A NEW SOLAR COOKER OF PARABOLIC SQUARE DISH: DESIGN AND SIMULATION

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BSTRACT

A complete design and fabrication of a parabolic square dish solar cooker can be used for water distillation as well as cooking in an isolated area. A simulation model for transient state was introduced to predict the pot, fluid air gap and the cover temperatures. Satisfactory agreement are obtained between experimental and theoretical results.

OMENCLATURE

area of the top surface of the fluid, m^2
the inner area of the pot wetted by the fluid,m^2
the projected area of the concentrator,m^2.
the area of the shadow caused by the pot cover over the reflector = 0.2 m^2
the outer side surface area of the pot, m^2 .
the surface area of the cover, m^2.
the specific heat, KJ/Kg °C.
= 1 - A_{sb}/A_c= the shading factor of the pot.
heat transfer coefficient between the fluid (or food) and inner surface of the pot, W/m^2 °C. (for water=912 [11]
heat transfer coefficient between the surface of fluid in the pot and the lower surface of the cover, = 3 W/m^2 °C [11].
heat transfer coefficient between the outside air and the outer surface of cover,W/m^2 °C. = 5.7 + 3.8 V_{wind} [11]
the direct normal solar radiation,W/m^2 .
m mass, kg.
t time, sec.
T temperature, C.

SUBSCRIPTS

c	cover
f	fluid or food
g	gas or air between the pot and the cover.
p	pot

Greek Symbols

α	absorbtivity = 0.5 for the bottom of the pot.
ρ	reflectivity = 0.55
σ	Stefan-Boltzmann constant = 5.67 x 10^{-8} W/m^{2}K^4
ϵ	emissivity. (for outside cover = 0.8, for the pot body = 0.6)

INTRODUCTION

The solar cookers are practical due to inherent simplicity and consequent lower cost. Also the food is physically protected from contamination. The solar cookers are very important especially for armed forces in isolated areas, where there is no modern life and fully supply, moreover, solar cooker may be used in a picnic.

Solar cookers may be classified into three main categories:

1) box type, 2) two phase thermosiphon solar cookers, and 3) concentrator solar cookers. Researchers [1,2 and 3] reported that solar ovens showed greater promise due particularly to higher efficiency, ease of operation and ease of construction with the available local skills and materials.

Mullick et al. [4] had provided some guidelines for thermal evaluation of box-type solar cookers. Suitable thermal tests have been proposed and appropriate parameters are identified. which pertain to be solar cooker and are relatively independent of climatic variables as well as the cooked product. A new box-type solar cooker design with a single reflector at the hood had been introduced by Tiwari [5]. Unlike the conventional box-type solar cooker, in this design , the base of it acts as the lid; thus the problem of preheating in the conventional box-type solar cooker is solved.

Theoretical analysis for the simple model of the solar cooker was reported by Shrestha [6]. The effect of the present box-type solar cooker is modified slightly, and three versions were analyzed mathematically and simulated by computer in order to see the effect on the stagnant temperature of the cooker under simulation conditions. It was found that the stagnant temperature was much enhanced in all modified models. If the external surface of the absorbing top plate is treated with a selective coating, the performance is very much enhanced.

The fist attempt to use a two-phase thermosiphon in solar cooker was made by Battacharya and Kapur [7]. They proposed the use of one thermosiphon leg in outdoor collectors. Swet [8] described similar conceptual design. More recently, testing of heat-pipe at the Brace Research Institute [9] resulted in an inconclusive performance.

In a trial of installing solar energy into Kitchens, Khalifa et al [10] had design two different solar cookers utilizing the heat pipe principle. A cooker utilizing an east-west line focusing collector, designated Mecca-1, was developed for this purpose. The second cooker was a flat-plate heat-pipe cooker, "Mecca-2". A single heat pipe in each cooker absorbed the energy at the collector, transported it into the kitchen and delivered it to an insulated oven at the condenser end. It was found that the "Mecca-2" cooker with tripe glazing had a utilization efficiency of up to 19% and could boil one liter of water in 27 minutes for a solar insolation of 900 W/m^2 .

