Use of a Hybrid Solar Oven for Houses in Dry Climates: An Experimental Study of Thermal Performance

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Abstract- This paper presents a hybrid solution to problems presented by box-type solar ovens in night and cloudy conditions. The developed hybrid solar oven is supplied with both electric and solar energy and can be used in early morning hours, on cloudy days, or when solar radiation decreases or disappears: The findings from thermal tests and the hybrid performance analysis are presented. The merit figures for F1 and F2 ovens, as well as the cooking power were determined, in accordance with the Ibero-American Network of Solar Cookers guidelines. These experimental results demonstrate that these ovens are suitable for home use in dry climates. The ovens can be implemented and developed as a component of existing government programs and they can supply cheap, reliable power to underpriviledged communities and help to reduce deforestation.

Keywords- Hybrid solar oven, Solar electric oven, Houses, Dry climates, Thermal performance.

1. Introduction

The people in Argentina rely on the Interconnected Electricity Network, and bottled gas, to prepare food and light their houses in remote and dry climates, such as San Juan (31.5372º S, 68.525º W), Argentina. However, gas can be costly, lacking, and difficult to obtain, so people increasingly use trees and shrubs as an alternative fuel for heating, (Saravia, 2007 [1]) boiling water and cooking (Nandwani, 20051 [2]). This contributes to deforestation. To tackle these issues and utilize the high levels of available sunlight, a hybrid solar thermal oven (HSO) for cooking and preparing food has been developed.

This hybrid system uses solar and electric energy, since it would be difficult to combine solar box-type ovens with propane, or wood. The use of solar, and electric power (Azam, 2009 [3]), also resolves the limitations of other systems (Nandwani, 2009 [4]), in dry climates. The Phase Change Materials (PCMs) have the capacity of solar heat storage and one option for night / evening cooking (Buddhi, 1997 [5]), (Sharma, 2000 [6]), (Buddhi, 2003 [7]), (Sharma, 2005 [8]).

The HSO is also a solution for environmental issues (Buigues Nollens and Rojos, 2009 [9]), and it is capable of providing functional, affordable, and emergency energy. This paper describes the oven design, presents the findings of research and comparative studies, and concludes by showing that the advantage of this oven is that it can be developed in conjunction with existing local government programs (Javi, 2001 [10]).

2. Thermal Performance of Hybrid Solar Ovens with Solar Energy

Several different tests were used to evaluate thermal performance: according to the guidelines created by the Ibero-American Network of Solar Cookers (IANSC), measuring solar energy performance, cooking power, and figures of merit for F1 and F2 ovens (Castell et al., 1999 [11]).

By further tests, the hybrid energy function was measured at the time of electric power supply and with the possibility of a simultaneous action with the sun using an automatic thermal controller to regulate power and maintain the temperature.

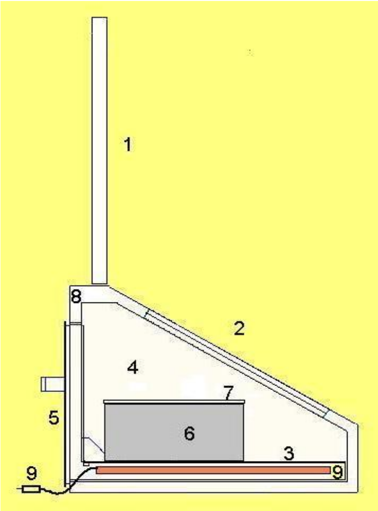

Fig. 1. Cross section of hybrid solar oven

The HSO design with 1- Reflective area, 2- Inclined double-glazed cover, 3- Black horizontal plate, 4- Interior reflective surface, 5- Vertical front door, 6- Pot, 7- Black grill cover, 8- Galvanised sheet walls with spun glass, 9- Heating unit appear in Fig. 1. The double-glazed, features an inclined cover based on the local latitude and has fixed and mobile units. It has a fixed transparent collector surface of 0.380 m^2 with a solar horizontal projection height corrected of 0.500 m^2 and an absorbent surface of 0.334 m^2 (Castell et al, 2000 [12]). The metal box, made of galvanised sheet walls, is insulated by three inches of spun glass.

