

DESIGN OF A SOLAR HEATING SYSTEM FOR INDOORS COOKING

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ABSTRACT:

A natural circulation solar heating system for indoors cooking and general household utilization was designed. The system could be integrated within the building kitchen and mainly composed of a simple manually tracked Compound Parabolic Concentrator (CPC) collector, the cooker itself and the necessary piping and fittings. The design specifications and the dimensions of the various parts of the system were given. A natural circulation theory for the system has been presented and a computer program was developed to assess the overall performance of the system. The circulation velocity, the mass flow rate of the working fluid (heat transfer oil), the heat removal factor, the cooker hot plate temperature, the useful heat gain and the collector instantaneous efficiency were predicted.

From the system performance analysis, the useful heat gain and the maximum instantaneous efficiencies were found to be (1428W,47%) , (827W,36.8%) and (1411W,45.9%) for three typical days in Khartoum for the months March , July and November respectively.

1. Introduction and Description of the system :

In the literature, there were different designs of solar cooking devices ranging from the simple hot box to the various types of solar concentrators (Haggar, 1998; Eltom, 2000; Magzoub and Elbahary, 1999).

All of these devices, however, have to be used outdoors in the open hot spaces. These proved to be inconvenient and hardly acceptable especially by the main target group namely the housewives.

In this paper, a simple solar heating system for indoors cooking was designed. The system in comprised mainly from a CPC collector, a simple cooker, piping and the necessary fittings and accessories. The CPC collector (see Fig. (1)) has an acceptance angle of 18° and 50% truncation it was inclined to the south such that it would make an angle of 40° with the horizontal. The CPC collector was composed of main three parts: an absorber, a parabolic reflecting surface and a cover. The absorber was basically a black rectangular steel plate (3m x 0.2 m) having four copper tubes firmly welded underneath it. There were two headers connecting these four tubes, one at the bottom and the other at the top to feed the cooking device. The parabolic surface was a metallic sheet and lined from the inside with

small mirror segments taking the same shape of the parabola. The cover was made of a 3mm single glazed wooden frame. The cooker (see Fig. (2)) was manufactured from two identical circular steel plates (40 cm dia each) separated at their boundaries by a circular steel stripe 3 cm in height to make a suitable circular void for the expansion of the heat transfer oil from the CPC collector. Glass wool insulation was used to cover the sides and the bottom plate tightly while the top plate was left without insulation for cooking purposes. Different kinds of food could be made easily in this hot plate such as Burgers, Omletts and various traditional Sudanese food. The CPC collector plus its inlet and outlet piping system could be manually tracked through two deep groove ball bearings located at points C & F (see fig. (3)). The hourly tracking could be accomplished easily by the assistance of flexible wheels installed at the system base. All the necessary piping connections were installed to complete the system loop and they were properly insulated to minimize any heat transfer losses from the system.

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2. Theoretical Analysis:

The pressure differences, which cause the circulation of fluid in a loop are due to gravity, friction and velocity changes or acceleration. The basic condition to be satisfied for circulation in the loop to exist is that the net changes in pressure around the whole loop must be zero (Magzoub, 1981).

$$\therefore \int dp_g + \int dp_f + \int dp_a = 0 \dots\dots\dots (1)$$

The intergrals in equation (1) were evaluated around the circuit shown in Fig. (3) and the end results can be shown to be :

$$\begin{aligned} \int dp_f = & 0.5\rho_1 V_1^2(4f_1 L_1/d_1+k_1) \\ & +0.5\rho_2 V_2^2(4f_2 L_2/d_2+k_2) +0.5\rho_3 V_3^2(4f_3 L_3/d_3+k_3) \\ & +0.5\rho_4 V_4^2(4f_4 L_4/d_4+k_4) \dots\dots\dots (2) \end{aligned}$$

$$\int dp_a = \int (V/v) dv \dots\dots\dots (3)$$

Since the nature of the flow is assumed to be laminar and the changes in velocity are small, the kinetic energy is negligible.

