HIGH TEMPERATURE SOLAR COOKING SYSTEM WITH A PCM ENERGY STORAGE UNIT

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Abstract: This work evaluates the feasibility and viability of a high temperature indirect solar cooker operating in Aveiro (Portugal), allowing the thermal energy storage at high temperatures using a phase change material (PCM), and the use of a conventional pan. The studied system includes a parabolic dish concentrating collector, in which circulates the heat transfer fluid (HTF) carrying the absorbed energy to the kitchen. In the kitchen, the energy storage system and the cooker are joint systems. Thermal energy is stored in a high temperature (142 °C) melting PCM. During the cooking periods the stored thermal energy is recovered by the HTF from the PCM and delivered at the pan bottom. Numerical simulations of the complete system (collector + circulating HTF + PCM thermal energy storage unit + cooker) are performed for successive days, giving the time required to boil 1 L of water and to cook 500 g rice at two periods, one at noon and one at night. Results show the feasibility of cooking using the stored thermal energy at high temperature even in winter. A minimum of 26 min is required at the noon period and 23 min at the night period to start boiling 1 L of water. For both periods, noon and night, system ensures the water boiling at 100 °C during 20 min to cook 500 g rice.

Keywords: Solar cooker, High temperature, Thermal energy storage, Phase change material, Concentrating collectors.

1. INTRODUCTION

Solar cooking is not a novelty. Plans and studies of some types and models of direct solar cookers are present in the literature. Many refer to homemade systems, even if some of them are available in the market. However, the solar cookers and ovens are still not so effective when compared to conventional cooking systems. It is thus of major relevance to develop solar cookers enabling cooking at conditions similar to those of the conventional cooking systems, even in periods or locations when/where solar radiation is absent for some time. Pressure is thus on the development of high temperature indirect solar cookers, including high temperature thermal energy storage capabilities.

Energy for cooking accounts for nearly 40 % of the primary energy consumption, what has increased the demand for renewable energy applications [1]. Since cooking is one of the basic needs for living, solar cooking is receiving increasing interest [2]. Although some solar cookers are in the market, current cooking systems are still not so effective when compared to conventional cooking systems. High temperature solar cooking will allow times of cooking similar to those of conventional cooking, thus opening larger opportunities for solar cooking development and use.

Solar cookers are of the direct or indirect main types. In a direct solar cooker, cooking is mainly possible outside the kitchen, when and where direct solar radiation is available. In an indirect solar cooker the collector is kept outside and the cooking chamber is kept inside the kitchen, and the two parts communicate through ducts where a HTF circulates [2], allowing cooking even when solar radiation is absent thanks to an energy storage system. It is thus important to develop high temperature indirect solar cookers, including high temperature thermal energy storage capabilities, compatible with the thermal levels required by conventional cooking. PCMs are successfully used for thermal energy storage, delivering the stored heat at an essentially constant temperature [3].

This work evaluates the feasibility and viability of using a high temperature indirect solar cooker operating in Aveiro, allowing the thermal energy storage at high temperatures using a PCM. The studied system includes a parabolic dish concentrating collector to capture the solar energy, in which circulates the HTF, carrying the absorbed energy from the collector to the kitchen. In the kitchen, the energy storage system and the cooker are joint systems, the thermal energy being stored in a high temperature (142 °C) melting PCM. During the cooking periods the stored thermal energy is recovered from the PCM by the HTF and delivered to the pan. Numerical results show the viability and feasibility of the system, both at the noon and the night periods, in winter and in summer, the times required for cooking 500 g rice being of the same order of that required when using conventional cooking systems.