A new oven that permitted heating from the bottom and sides was developed by khalifa et al [11]. This oven consists of a spiral concentrator and glazed oven placed at the focus: Simulation studies were conducted for predicting the thermal behavior of this cooler for which concentrated solar energy would be supplied via a spiral concentrator.

In a trail to see the wind effect on the performance of a solar cooker, Garg et al. [2] found that the wind speed exceeds about 10 km/h, the pot temperature does not exceed 80C under Delhi conditions. The same pot containing one liter of water comes to a boil in less than half an hour in calm weather.

In the present work, a new concentrating type solar cooker which may be used as a cooker and/or a water distiller is presented. Such a cooker would have a short cooking time, heat the pot from its bottom and not have condensation problem on the top glazing insulation like the one proposed by Talks [12]. The solar cooker presented here is fordable too, so that it can be easily transported to picnic sites.

SOLAR COOKER DESIGN

Figure (1) shows a schematic diagram for the proposed solar cooker. It consists of a parabolic square dish reflector, made of a wooden matrix, covered with rectangular stainless steel strips, each 10 cm wide and 171.5 cm long and a flexible frame which can be compacted to a small size. There are four wheels at the base of the frame to allow sun tracking. The pot is set on two steel bar of one cm diameter each. A wind protector cover of cylindrical shape, 37 cm long and 35 cm in diameter, made of galvanized steel, painted on the outside surface by black paint is present. Table 1 shows more details of the parabolic disk reflector.

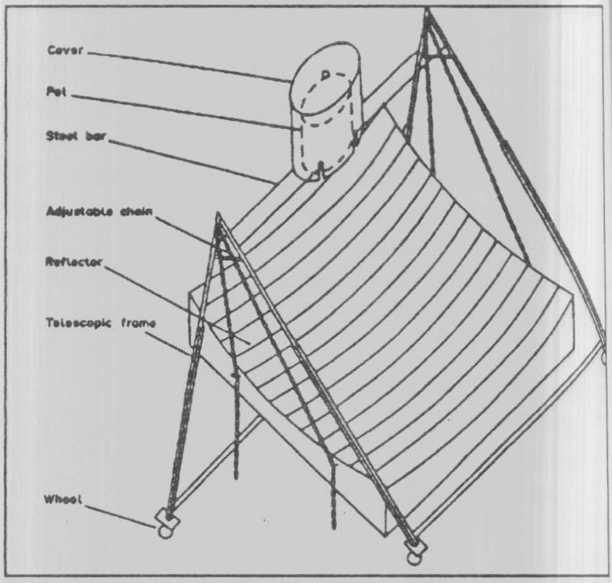

Figure 1. Diagrammatic sketch of the solar cooker.

The square dish was suspended on the frame by four chains. There are four hooks, two on each opposite side of the dish, in which the chains were attached to allow adjusting of the dish to any desired inclination angle, so that a focus on the bottom of the pot is performed.

The pot used is made from galvanized steel of cylindrical shape with a height of 25 cm and of diameter 25 cm. however, any other dish can be used.

Table 1. Details of the parabolic square disk reflector

Base material	wooden matrix
Design equation for* the wooden matrix (see Fig. 2)	$Y = \frac{L^2 + X^2}{4f}$
Aperture area	1.96 m^2
Reflector surface	polished stainless steel 0.5 mm thickness
Focal length (f)	1 m
Rim angle	44.5 degree
Geometric concentration ratio (based on 1 degree acceptance angle)	791
Approximate actual concentration ratio	250

*where X, Y and L are the coordinates of a point located on the surface of a strip refereed to the center of the dish.

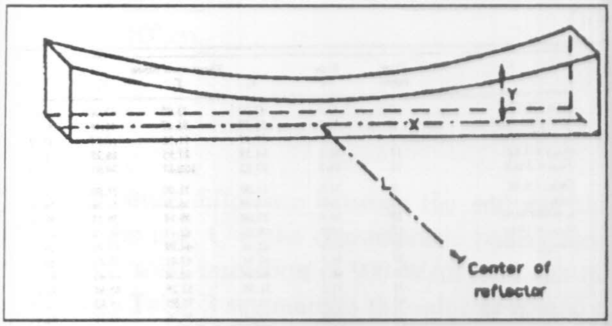

Figure 2. Design parameters used in evaluating the profile for each strip.

