with heat storing cookers heating the PCM is useful too. Thus, for a moment let's suppose that in Eq. (3) $C_R = 1$ so that C substitutes C_l for a modified figure of merit $F_{2,mod}$. This way F_2 can be obtained when the PCM is fully melted, necessarily T_1 and $T_2 < T_{st}$ and there is a sensible temperature spatial homogeneity. But this could be not the case.

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 temperature distribution more homogeneous than with PCM is attained and testing at temperatures lower enough to T_{st} is possible, yielding C' and still using $C_R = 1$ in Eq. (3). Now F'_{he} can be slightly different. This $F_{2,mod}$ will put heat storing cookers under the same basis for evaluation than non-storing cookers.

2.2.3 Optical efficiency η_o

The effect of F'_{he} could be eliminated with a test 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 $t_2 = t_0 + \Delta t$; then, on average $U(\frac{T_{e,1} + T_{e,2}}{2} - T_a) = 0$ 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 or just air substitutes the PCM so that spatial variations of T are negligible, as just above is proposed, because near T_a the PCM is solid. The result is that η_o can be determined with the following equation:

$$\eta_o = \frac{C'}{A_a G} \frac{\bar{T}_{e,2} - \bar{T}_{e,1}}{2\Delta t} \quad (4)$$

\bar{T}_e is a spatially averaged surface temperature. As η_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 η_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_a is described in [12], although it requires additional testing hardware.

Typical values of η_o 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

- **Non-storing cookers.** A characteristic useful heating power, \dot{Q} in Eq. (1) with $C_s = 0$ and $\dot{Q}_x = 0$ and considering only C_l has been proposed as a figure of merit, quantifying only liquid load heating capacity of the cooker under standard conditions of almost null wind speed. $G_{T,stan} = 700 \text{ W/m}^2$, reasonably measuring it normal to sun rays with a pyranometer or solar meter and also reasonable using only the beam component for concentrating cookers $G_{T,b}$. As \dot{Q} diminishes with the body temperature, Eq. (1), a characteristic value with an over-temperature of $50 \text{ }^\circ\text{C}$ is specified by the ASAE S580 standard [15] for non-storing cookers with the nominal load $m_{l,nom}$. Additionally, if sun conditions do not match the specified $G_{T,stan}$ the following correction applies:

$$\dot{Q}_{stan,sun} = \left(\dot{Q}_l \Big|_{T_l - T_a = 50 \text{ }^\circ\text{C}} \right) \frac{G_{T,stan}}{G_T \Big|_{T_l - T_a = 50 \text{ }^\circ\text{C}}} \quad (5)$$

T_l is the temperature of the liquid inside the utensil. If the system is being studied with numerical methods that consider the liquid a node, the centred, second order accurate, finite differences algorithm for calculating \dot{Q} at the discrete points i of measurement is based on Eq. (1), giving:

$$\dot{Q}_{l,i} = C_l \frac{T_{l,i+1} - T_{l,i-1}}{t_{l,i+1} - t_{l,i-1}} \quad (6)$$

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 liquid load heating power, a procedure for establishing whether preheating of the PCM is performed or not is lacking. On this respect some possibilities can be envisaged.

- **Storing cookers.**

1. Separate heating of the PCM.

- A. Heating the liquid load in the shade starting at T_a with the PCM fully charged at higher temperature, 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 load. A variety of this test is to pre-charge the PCM with an electric heater indoors.

- 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)

Still the PCM charging capacity and charging rate is not characterized. The conclusion is that special considerations have to be raised in respect to this figure of merit when analysing storing cookers, the next section addresses this issue. There is the possibility of charging the PCM and also a load of liquid inside the cooking pot, inner one in Fig. 2. This way hot liquid is ready for instantaneous cooking. Evaporation and boiling must be avoided.

3 Additional figures of merit for heat storing solar cookers

3.1 Nominal stored heat

The nominal heat stored in the whole utensil, eventually loaded with liquid, as just above mentioned, is:

$$Q_s = m_s [L + \tilde{c}_s (T_0 - 70^\circ\text{C})] + C_{p+b} (T_0 - 70^\circ\text{C}) + C_l (T_0 - 70^\circ\text{C}) \quad (7)$$

for a temperature $T_0 > T_m$ (PCM melting temperature) $> 70^\circ\text{C}$, reached after a full storage. This equation considers the same average specific heat in liquid than in solid state for the PCM, namely \tilde{c}_s and respectively considers a heat capacity of pots and eventually box C_{p+b} . 70°C is considered the minimum temperature for sterilization [18]. This heat Q_s 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. Q_s yields a figure of merit evaluating the theoretical heat storage capacity compared with the heat desired for cooking the nominal liquid mass load $m_{l,nom}$, 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 $m_{l,nom}$ to an equilibrium temperature T_{eq} , leads to the limit over-temperature that is the liquid temperature increase for the simplifying case indicated:

$$T_{eq} - T_a = \underbrace{\frac{m_s}{m_{l,nom}} \frac{L + \tilde{c}_s (T_0 - T_{eq})}{c_l}}_{\Delta T_s} + \underbrace{\frac{m_{p+b}}{m_{l,nom}} \frac{c_{p+b} (T_0 - T_{eq})}{c_l}}_{\Delta T_p} + \underbrace{\frac{m_l}{m_{l,nom}} \frac{c_l (T_0 - T_{eq})}{c_l}}_{\Delta T_l}; \quad T_0 > T_m > T_{eq} \quad (8)$$