The design incorporates innovative mobile units. For example, the front vertical door, as seen in Fig. 2, is joined to the black horizontal plate, which allows the user to move the entire assembly as a tray. Ball bearings provide lateral movement to this removable box, facilitating maintenance and convenient cooking. The reflective area is made of pivoting panels that open or closes according to the need of capturing energy.

These panels can be opened and closed during operation, allowing the user to monitor the food without shading the collecting surface.

Fig. 2. View of components

The 0.538 m^2 reflective surface also rotates as a single sheet, insulating the HSO from the external environment as is shown in Fig. 3. The components are ergonomic and resistant and they are easily reoriented to capture sunlight.

Fig. 3. View of hybrid solar oven

Generally solar energy can be used to prepare food during the day. By contrast, electric power collected from photovoltaic panels or the Interconnected Electricity Network is also used to heat foods at night, in early morning hours, or when solar energy is insufficient. The two sources are combined, creating a hybrid approach. After the oven is preheated, it can cook food without the use of additional energy. It can also be used to keep cooked food warm.

The HSO has two settings that can be manually changed, as necessary, based on the availability of sunlight. The first is a purely solar setting, and the second is a hybrid setting with automatic temperature control. The control system monitors the temperature inside the oven and regulates the use of energy in order to maintain the temperature. These settings are similar in function, but their performance is analyzed separately.

3. First and Second Merit Figures

The F_1 and F_2 merit figures enable the evaluation and future comparisons of solar ovens. The hybrid solar oven's thermal performance can be compared by two merit figures which are obtained by experimental testing and are used to improve the HSO design.

The first F_1 merit figure accounts for the relationship between optical efficiency and heat loss from the transparent collector surface. The values and proposed components for an oven with an inclined cover are shown in Fig. 4.

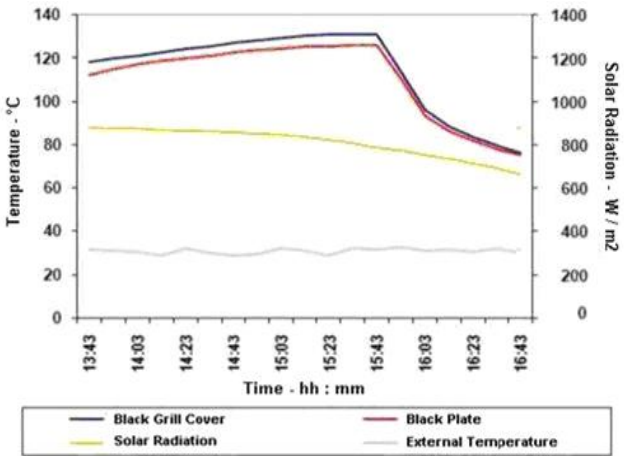

Fig. 4. Measurements obtained for the F1 analysis

These values were obtained from measuring the temperature inside the HSO and the ambient temperature, while the system is subjected to global radiation on a horizontal plane of 800 W/m^2.

Typical solar radiation in San Juan ranges from 980 W/m2 in summer to 600 W/m^2 in winter, as measured at noon with a clear sky.

$\eta_o A_v I_v = A_p U_L (T_p - T_a)$

$F_1 = \eta_o / U_L = A_p (T_p - T_a) / A_v \ I_v$ (1)

Thus the value by Eq.(1) of $F_1 = 0.12$°C m^2 / W

where,

F_1= first merit factor
η_o = optical efficiency
U_L = loss coefficient
A_p= absorbent plate area
A_v= transparent surface area
I_v= solar radiation on transparent surface
T_p= plate temperature
T_a= ambient temperature

Mullick *et al.* [13] and [14], found a high optical efficiency (η_o), and low heat loss factor (U_L), in the first merit figure.