The Normal incident radiation was measured using Normal Incidence Pyherliometer (NIP). The wind speed was measured using Hand Held Anemometer. The temperature of the fluid inside the pot was measured using a thermocouple sensor of K type (Ni-Cr/Ni-Al), inserted at the middle height of the fluid.

THEORETICAL ANALYSIS

Let us define the energy received by the food due to heat convection from the pot as q_f. Part of this energy is used to raise the internal energy of the fluid, and the rest is lost as heat convected by the air to the top surface. This part is defined as q_t . Therefore the energy balance equation for the food may be expressed as:

$$q_f = q_t + m_f c_f dT_f/dt \tag{1}$$

$$= h_f A_f (T_p - T_f)$$

Moreover the pot itself is heated by the reflected radiation energy which is defined as q_1. This energy may be divided into three parts. Fist, the energy transferred to the cooking fluid as useful energy (i.e. q_f). Second, the energy stored in the material of the pot as an increase of the internal energy. Third, the energy lost by convection from side walls; convection to the air from the bottom; radiation from the bottom to the ambient and radiation from sides to the cover. These energies are defined as q_{cs}, q_{cb}, q_{r1} and q_{r2} respectively. (see Figure 3).

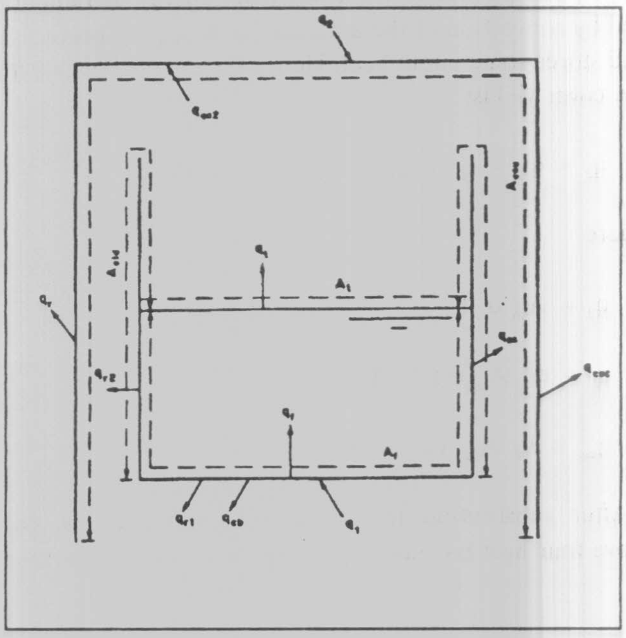

Figure 3. Different types of energy transfer.

$$q_1 = m_p c_p dT_p/dt + q_f + q_{cs} + q_{r1} + q_{r2} + q_{cb} \tag{2}$$

with $q_1 = \alpha\rho F_s I_b A_c$

$$F_s = 1 - A_{sh} / A_c$$

$$q_{cs} = h_g \; A_{sid} \; (t_p - t_g)$$

$$q_{cb} = A_t \; h_a \; (T_p - T_a)$$

$$q_{r1} = \sigma \epsilon_p \; A_t \; (T_p^4 - T_a^4)$$

$$q_{r2} = A_{sid} \; (T_p^4 - T_c^4) \; / \; (1/\epsilon_p + 1/\epsilon_c - 1)$$

The air contained in the air gap receives heat from and/or delivers heat to both the pot and the cover therefore the energy balance equation for the air gap is given as:-

$$q_{cs} + q_t + q_{cs2} = m_a \; c_a \; dT_g/dt \tag{3}$$

where

$$q_{cs2} = h_g \; A_{csu} \; (T_c - T_g)$$

The last lumped element in this model is the cover. The cover receives energy by direct radiation (q_{r2}) and looses or gains energy by convection from inner surface areas (q_{cs2}) . The surface of the cover loses energy by radiation and by convection to the ambient (qr & q_{csc}. respectively), and stores some latent heat. Hence the energy balance for the cover yields:

$$q_2 + q_{r2} = q_r + q_{cs2} + q_{csc} + m_c \; c_c \; dt_c/dt \tag{4}$$

where

$$q_2 = A_{sh} \; \alpha_c \; I_b$$

$$q_r = \sigma \epsilon_c \; A_{csu} \; (T_c^4 - T_a^4)$$

$$q_{csc} = h_a \; A_{csu} \; (T_c - T_a)$$

After substitution for the corresponding terms, the above four heat balances equations (1-4) can be rewritten as

$$dT_f / \, dt = F_f \; (T_f, T_p, t) \tag{5}$$

$$dT_P \; /dt = F_p \; (T_f, T_p, T_g, T_c, t) \tag{6}$$

$$dT_g \; /dt = F_g \; (T_f, T_p, T_g, T_c, t) \tag{7}$$

$$dT_c \; /dt = F_c \; (T_p, T_g, T_c, t) \tag{8}$$

A forth order Runge-Kutta algorithm [13] was used for the numerical solution of this set simultaneous fist order differential equations.

RESULTS AND DISCUSSION

A computer program was prepared to solve the set of equations (5-8) (The integration time interval was selected to be six seconds). The predicted temperatures for the pot, fluid, air gap and cover as well as the experimental results are tabulated in Table 2 and plotted in Figure 4. It is clear that the theoretical model fits the experimental results with a maximum difference of 6.9%. It was also found experimentally that one kg of water requires 16 minutes to boil, while 4 kg of water requires 54 minutes. The decrease in boiling time per one kg of water comes from the fact that the amount of energy required to heat the pot is the same in both cases. from Table 2, the time required to heat up one kg of water to 63 °C, was 6 minutes, for an average wind speed of 3 m/s. While the average time to boil the same amount of water at an average wind speed of 3.5 m/s was 6.3 minutes. This indicates the effect of wind speed on the boiling time.

Table 2. The experimental and theoretical temperature distribution versus time.

	Time (min)	Exp.	Theoretical result			
		T_f	T_f	T_p	T_g	T_c^*
Date: 25/7/89	0	43.0	43.00	43.00	43.00	43.00
Start time 12:56 pm	2	50.0	51.28	56.47	46.44	42.84
I_b = 960 W/m²	6	63.0	67.57	71.98	56.91	45.27
m_{water} = 1 kg	11	86.2	84.39	87.95	66.28	48.85
V_{wind} = 3 m/s	16	94.5	97.82	100.67	74.01	52.20
Date: 1/8/89	0	31.0	31.00	31.00	31.00	31.00
Start time 11:45 am	5	33.0	33.99	36.20	37.26	38.34
I_b = 900 W/m²	10	36.0	37.00	39.18	39.33	40.27
m_{water} = 10 kg	15	39.6	39.97	42.11	40.72	40.27
V_{wind} = 3.5 m/s	20	43.1	42.88	44.99	41.99	40.64
	25	46.5	45.74	47.81	43.23	40.98
	30	48.1	48.54	50.58	44.45	41.32
	35	51.5	51.30	53.29	45.64	41.66
	40	53.8	53.99	55.95	46.82	42.00
	45	55.8	56.64	58.56	47.98	42.34
	50	58.0	59.23	61.12	49.11	42.68
	55	60.4	61.78	63.62	50.23	43.01
	60	62.3	64.27	66.08	51.33	43.34
	65	64.3	66.71	68.48	52.41	43.67
	70	66.2	69.10	70.84	53.47	44.00
	75	68.0	71.44	73.14	54.51	44.33
	80	69.8	73.73	75.40	55.53	44.65
	85	71.5	75.97	77.61	56.53	44.97
	90	73.1	78.17	79.77	57.51	45.29
Date: 6/8/89	0	35.0	35.00	35.00	35.00	35.00
Start time 11:47 am	3	38.6	39.05	42.84	40.04	38.71
I_b = 900 W/m²	8	46.6	45.91	49.53	44.27	40.95
m_{water} = 4 kg	13	50.9	52.44	55.88	47.71	42.16
V_{wind} = 2 m/s	18	58.4	58.63	61.89	50.90	43.41
	23	66.0	64.47	67.56	53.92	44.21
	28	71.6	69.99	72.90	56.79	45.19
	33	76.8	75.20	77.94	59.51	46.14
	38	82.1	80.09	82.67	62.09	47.07
	43	87.5	84.68	87.97	64.52	47.96
	48	89.9	89.00	91.29	66.81	48.82
	53	93.2	93.04	95.94	69.39	49.81

* All temperatures in °C.