2. SYSTEM'S DESCRIPTION

Usual indirect solar cooking systems require a specific cooking reservoir/pan, reducing their use and viability. Taking that in consideration, the proposed system allows the use of a conventional pan. Since it is intended to cook at high temperatures, the proposed system, illustrated in Figure 1, includes a parabolic dish concentrating collector to capture the solar energy. In the kitchen, the high temperature energy storage unit and the cooker are a single unit. The energy storage unit consists of rectangular cross section PCM modules, and channels with the same geometry where flows the HTF. The circulating HTF carries energy from the solar collector to the PCM during the energy charging periods, and from the PCM to the top of the cooker, over which is placed the pan, during the heating and cooking periods. During the energy charging periods, the top of the cooker is covered with a thermal insulation board, to reduce the thermal losses from that surface to the indoor environment.

One pump and three valves allow the HTF circulation in two distinct circuits. The primary circuit connects the collector to the energy storage unit, for energy charging and eventually for simultaneous energy charging and cooking (V1 and V3 open, and V2 closed). When the PCM temperature overcomes the HTF temperature the primary circuit is disabled, and the secondary circuit allows recovery of the thermal energy from the PCM storage unit (V1 and V3 closed, and V2 open).

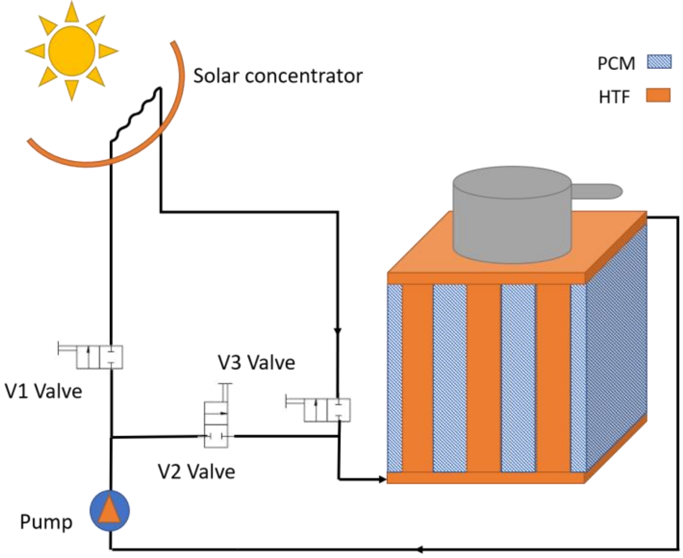

Figure 1. Schematics of the system's configuration.

Therminol-66 was selected as the HTF; Table 1 summarizes its relevant thermophysical properties [4].

Table 1. Therminol-66 thermophysical properties at 150 ºC [4].

Therminol-66	
ρ	920.6 kg/m^3
c_p	2014 J/(kg.K)
k	0.11 W/(m.K)
μ	1.519x10^{-3} N.s/m^2

HITEC Heat Transfer Salt was selected as the high melting temperature PCM. Table 2 [5] summarizes its relevant thermophysical properties.

Table 2. HITEC PCM thermophysical properties [5].

HITEC - Heat Transfer Salt	
T_{melt}	142 ºC
Δh_{mf}	81.45 kJ/kg
ρ	1940 kg/m^3
$c_{p,s}$	1340 J/(kg.K)
$c_{p,l}$	1560 J/(kg.K)
k	0.57 W/(m.K)

3. NUMERICAL MODELING

The proposed system must have the standard dimensions of household kitchen appliances (maximum w*d*h=60*60*80 cm^3) in order to be easily installed in any kitchen. Thus, the PCM and HTF modules have 40 cm of total width and depth, allowing additional 20 cm thermal insulation at the lateral and bottom walls. It was designed a configuration of 17 modules, corresponding to 8 HTF passages and 9 PCM modules, both with 2.2 cm width and 70 cm high, as illustrated in Figure 2.

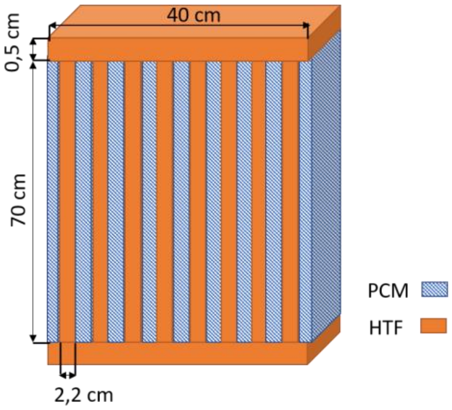

Figure 2. Schematics of the energy storage unit.

