SOLAR COOKER AS A PUBLIC FURNITURE. THERMAL MODELING

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Abstract: *Solar cookers and solar oven are typically operated by trained people and after operation they are collected for cleaning and protecting them of outdoors weather and spoilage. Exceptions are large solar concentrating solar cookers, such as the ones based on the Scheffler type. But they are always protected outdoors.*

The possibility of having a solar cooker that can be left outside permanently with no maintenance, but just a minimum, and that can be accessed whenever the user desires would be very interesting.

This calls for a heavy and robust design. The risk for eyes precludes the sun concentrating types. Still some risk for children ask for an elevated construction. Sometimes a heavy cooking is not necessary, e. g. schools, workplace, beaches, rest areas of parks, etc. where already prepared food just need heating. Preventing the contamination by dust calls for an enclosed construction, like an oven.

Within our team, taking in mind those considerations, and after a conceptual stage the result is a solar cooker/oven of a new kind: it should be like any other urban furniture.

This solar cooker works like a flat solar collector. The absorber plate is thick in order to transfer by conduction the heat to an attached cavity under it, forming the oven. At the same time this thick plate acts as a heat storage, so that when the user opens the oven, it is already hot. In order to maximize solar collection, azimuthal manual orientation is allowed with a latch for wind resistance.

The non-conventional layout and operation asks for a full modeling for ascertaining its potential and minimizing cost.

The paper offers the numerical detailed modeling and the results, supporting the concept.

Results show that a 1D lumped parameters modeling gives orders of magnitude of the relevant parameters, but because of the extension of the absorber plate (2m×2m) a low order 2D model better predicts the behavior, although the computer effort is higher.

Keywords: Solar cooker, oven, public furniture, community, renewable

1. **INTRODUCTION**

Solar cooking is typically performed with devices of:

- Small format. Individual or family size of aperture area $A_a \sim 1\ \text{m}^2$. They are collected from the outdoor location after their use in order to avoid spoilage.
- Intermediate format. They serve small communities. $A_a \sim 10\ \text{m}^2$. They stand outdoors. Typically they are of the concentrating type, such as the Scheffler type.
- Large format. Such are those preparing hundreds or thousands of meals at the same time. There is a field of solar concentrators and a heat carrying fluid to cook remotely, typically indoors, in a communal kitchen. $A_a \sim 100 - 1{,}000\ \text{m}^2$.

Typically all these types of solar cookers are of use in regions where there is a necessity of using the solar energy instead of a conventional heat source [1]. The main reason is to avoid the many inconveniences of burning wood or another type of biomass. Such are the formation of toxic fumes, the heavy work or high cost of procuring firewood, the risk of fire, deforestation, among others.

There is a lack of knowledge of the capabilities of solar cooking. Actually, much people initially reject the idea of cooking with the sun or just feel surprised. Moreover, solar cooking is almost non-existent in developed countries as the energy consumption for cooking is a small fraction of the energy bill, especially if the use of pre-cooked food still advances more than it has nowadays. Only reduced groups master their use and possibilities. This is in contrast with the well-known renewables energies, like photovoltaics, wind and solar thermal for water preparation or for the production of electricity. They are much publicized in the media.

All this is a barrier for getting attention and help for developing actions to fight energy poverty in the undeveloped and developing countries, where the use of biomass is causing much trouble and where solar cookers can be of much help.

Having a solar cooker that can be used by anyone as you go, that does not need a permanent care and that can stand outside under the view of the general public can be of much help in developed countries for:

- Creating conscience of the energy poverty.
- Familiarizing with solar energy.
- Making solar cooking visible.
- Avoid wild fires caused by outdoors barbequing.
- Avoid fumes and smells in a condominium caused by barbequing.
- Heat a meal and even cook it with the sun in open public spaces, such as parks, beaches, etc. Also in shared private patios.
- Educate children in renewables and being clean in the energy use, both in open public spaces and in schools.
- Show an image of corporate responsibility by offering the employees a way of having a warm lunch at work.

Such solar cooker seems not existent. In energy poor countries this cooker can perform similar duties, but also can be useful as a first entrance for disseminating solar cooking.