Several criteria were established by Khalifa et al. [14] for comparing the performance of solar cookers tested under different insolation conditions. Of these, the overall utilization efficiency and the characteristic boiling time t_c, were found to be especially useful in comparing the boiling water experiments: here

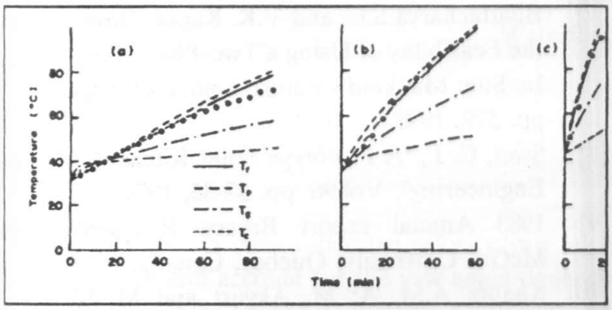

Figure 4. Comparison between the predicted temperature distribution and the experimental results; a : m = 10 kg; b : m = 4 kg; c : m = 1 kg of water.

$$\eta_u = \frac{mc\Delta T}{A_c I_b \Delta t} \tag{9}$$

and;

$$t_c = \frac{c\Delta T}{5.4\times10^4\times\eta_u} \tag{10}$$

where:-

ΔT = temperature difference between the end and the beginning of the test, t_c = the characteristic boiling time for a reference solar insolation of 900 W/m^2 and one m^2 area (min/kg). Table 3 summarizes the value of η_u and t_c for the present cooker. Also included are the calculated values, reported in the literature for several other cookers. It is clear from Table 3 that the present design gives the lowest characteristic time, which gives a good indication for fast cooking.

As an extension for the use solar cooker, a simple closed pot was designed for the purpose of distillation (Figure 5). The feed water surrounding the condensation coil condenses the steam outlet from the pot. The result obtained is tabulated in Table 4. The average beam solar insolation was 930 W/m^2 during the time of the test. The total efficiency was calculated and was found to be 17.46%.

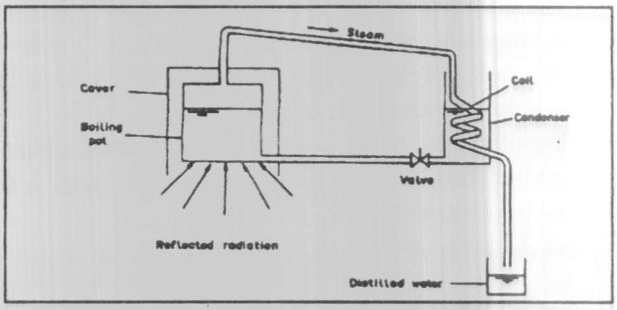

Figure 5. Diagrammatic sketch of apparatus used for distilled water.

Table 3. Performance comparison of solar cookers

Source	Type of cooker	Mass of water (kg)	$_u$%	t_c [min/kg]
Current research	parabolic concentrator	1	11.8	33.60
		4	17.34	25.97
		10	18.40	17.60
Khalifa et al.[10]	Macca-2	4	12.15	43.30
		6	13.64	39.70
		4	19.20	27.00
Khalifa et al. [14]	Mina-1 oven	0.45	23.80	22.70
	Mina-2 oven	0.80	25.80	23.00
Rajput and Singh[15]	Steam cooker	1.60	7.40	66.70

Table 4. The experimental results for water distillation.

Time	11:15	11:30	12:00	12:30	13:30	13:45
m_{steam} (gram)	00	98	252	200	375	136

CONCLUSIONS

The following conclusive remarks can be mentioned:-

- The proposed solar cooker was a double function, for cooking and/or for distilling water.
- The feasibility to produce the proposed solar cooker in a commercial scale is quite possible.
- The efficiency of the present cooker can be increased around 30% if a high temperature black paint is used for the bottom of the pot.
- As the mass of water increases, the required time per unite mass decreases, whereas increase in wind speed, increase the time required for heating unit mass.

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