The system is required to start boiling 1 L of water, and to cook 500 g rice during 20 min in the boiling water at 100 ºC. The noon cooking period starts at 12 pm, and the night cooking period starts at 7 pm.

3.1. Solar concentrator

High reflectivity commercial parabolic dish collectors have an optical efficiency of 70%. Assuming a thermal efficiency of 50%, a total efficiency of 35% is obtained. Therefore, their total efficiency depends of the solar radiation, G_b, the HTF inlet temperature, T_{in}, and the ambient temperature, T_{amb}. Assuming the collector with a tracking system, the total collector's efficiency can be evaluated as [6]

$$\eta_{total} = 0.35 - 0.4632\left(\frac{T_{in} - T_{amb}}{G_b}\right) \tag{1}$$

3.2. Primary and secondary circuits

Apart from the valves, primary and secondary circuits are made of 20 mm ID steel ducts, thermally insulated with a 40 mm thickness ceramic fibre with a thermal conductivity of 0.05 W/(m.k) [7].

3.3. PCM energy storage unit

The high temperature PCM energy storage unit was considered to be perfectly insulated, neglecting its heat release to the surrounding environment. This simplifying assumption allows consideration of one HTF and PCM representative module only, as all HTF and PCM modules have the same behavior. To do that, the extreme side PCM modules have one-half of the width of the internal ones.

The HTF mass flow rate m_f for one HTF passage is obtained dividing the total HTF mass flow rate by the total number of HTF passages. A_i is the area through which the HTF control volume i exchanges heat with the PCM, A_c, is the cross-sectional area through which flows the HTF, and Δy is the distance between the centers of two contiguous HTF control volumes. As the HTF velocity is low, the conductive heat transfer in the HTF itself is also considered. Adopting an explicit method, Equation (2) is used to obtain the time evolution of the HTF temperature for each HTF control volume *i*. Similarly, Equation (3) is used to obtain the time evolution the PCM temperature for each PCM control volume *i*.

$$T_{f,i}^{t+\Delta t} = T_{f,i}^{t} + \frac{\Delta t}{m_{f,i} c_f}\left[U_i A_i\left(T_{s,i}^{t} - T_{f,i}^{t}\right) + \frac{k_f A_c}{\Delta t}(T_{f,i-1}^{t} - 2T_{f,i}^{t} + T_{f,i+1)}^{t}\right] \tag{2}$$

$$T_{s,i}^{t+\Delta t} = T_{s,i}^{t} + \frac{\Delta t}{m_{s,i} c_s}\left[U_i A_i\left(T_{f,i}^{t} - T_{s,i}^{t}\right) + \frac{k_s A_c}{\Delta t}(T_{s,i-1}^{t} - 2T_{s,i}^{t} + T_{s,i+1)}^{t}\right] \tag{3}$$

3.4. Cooker's upper part and pan

Temperature evolution of the HTF in the cooker's upper part follows the same methodology as described previously for the HTF in the energy storage unit, but it is necessary to implement two different configurations. During the energy charging periods, the insulation board (of the same thermal insulation material as used in the ducts), with 50 mm thickness, was considered. During the cooking periods this insulation board is absent, and the pan is placed on the top of the cooker. The time evolution of the water temperature in the pan is obtained using Equation (4). The overall heat transfer coefficient for the pan is obtained using Equation (5), where R_c is the contact thermal resistance between the upper surface of the cooker and the bottom external surface of the pan. The convective heat transfer coefficient for the water in the pan, h_{pan} = 1130 W/(m^2.K) was obtained for natural convection.