2. DESIGN

A concept study has been endeavoured to develop a solar cooker design that can offer no-compromise performance in a permanent outside location, being robust and resistant to weather action, as safe as possible, even for children, and ready to operate. Moreover, it should be resistant to vandalism. A grounded installation was conceived as necessary and with simple operation, including sun tracking. For that a non-concentrating design was decided, more like an oven that an open air cooker. Some kind of simple and durable heat storage is necessary. The result of this study was a design, sketched on Fig. 1. It actually is an urban furniture with a look as a tree, giving some shadow to the users. This version is tall, trying to avoid dog and children damage, but a less elevated version is possible. The vertical post allows a manual sun tracking with a lock function to avoid motions caused by wind. Only a manual rotation every 30 min approximately. The azimuthal orientation is mainly toward the equator. The tilt angle is fixed to near the local latitude when manufacturing.

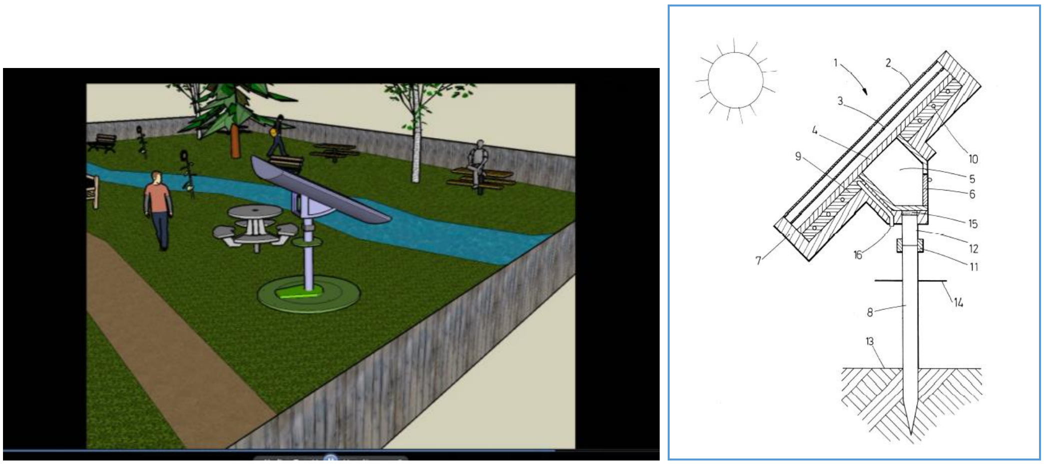

Figure 1. (left) Solar cooker rendering, shown in a park. A step allows reaching the oven door. A shelf facilitates cooking manoeuvres and ingredients storage. The height avoids children damage. (right) cross cut of the design, including extra heat storage below the absorber plate and the capability of heating water for cleaning.

The solar is composed by two main parts. The upper one is a 1.5×1.5 m to 2.0×2.0 m flat panel solar collector with heat storage capabilities. One or two parallel flat glass upper covers give the greenhouse effect. The lower one can be made of plastic. Below them there is a flat absorber plate made of thick metal, either aluminum of iron. Its purpose is to store and conduct the absorbed heat to the center part where the oven is hanging. Its upper side can be black painted or covered with solar selective paint either with adhesive optically selective film. On the lower side, a small box is soldered, around 30 to 40 cm side length, forming the oven. Its thick walls are heated by conduction from the absorber plate. An oven transparent double walled door allows managing the food under cooking. The oven box supports the device as it is connected to the central column, which in this embodiment is founded on the ground. The side and lower sides are thermally insulated with a thick layer of fiberglass mat that is externally protected to be impervious. This design has been patented [2].
The unconventional proposal calls for:

- A thermal modeling that estimates its performances and allow to optimize the design.
- A public security study and a civil regulations study.
- An evaluation of a prototype including a user’s and by passers survey to gather their opinion evaluation in terms of social value.

This paper addresses the first duty. The main questions are: Does this layout reach high enough temperatures? Is it fast enough for heating and cooking? Does the heat last enough to work on the go?.

3. THERMAL MODELING

The first approach is to resource to the simplest modelling. This is a lumped parameter 1D thermal model of capacitances and resistances, as indicated in Fig.2. A better modelling is obtained discretizing (Δx and Δy) the absorber plate surface, yielding a 2D model with more time dependant unknown temperatures to be solved. This modelling introduces the thermal conduction resistance in the x and y direction. This means the plane of the absorber plate. Side heat losses are neglected in front of upper and lower convection and radiation heat losses. Water is allowed to boil. Fig. 3 indicates the thermal circuit and the modes of heat transfer considered.