The same formulas accounting for the area's dry climate were used. Local variables in San Juan such as solar radiation (I_v) reaches 800 W/m^2, and ambient temperature (T_a) is higher than 15 ºC in the order of 30 ºC. Though in Mullick´s experiment the oven temperature was equal to or greater than 111 ºC, in our case, the temperature was always above this threshold.

The final result obtained shows:

A minimum thermal performance level when reaching the lowest allowable limit.

A stagnation temperature high enough to ensure the oven temperature will reach the boiling point.

The second merit factor (F_2) measures the efficiency of heat transfer to the container. Water was heated in a pot on the HSO and the time until it reached 80 °C and the boiling point was measured. The time during which the water remained above 80 °C without the user´s intervention was also determined, as seen in Fig. 5.

1. The test began at 10 a.m.

2. A 2.338 kg pot of water was placed in the HSO (derived from the standard 7 kg/m^2). The oven was oriented towards the sun with the transparent collector surface positioned towards the solar noon.

3. The oven was reoriented every fifteen minutes based on the solar tracking table, Fig. 3.

4. When the water began to boil, the oven was re-oriented to an optimal position, and user operation ceased. The period of time during which the water continued to boil was then recorded.

5. When the temperature dropped three degrees below the boiling point (96° in San Juan), the oven was covered with mobile components, Fig. 1. It took 100 min for the water temperature to reach 96 °C, and the temperature remained above 80 °C for 3 h 30 min. The temperature remained above 96 °C for 1h 20 min, and the temperature took 4 h to reach the ambient temperature. The time without a user´s intervention above 80 °C was of 2 h 40 min.

The resulting values are shown in Fig. 5, (Fayadh M. [15]). Given the analyzed values, *F2* by Eq.(2) was obtained:

$F_2 = F'\eta_0 \ C_r = [F_1 \ (M_c)_w \ / \ A_v \ \zeta] \ ln \ (I_v - [(A_p / A_v F_1) (T_{W1} - T_a)] / [I_v - (A_p / A_v F_1)(T_{W2} - T_a)]$ (2)

where,

F'= heat exchange efficiency factor
η_0 = optical efficiency
F_1 = first merit factor
$(M_c)_w$ = system´s heating capacity (water, vessel, and oven interior)
ζ = time interval between T_{w1} and T_{w2}
I_v = solar radiation on transparent surface
A_v = transparent surface area
A_p = absorbent plate area
T_{w1} = initial water temperature
T_{w2} = final water temperature
T_a = ambient temperature

Thus the value of $F_2 = 0.246$.

The results were:

- The heating capacity of the vessel walls was lower than that of the vessel´s contents.

- The heating exchange factor was appropriate (F').

- The intervening factors and parameters obtained in this figure of merit are relatively independent from the ambient variables.

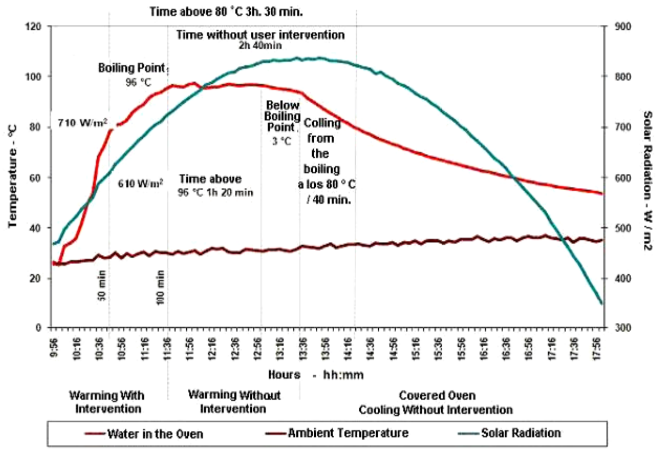

Fig. 5. Temperature and radiation values for F2 analysis

4. Calculating Cooking Power

The most representative merit figure in thermal efficiency is the Effective Cooking Power (ECP). To calculate ECP, we followed IANSC protocols (Esteves, 2001 [16]):

- Cooking power is the difference in water temperature every five minutes, multiplied by mass and the water specific heat, calculated for the range between 40 °C and the boiling point minus 5 °C (91 °C). This product is divided by 300 s, yielding the ECP in W.