$$T_w^{t+\Delta t} = T_w^t + \frac{U_{pan} A_c (T_f^t - T_w^t)\Delta t}{m_w c_{p,w}} \tag{4}$$

$$U_{pan} = \frac{1}{\frac{1}{h_{pan}} + \frac{e_{pan}}{k_{pan}} + R_c + \frac{e_{wall}}{k_{wall}} + \frac{1}{h_f}} \tag{5}$$

The HTF flows with reduced velocities (laminar flow conditions) inside the ducts of both primary and secondary circuits. Reduced HTF velocities allow reduction of the HTF channel's height in the cooker's upper part, leading to an increase on the overall heat transfer coefficient to the pan. As illustrated in Figure 2, this upper channel has 5 mm height, leading to a U_{pan} = 75 W/(m^2.K) overall heat transfer coefficient.

When the 1 L water in the pan reaches the boiling temperature (100 °C), 500 g of rice (with a specific heat of 1549 J/(kg.K)) at 25 °C is added, leading to a temperature of 88.08 °C for the water + rice mixture [8]. The time evolution of the water +rice mixture temperature, T_{w+r}, is obtained using the equation

$$T_{w+r}^{t+\Delta t} = T_{w+r}^t + \frac{U_{pan} A_c (T_f^t - T_w^t)\Delta t}{m_w c_{p,w} + m_r c_{p,r}} \tag{6}$$

The water mass reduction due to the water vaporization during the cooking period is evaluated as

$$\Delta m_w = \frac{U_{pan} A_c (T_f^t - T_w^t) \Delta t}{\Delta h_{vapor}} \tag{7}$$

It was assumed that the pan is placed at the center of the cooker's upper surface, with a rectangular section with dimensions of 25x20 cm^2. Details on the physical model and numerical simulation can be found in [6].

3.5. Solar data

Simulations were performed using the solar data available from EnergyPlus software, for Aveiro, regarding the direct radiation received in a perpendicular plane to Sun's rays propagation direction at 1 h intervals. Due to the need of using reduced time intervals for numerical simulations, data were interpolated in 5 min sub-hourly intervals. Solar data for typical (representative) Summer and Winter days are illustrated in Figure 3.

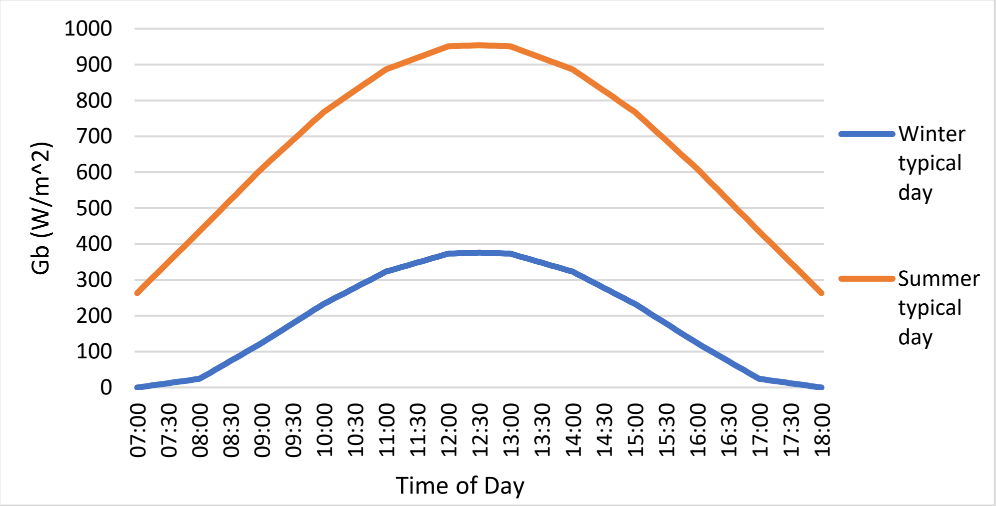

Figure 3. Time evolution of the direct solar radiation for the typical Summer and Winter days**.**

4. NUMERICAL RESULTS

Numerical results were obtained using the explicit method with a time step of 3 s. The PCM and HTF modules were divided in 15 control volumes along the vertical direction, leading to Δy=4.7 cm.