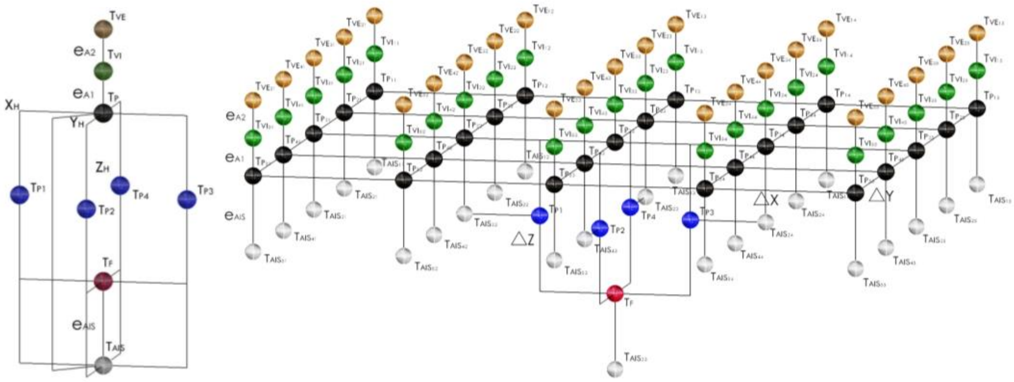

Figure 2. 1D (left) and 2D (right) temperature nodes of the solar oven, ambient temperatures omitted. Bullet are for temperature nodes, colors: brown and green are for the two glass plates with $_A$ for intermediate air. $_E$ for external and $_I$ for internal glasses, black are for the absorber plate $_P$, blue are for the oven lateral cavity walls $_P$, red are for oven bottom wall $_F$, and grey are for the lower insulation $_{AIS}$. Δz is the oven average height. e is for uniform thicknesses.

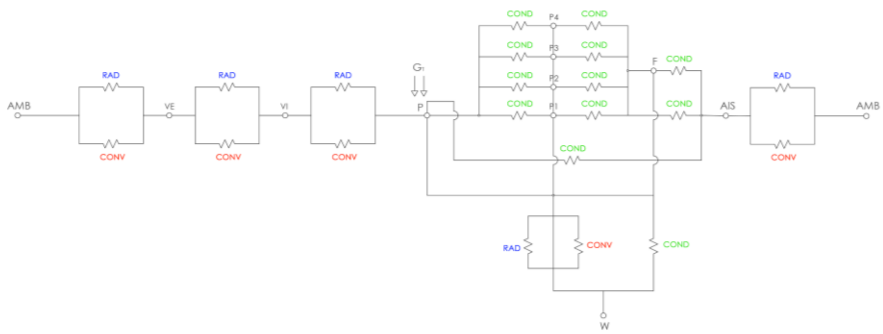

Figure 3. 1D thermal circuit of the model. G_T indicates the tilted solar irradiance. W is water and pot.

3.1. Equations

The general equation is heat conduction with temperature T. The thermal diffusivity is $\alpha = k\rho^{-1}c^{-1}$:

$$\nabla^2 T + \frac{\dot{q}'''}{k} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \tag{1}$$

$\dot{q}'''$ is the volumetric net heat power, solar input when applicable and convection and radiation losses when applicable. This equation is discretized and the material properties, boundary and initial conditions applied. Explicit time-marching algorithms have been implemented in Mathcad® to solve the system of simultaneous equations for each time step $p \rightarrow p+1$. This way $T^{p+1} = A \cdot T^{p} + B$. Lateral losses are avoided as: $T_{P\begin{cases}0,n\\6,n\\m,0\\m,6\end{cases}}^{p} = T_{P\begin{cases}1,n\\5,n\\m,1\\m,5\end{cases}}^{p}$.

4. RESULTS AND DISCUSSION

Table 1 presents the main parameters of the solar cooker modeled. The heat transfer modes considered are between:

- Glass plates, VI and VE: convection and radiation.
- Absorber plate, convection and radiation with VI and conduction with AIS and P1 to P4. AH convection and radiation with average temperatures of the rest of oven walls.
- Bottom oven wall (F) and rest of oven walls by convection and radiation using average temperatures of P1 to P4.
- Water temperature is limited to $T_w \leq 373\,\mathrm{K}$ further heat addition results in boiling.
- All runs start with a homogeneous ambient temperature T_{AMB} with $\Delta t = 10\,\mathrm{s}$.