- Plotting and regression are displayed in two graphs. Fig. 5 plots the water temperature against time, and Fig. 6 plots cooking power at various temperature intervals.

- To standardize cooking power, a standard solar radiation of 700 W/m^2 was corrected by multiplying the observed power by 700 W/m^2 of radiation and dividing the product by the average recorded temperature during the corresponding interval.

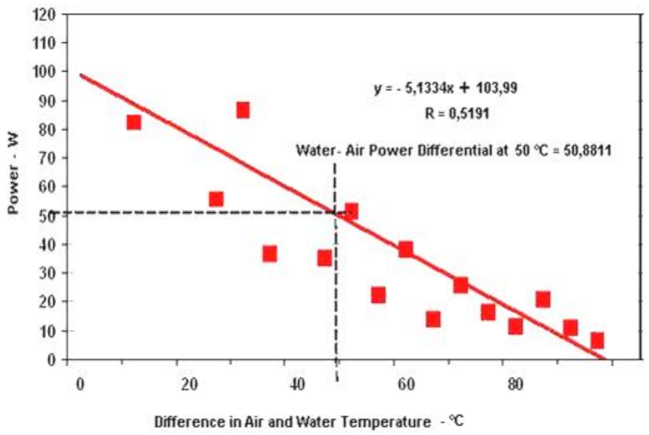

Fig. 6. Effective solar cooking power for hybrid cookers

- The temperature differential between the pot and the environment at each interval was calculated.

To measure performance, the value for the standard cooker corresponding to a 50° C water and air temperature differential was calculated. The effective cooking power was 50.88 W.

5. Performance of Hybrid Ovens with Thermal Controls

The temperature requirements were set at + / - 5 ºC, a range that could be easily met, given the appropriate controls. This system was designed to harness twelve volts of solar energy and electricity. We used a yes/no control for the temperature controller (Kuo, 2002 [17]). To verify the temperature controller performance, the Fluke 2000 data acquisition system (Pallas-Areny, 2011 [18]) was used.

The control strategy was to measure the temperature inside the hybrid oven with a thermocouple (Fonseca, 2003 [19]), (Passamai, 2005 [20]), (Szklanny and Behrends, 2004 [21]).

A microcontroller gauges the temperature, compares it to the programmed target temperature range, and determines whether to activate the heating unit. The applied voltage is 220 V rms and the heating unit (45 cm long and 27 cm wide) has a

resistance of 22 Ω so there is a constant power value of 2200 W.

6. Setting up the Thermal Controls

To test the effectiveness, performance for prolonged periods of time were evaluated and

the following results were obtained:

Stage 1: When the open-loop heating element was connected, the temperature reached 260 ºC in 7.5

min without the intervention of the control system.

Stage 2: In a transitional phase, an automatic temperature controller was set up.

Stage 3: When a range of 115 ºC to 125 ºC was programmed, with the temperature sensor on the oven floor, the temperature reached the prescribed 120 ºC in 6 min .

7. Hybrid Operations

For results, see Fig. 7 and Fig. 8, which show testing over two hours and forty minutes with sun exposure.

Stage 1: The remote control system was activated for four minutes while the temperature was below the 125 ºC control temperature.

The heating unit, located below the black plate, was programmed to a range of 120 ºC - 135 ºC.

Because of incoming solar energy and thermal insulation, the temperature continued to be above the control temperature, reaching 140 ºC without the help of the heating unit.