4.1. Winter typical day

Since received solar radiation is lower in Winter season, simulations were firstly performed for the Winter typical day, in order to select the best operating parameters, like the primary and secondary HTF mass flow rates and the needed solar collector area.

According to the literature, the solar collector's efficiency is maximum for HTF mass flow rates between

0.01 kg/s and 0.05 kg/s [10]. The mass flow rates of 0.01, 0.02 and 0.04 kg/s were tested in the two circuits using only one circulating pump, and then it was also studied the possibility of having different mass flow rates during the charging and discharging (cooking) periods adding another circulating pump. As the 0.01 kg/s mass flow rate is associated to a low fluid velocity, this increases the solar collector efficiency and allows a more effective PCM - HTF heat exchange. However, this low mass flow rate also increases the heat losses in the non-contacting sections of the pan and takes longer times to reach the top of the stove.

On the other hand, the 0.04 kg/s mass flow rate is associated to a higher HTF velocity, and does not allow the complete PCM phase change, which increases the cooking time and decreases the collector's thermal efficiency, reaching only low HTF temperatures.

From these preliminary tests, the 0.02 kg/s mass flow rate was taken as the most suitable for this application in both HTF primary and secondary circuits, requiring only one HTF circulation pump. The referred results correspond to a 26.5 m^2 solar collector area, needed to reach the PCM melting temperature in the Winter season, as illustrated in Figure 4.

Under these conditions, it takes 26 min to the 1 L water heat from the environment temperature and start boiling in the pan at noon period, and nearly 23 min at night period. At both noon and night periods, approximately 7 min are required for the water + rice mixture heat from 88.08 °C to 100 °C, and is confirmed the maintenance of the 100 °C temperature during the effective 20 min cooking time of. The water mass reduction in the pan due to vaporization is close to 0.068 kg at both noon and night periods.

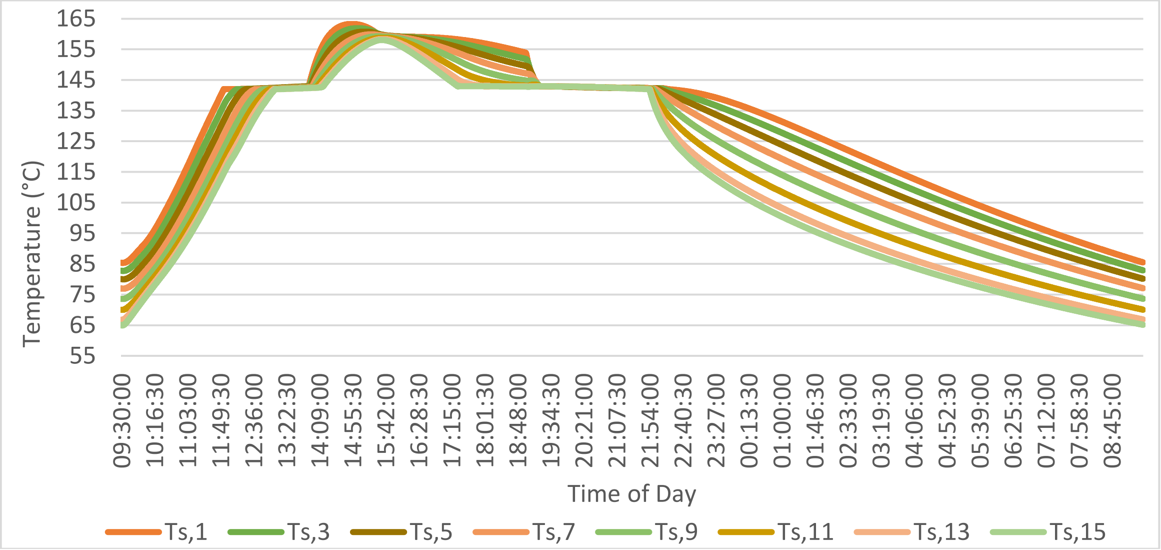

Figure 4. PCM temperature time evolution in the Winter typical day.