The internal heat resistances in the pot are so low that numerical instabilities arise for the time step chosen, so that $T_W = T_F$ has been imposed.

The first kind of runs, Section 4.1 have been performed with constant solar irradiance in order to ascertain the cooker basic performances, like characteristic heating and cooling times, water boiling rate and stagnation temperature, and normalized tests, with the aim to compare 1D with 2D models. The second kind of runs, Section 4.2, aims at representing consecutive working days. Here only clear days in Madrid have been considered.

Table 1. Main parameters of the modelled solar oven.

Thermal parameters	**Geometrical parameters**
Absorber emittance $\varepsilon_{RS} = 0.35$	Optical efficiency: $\eta_o = 0.75$
Absorber absorbance $\alpha_{RS} = 0.91$	Pot size $h_O = 25\,\mathrm{cm}$; $r_O = 15\,\mathrm{cm}$
Insulation conductivity $k_{AIS} = 0.038\ \mathrm{W\ K^{-1}\ m^{-1}}$	Mass of water: $m_w = 2\,\mathrm{kg}$
Glass emittance $\varepsilon_V = 0.95$	Tilt angle $\beta = 40\,\mathrm{deg}$
Aluminum emittance $\varepsilon_V = 0.07$	Insulation thickness $e_{AIS} = 0{,}1\,\mathrm{m}$
Pot heat thermal capacity: $C_{po} = 2{,}637.0\ \mathrm{J\ K^{-1}}$	Aperture area $A_a = 2.0\,\mathrm{m} \times 2.0\,\mathrm{m}$
Between absorber and inner glass h_{A1} Hollands et al. 1976	Plates thickness $e = 0.01\,\mathrm{m}$
In between glasses: $h_{A2} = 1{,}25 \cdot (T_{VI} - T_{VE})^{0{,}25}\ \mathrm{W\ K^{-1}\ m^{-2}}$	Oven size $0.4\,\mathrm{m} \times 0.4\,\mathrm{m} \times 0.4\,\mathrm{m}$ av.
Collector top-air: $h_{SUP} = 11.8\ \mathrm{W\ K^{-1}\ m^{-2}}$	Glass plates thicknesses $e_{VI} = 0.03\,\mathrm{m}$; $e_{VE} = 0.05\,\mathrm{m}$
Collector bottom-air: $h_{INF} = 7.0\ \mathrm{W\ K^{-1}\ m^{-2}}$	
Oven-inner air convection with pot: $h_{aH} = 10.0\ \mathrm{W\ K^{-1}\ m^{-2}}$	

4.1. Constant irradiance heating and cooling tests

Heating is first analyzed, with $G_T = 1.0\ \mathrm{kW\ m^{-2}}$ and $T_{AMB} = 30\ ºC$ starts until temperatures stabilize at the stagnation temperature. Figure 3 shows main temperatures with an empty pot to avoid water evaporation. The 1D model gives constant temperature to the whole absorber plate T_P, while the 2D model gives higher temperatures to the outer elements, implying higher heat losses, because heat diffusion toward the center element that is the oven ceiling.

Figure 4 shows the comparison between the 1D and the 2D model. There are evident differences in the heating curve, being faster in the 1D model as a result of thermal diffusion in the absorber plate and lower heat losses. The total power initially reached the correct value of $1.0\ \mathrm{kW} \times 4.0\ \mathrm{m^2} \times 0.75 = 3\ \mathrm{kW}$ and tends to null at a similar stagnation temperature between the two models for long times, around 200 ºC. This seems satisfactory, both as a check of the model and supporting the viability of the concept. This also indicates that the 1D model is insufficient to describe the losses.

Figure 5 indicates the cooling process ($G_T = 0$) of a previously heated cooker, relevant for keeping the cooker hot during cloudy intervals and during the night. Initial temperature was 200 ºC. The characteristic cooling times, time for 1/*e* reduction of the over-temperatures, [1] of the oven floor have been calculated, $t^*_{en0D\ H} = 2{,}73\ \mathrm{h}$ and $t^*_{en2D\ H} = 10{,}94\ \mathrm{h}$.