In heat storing solar cookers it is reasonable to assume $\Delta T_p, \Delta T_l \ll \Delta T_s$ owing to the high melting heat L . Thus a simplification is possible, leading to $T_{eq} - T_a = \Delta T_s$. This temperature increase is an additional figure of merit.

As with the stagnation test, if the resulting temperature is higher than 100°C , oil must be selected for the liquid or 100°C declared plus the theoretical quantity of boiled water. ΔT_s in Eq. (8) varies between $\approx 50^\circ\text{C}$ for paraffins up to $\approx 110^\circ\text{C}$ for erythritol, so that with no losses boiling is possible with a unity ratio of PCM mass to liquid mass $\frac{m_s}{m_{l,nom}} = 1$, using the reported values.

3.2 Useful heating power

Equation (8) 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 to the heating test used for determining F_2 , Eq. (1), with no cover insulation, $\dot{Q}_{Solar} = \dot{Q}_x = 0$, and assuming two spatially averaged temperatures: T_s for PCM under de-storage and T_l for the liquid under heating. Splitting the body in two sub-bodies: liquid (l) and the PCM (s) plus the corresponding part of the utensil, generally pots (p), assumed at the same temperature T_s , one obtains:

$$\underbrace{m_l c_l \frac{dT_l}{dt}}_{\dot{Q}_l} + (m_s c_s + m_p c_p + m_w c_w) \frac{dT_s}{dt} = -F'_{co} AU \langle T_s \rangle (T_s - T_a) \quad (9)$$

\dot{Q}_l can be measured directly using a similar scheme than in Eq. (6). For an over-temperature of 50 °C a standard heating power with PCM can be experimentally obtained:

$$\dot{Q}_{stan,PCM} = \dot{Q}_l \Big|_{T_l - T_a = 50 \text{ }^\circ\text{C}} \quad (10)$$

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} .

Integration of Eq. (11) 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 (*sol*) and liquid (*liq*) PCM, can be built assuming a uniform step change during the melting temperature interval ΔT [6]:

$$c_s : \begin{cases} T < T_m - \Delta T / 2 \rightarrow c_s = c_{s,sol} \\ T - \Delta T / 2 \leq T_m \leq T + \Delta T / 2 \rightarrow c_s = \frac{c_{s,sol} + c_{s,liq}}{2} + \frac{L}{\Delta T} \\ T > T_m + \Delta T / 2 \rightarrow c_s = c_{s,liq} \end{cases} \quad (11)$$

ΔT is null for pure substances and $\approx 10 - 20 \text{ }^\circ\text{C}$ for mixtures, like technical paraffins. During this interval a mushy state has been reported. As the position of the phase change front is not known, an empirical temperature interval for pure substances is generally accepted. No supercooling is proposed in this model for simplicity, because of the many parameters influencing on this undesirable effect, although up to about 14 °C has been reported after some thermal cycling, e. g. [9]. Supercooling could be included modifying T_m accordingly and delaying the delivery of L .

T_l and T_s have to be linked by a heat transfer modelling:

$$\dot{Q}_l = A_{ls} U_{ls} (T_s - T_l) \quad (12)$$

Integration of Eqs. (9) plus Eq. (10- 12) allow a numerical estimation of T_l if known or modelled values for both U and U_{ls} are used. It could be the experimentally obtained constant value $U \langle T_{st} \rangle$, obtained

through Eqs. (2) and (3), albeit accepting some error as $T_{eq} < T_{st}$. A better estimation can be obtained if a correction is applied, according to the theory of natural convection, accepting $U \langle T \rangle \propto (T - T_a)^{0.25 \text{ to } 0.4}$

[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 $U \langle T \rangle$ can be obtained.

U_{ls} can be experimentally estimated by application of Eq. (11) on the experimentally obtained value of \dot{Q}_l . This value is not very precise because of the uncertainty in T_s . It can be spatially non homogeneous during the beginning of this test.

4. COOLING TEST

If in Eq. (1) the solar power is null, $\dot{Q}_{solar} = 0$ in addition to $\dot{Q}_x = 0$, the differential equation becomes representative of a cooling test (*coo*), reducing to a homogeneous temperature if it is slow enough:

$$\frac{dT}{dt} = -\frac{T - T_a}{t_{coo}^*} ; t_{coo}^* = \frac{C}{(F'U)_{coo} A} \quad (13)$$

In the left hand equation $t_{cool}^* \langle T \rangle$ 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 discretizing algorithm in Eq. (6).