4.2. Summer typical day

In the summer season, the cooker's performance is highly increased. In this case, at both noon and night periods, only nearly 8 min are required for the 1 L water to heat from the environment temperature and start boiling, and nearly 1 min for the water + rice mixture to reach the water boiling temperature. The cooking temperature is maintained at 100 ºC during the 20 min cooking period, and in this case the water mass reduction due to vaporization is close to 0.35 kg (even if the cooking temperature is the same a higher heating power is delivered to the pan, thus promoting a higher water vaporization).

It is to be noted that the thermal losses from the PCM modules were not considered in the simulations, which would lead to lower temperatures in both PCM and HTF modules, leading to longer cooking times. However, the convective heat transfer coefficient for natural convection from the pan to the water was kept constant and equal to 1130 W/(m^2.K), which in fact can reach the higher values associated to water boiling phase change, what will improve de cooker's performance. This is not critical, as this is a feasibility/viability study.

12. CONCLUSIONS

The objective of this work was to study the feasibility/viability of an indirect solar cooking system capable of cooking at high temperatures even when solar energy is not directly available, requiring cooking times similar to that required by the conventional cooking systems. The proposed solar cooker proved to be feasible and viable for cooking at high temperatures, and could be an interesting solution to minimize current dependence on fossil fuels for cooking. It has been proved to be feasible to cook using previously stored solar energy as thermal energy using a high melting temperature PCM (considering the thermal levels required for quickly cooking food) in both Winter and Summer seasons. Nevertheless, results show that the cooker's performance at the noon period depends mainly on the amount of PCM used, leading to a longer cooking time than at the night cooking period (as more thermal energy is stored in the PCM at the end of the day).

More realistic simulations need to consider the thermal losses from energy storage system, and analysed the temperature evolution of each single HTF and PCM modules.

REFERENCES

[1] Indora S, Institutional cooking with solar energy: A review, *Renewable Energy and Sustainable Energy Reviews*, 2018, **84**:131-154.

[2] Cuce E, Cuce P.M, A comprehensive review on solar cookers, *Applied Energy*, 2013, **102**:1399-1421.

[3] Sainil S, Kumar N, Thermal performance of solar cooker based on evacuated tube collector and PCM storage unit, *Asian Review of Mechanical Engineering*, 2017, **6**:32-45.

[4] Therminol 66, http://twt.mpei.ac.ru/TTHB/HEDH/HTF-66.PDF, accessed on 2019.05.02.

[5] HITEC Heat Transfer Salt, http://stoppingclimatechange.com/MSR%20%20HITEC%20Heat%20Transfer%20Salt.pdf, accessed on 2019.05.02

[6] Bellos E, Experimental investigation and parametric analysis of solar thermal dish collector with spiral absorber, *Applied Thermal Engineering*, 2017, **121**:126-135.

[7] Fiberfrax, Manta Durablanket, http://www.brascoterm.com.br/uploads/produtos/1330031392manta_durablanket.pdf, accessed on 2019.05.02.

[8] The Engineering ToolBox, Specific Heat of Food and Foodstuff, https://www.engineeringtoolbox.com/specific-heat-capacity-food-d_295.html, accessed on 2019.06.18.

[9] Alves, O, *Sistema de Cozinha Solar de Alta Temperatura*, MSc. Thesis, University of Aveiro, 2019.

[10] Karimi R, Gheinani TT, Avargani VM. A detailed mathematical model for thermal performance analsysis of a cylindrical cavity receiver in a solar parabolic dish collector system, *Renewable Energy*, 2018, **125**:768-782.