Now the boiling capacity is tested. Figure 5 also depict the time evolution when a load of 2 kg of water into the pot is heated. The times for boiling [1] are $t_{eb0D} = 1{,}06\ \mathrm{h}$ and $t_{eb2D} = 2{,}38\ \mathrm{h}$. In this case $t^*_{en0D\ W} = 4{,}18\ \mathrm{h}$ and $t^*_{en2D\ W} = 6{,}82\ \mathrm{h}$. During boiling the power to water have been computed: $Q_{W0D} \cong 175\ \mathrm{W}$ and $Q_{W2D} \cong 81\ \mathrm{W}$. The steam productions obtained are: $\dot{m}_{eb0D} = 1.250\ \mathrm{g\ h^{-1}}$ and $\dot{m}_{eb2D} \sim 448\ \mathrm{g\ h^{-1}}$ what sees satisfactory even for traditional recipes where much water is supposed to evaporate.

2D model further results:

- With the aim to reduce cost and weight, some test runs were performed with all the metal plate thicknesses reduced to 5.0 mm, obtained only moderate reduction in performance, thus being an attractive option.
- Increasing the load up to 10 kg of water, still boiling is reached, but taking longer times. Not surprisingly higher solar efficiencies are reached.

4.2. Clear day tests

The solar irradiance follows the Hottel model [3]. Ambient temperature follows a sinusoidal variation between a minimum T_{MIN} at 4:00 am to a maximum T_{MAX} at 4:00 pm, solar time. Several test have been performed, as follows: three day time evolution to reach the cyclic steady-state followed by the water boiling test. These runs were performed both in summer and in winter clear days. Some of the results are shown in what follows.

Favorable and extreme circumstances somehow show a range of capacities. June and January have been selected as extreme average temperatures and sunshine in Madrid, as it would be the place for testing a prototype. The aim of this test is to show the capacity of cooking the lunch and dinner after three previous days of equalization:

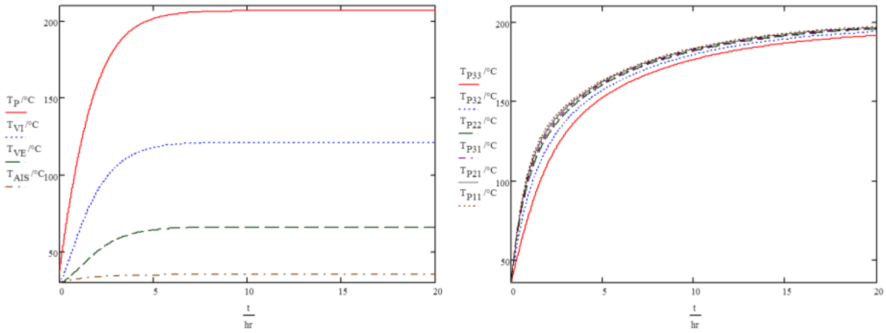

Figure 3. Time evolution of temperatures during no load test under constant irradiance (G_T = 1.0 kW m^{-2}). (left): Main temperatures of the 1D model. (right) temperature of some of the absorber plate elements of the 2D model.

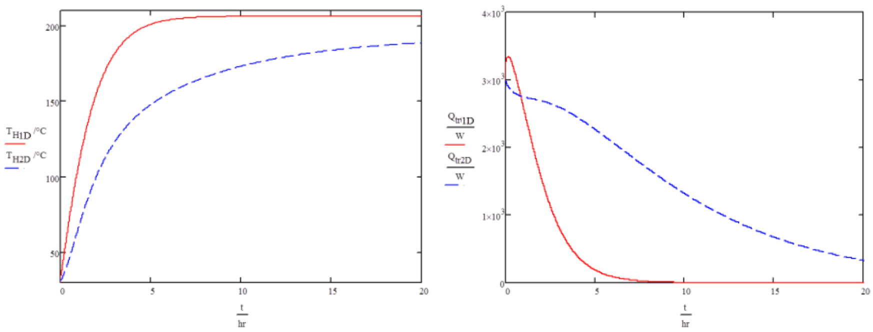

Figure 4. Comparison of time evolution during no load heating (G_T = 1.0 kW m^{-2}). (left): Temperature of the bottom wall of the oven T_H. (right): Total power time evolution. (red continuous line): 1D model and (blue dash line): 2D model.