4.1 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.

- **Non storing cookers.** C can be known with relative accuracy and it is constant neglecting water loss by evaporation. This test allows to determine $(F|_{cool} U) \langle T \rangle$ which differs from U only in the factor $F|_{cool} < 1$ because $T > T_e$. Integration assuming a constant value for $F|_{cool} U$ and an initial temperature T_0 at $t = 0$, leads to.

$$\frac{T - T_a}{T_0 - T_a} = \exp\left(-\frac{t}{t_{cool}^*}\right) \quad (14)$$

Minimum squares fit of this equation to the measured data with a free value of t_{cool}^* leads to an average t_{cool}^* that is a figure of merit for the whole cooling process. The typically longer time for cooling than for heating leads to a relative homogeneization of the spatial temperature distribution in the inner part of the body. This improves the accuracy of this test results in comparison with the heating test, and also leads to approaching $F|_{cool}$ to 1.0.

- **Storing cookers.** Because of the unknown value of C during solidification, it is not possible to determine an accurate value for $(F|_{cool} U) \langle T \rangle$ 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 $F|_{cool} < F|_{he}$ eventually acceptable. The substitution of the heat storing material should not have a substantial influence on U .

4.2 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. 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. This can increase the characteristic cooling time t_{cool}^* several times, thus either keeping the food warm or extending cooking in the afternoon. Temperature homogenisation is reached, so that Eq (9) with $T_l = T_s$ can be applied. The concept can be extended such that a highly insulating cover is devised for reaching efficient heat retention, avoiding water vapour escaping and interrupting hot air leaks. Figure 3 shows two prototypes developed for this task [6].

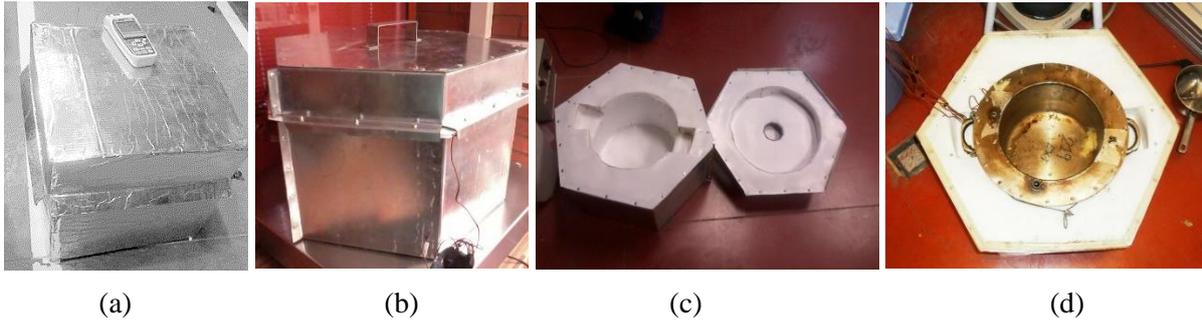


Figure 3 (a) Insulating cover based on cardboard and reflecting sheet. (b) Insulating cover, based on galvanized sheet and ceramic wool, for heat retention of a pot based storing solar cooker (c) View of the inside of the cover showing the cavity formed by Teflon sheet for allocating the heat storing utensil. (d) View of the heat storage utensil with the lid removed in order to show the cooking inner pot filled with 2 l of water and showing also the thermocouple wires for monitoring the experimenting.

The result with this prototype combined with the storage solar utensil shown in Fig. 2 is an increase of t_{coo}^* up to 30 hours making possible to cook the dinner and even the breakfast next day.

In Eq. (12) when $t = t_{coo}^*$ 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.

5. 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 in some cases:

- The stagnation test gives similar results and meaning for its figure of merit, F_1 , as losses are mainly dependent on external convection.
- Also de optical efficiency, η_0 , depends only on external geometry.

Some other figures of merit require considering the appropriate interpretation:

- The global heat transfer efficiency, F_2 , requires considering that useful heat is not only the one transferred to the liquid but also the one destined to the PCM.
- The useful heating power from solar irradiance has to take into account that storage cookers have two alternative heat sources: either the sun or the PCM when it has been thermally charged.

Finally some new figures of merit are required for these cookers:

- The nominal stored heat constitutes a new necessary figure of merit to take into account.
- A characteristic useful heating power from the PCM also becomes a new figure of merit. As commented above it interacts with the conventional concept of useful heating power from the solar irradiance.

This change of scenario requires additional tests to those of a non-storage cooker:

- 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 determine values and interpretations on 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 to ambient is temperature dependent.
- The optical efficiency is sensible to the sun-cooker geometry.

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