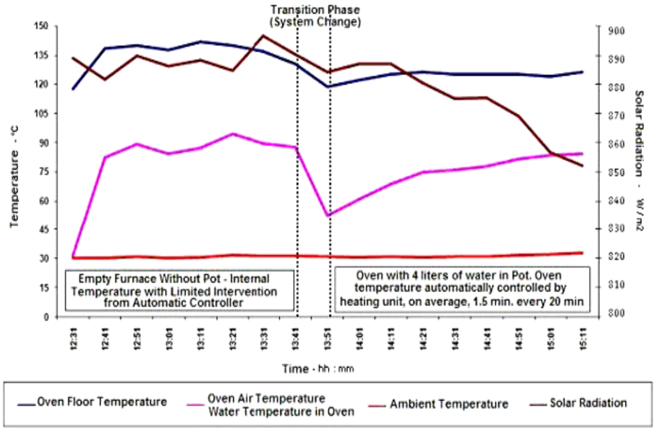

Fig. 7. Test with hybrid performance and thermal control

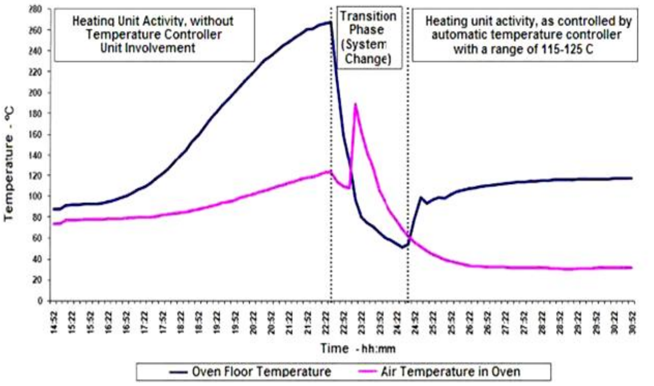

Fig. 8. Testing the control set-up

The temperature sensor is on the oven floor and the temperature control system regulates the power based on the local temperature. The temperature at the oven floor is higher than the circulating air.

Stage 2: The oven was quickly opened, and a vessel with four liters of water was placed inside. The temperature sensor was placed in the water. The process caused an immediate heat loss.

Stage 3: The automatic temperature control system reinitiated once the oven was closed. The system no longer exclusively used solar energy; as radiation decreased, the system used the heating unit more frequently.

The average frequency of operation of the heating unit was 1.5 min every 20 min.

8. Conclusion

This paper contributes to the available literature on solar ovens, accounts for possible lurking variables, and follows the Network of Solar Cookers guidelines. The conclusion is that this inclined-cover oven which uses available solar radiation and is designed according to local latitude presents optimal merit figures and cooking power compared with similar studies.

Because of hybrid performance and thermal control, the HSO maintains a stable temperature. From a consumer point of view, the effective control system saves cooking time, harnesses the maximum possible solar power, and as a result, uses less energy. From a practical standpoint, the HSO has positive externalities as well; it is more reliable than the non-hybrid version, and users who rely on the self-regulating control system can work or relax while food is being cooked.

Users can also avoid exposure to inclement weather and still use the hybrid oven in remote, dry areas when there is insufficient solar radiation, such as at breakfast time. These benefits would be impossible if a user had to continually monitor, adjust, and operate the oven, as with non-hybrid ovens.

Looking forward, the recommendation is that the oven should be developed in conjunction with existing local government programs, such as the Rural Electrification Program and the Unconventional Energy Program. Future designers should also work with the new Photovoltaic Panel manufacturing program in San Juan, which suggests that a solar park be connected to the network and includes the beneficiaries of the new federal housing plan and IPV government subsidised housing as producers. Future plans should also curtail desertification in dry regions like San Juan, reduce energy waste, and preserve environmental resources. Our hybrid oven meets these requirements and provides cheap, convenient, accessible power.

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