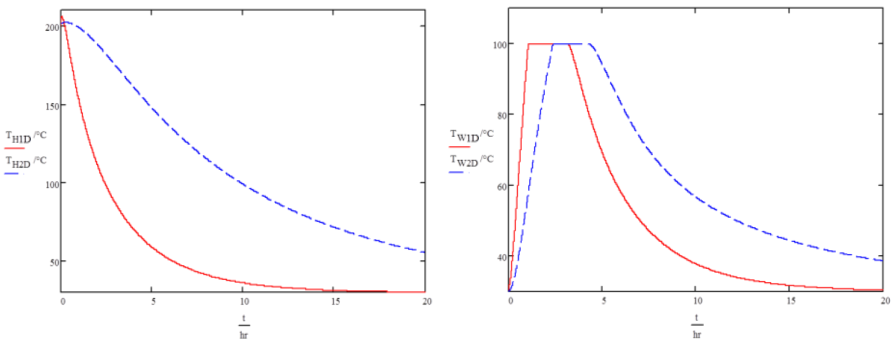

Figure 5. Results of different model and test cases. (left): Temperature time evolution during no load cooling (G_T = 0) of the bottom wall of the oven T_H. (right): 2 kg water load heating (G_T = 1.0 kW m^{-2}) with boiling and cooling. (red continuous line): 1D model and (blue dash line): 2D model.

- June: ambient $T_{MAX} = 40°C$, $T_{MIN} = 23°C$. With no load, maximum oven temperature is 160 ºC at 14:00 h solar time when $t_{ebMIN} = 12\ \mathrm{min}$, and during the night temperature minimum is 50 ºC at sunshine, $G_{T,\max} = 925 \text{ W m}^{-2}$, the water temperature time evolution is shown in Fig. 6. Lunch cooking can be performed in short time. Starting heating at 17:30 h. $t_{eb} = 31 \text{ min}$, and it seems that dinner food could be ready around 20:30 h.

- January: ambient $T_{MAX} = 11$ °C. $T_{MIN} = 1$ °C. With no load, maximum oven temperature is 128 ºC at 14:00 h solar time, and during the night temperature minimum is 28 ºC, with $G_{T,\max} = 802 \text{ W m}^{-2}$. Lunch cooking is possible but with a larger time for boiling than in summer. Starting at 14:00 h water boiling takes $t_{eb} = 46 \text{ min}$, and boiling lasts for 90 min. Starting later does not allow boiling.

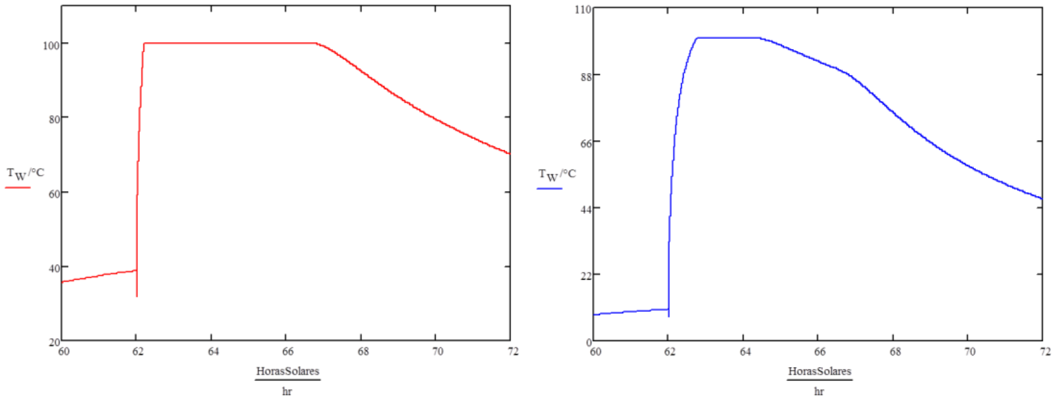

Figure 6. Water temperature time evolution, 2D model, starting with 2 kg water load in the afternoon. (left) June. (right) January. Start at 14:00 h after three previous days of equalization.

12. CONCLUSIONS

- An innovative solar cooker-oven has been proposed of a different kind than current. It will serve as an urban or free-space public furniture to work as you go, being permanently outdoors with minimum maintenance. It incorporates sensible heat storage into its materials.

- The thermal modeling performed promises good performances, supporting the concept. It can cook lunch and dinner during the whole year during a clear day at mid latitudes. Meal heating and sanitary hot water preparation is easier than cooking.

- The heat diffusivity of the absorber plate plane plays an important role in the oven temperature time evolution, so that 2D modeling can represent this phenomenon but not 1D modelling as here presented. The 1D model needs some improvements if better predictions are expected. The introduction of some diffusive element is suggested.

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