$$\therefore \int dp_a = 0 \dots\dots\dots (4)$$

The gravitational pressure difference or the driving force arises usually from the density difference between the relatively cold leg of the circuit inside the kitchen and the hot leg represented by the inclined CPC collector outside the kitchen. So, by summing the driving force of the different sections of the circuit yields the following:

$$\int dp_g = g(L_{1v} \rho_1 + L_{2v} \rho_2 + L_{3v} - L_{4v} \sin\beta) \dots\dots\dots (5)$$

Therefore, by adding equations (1) , (2) and (5) and substituting the necessary k and f factors from standard Fluid Mechanics textbooks (Streeter and Wylie , 1979) and the geometrical dimensions a simple equation having only one unknown variable could be obtained as follows:

$$V_1^2 + 0.095V_1 - 0.064 = 0 \dots\dots\dots (6)$$

Equation (6) is quadratic and can be solved numerically to find the circulation velocity V_1

and hence the mass flow rate of the oil around the circuit.

3. Performance Analysis

In this section , the performance of the whole system will be studied . The heat removal factor , useful heat gain, the fluid outlet temperature, the hot plate temperature and the instantaneous efficiencies will be calculated as follows :

Heat removal factor , F_R

F_R can be defined as the ratio of actual heat gain to the gain which would occur if the collector absorber plate was at the same temperature of the inside fluid to the collector T_{fi} (Duffie and Beckman,1991, Sukhatme,1995). F_R can be estimated from the following equation:

$$F_R = m_f (C_p / bLU_L) (1 - \exp(-bLU_L / m_f C_p)) \dots\dots\dots (7)$$

The mass flow rate m_f is calculated using the continuity equation :

$$m_f = AV\rho \dots\dots\dots (8)$$

Useful heat gain, Q_u

Q_u is the heat gain by the fluid from the CPC collector and given by:

$$Q_u = F WL(S - U_L (T_{fi} - T_a) / C) \dots\dots\dots (9)$$

Fluid outlet temperature, T_{fo}

T_{fo} is estimated as :

$$T_{fo} = Q_u / m_f C_p + T_{fi} \dots\dots\dots (10)$$

Hot plate temperature of the cooker T_p

T_p can be estimated as :

$$T_p = T_{fo} - Q_1 / (m_f C_p) \dots\dots\dots (11)$$

Instantaneous efficiency, η_i

The instantaneous collection efficiency, η_i , is defined as the useful heat gain divided by the incident total radiation.

$$\therefore \eta_i = Q_u / (G_b R_b + G_d R_d) * WL \dots\dots\dots (12)$$

$$R_b = \cos \theta / \cos \theta_z \dots\dots\dots (13)$$



$$\text{And } Rd = (1 + \cos \beta) / 2 \dots\dots\dots(14)$$

A computer program was developed and used to calculate the circulation velocity V_1 , mass flow rate m_f , heat removed factor F_r , useful heat gain Q_u , fluid inlet and outlet temperature T_{fi} , T_{fo} , hot plate temperature T_p and instantaneous efficiency η_i .

In the calculation, a constant load $Q_L = 550W$ was assumed on the hot plate.

The calculations were done for the dates 16th March, 17th July and 14th November for the city of Khartoum (Latitude = 15.5°N)

4. Results and Discussion :

From the output of the program, the performance results are shown in Fig. (4),(5) and (6) for the selected three days. From Fig. (4), (5) and (6), it could be noticed that the maximum value of heat gain from the CPC collector occurs just before and at noon time with maximum values of 1400W in March and November and about 830W in July. This is expected since July is known to be the rainy season in Sudan and clouds tend to minimize the direct solar radiation.

The temperature range of the cooker plate is between 100°C and 180°C throughout the day. Therefore, it is expected the all kinds of food including meat could be easily cooked at any time.

The maximum instantaneous efficiency of the collector ranges from 37% to 47% This is considered to be acceptable as compared to other types of collectors due to the good insulation and the concentration effect of the collector.

5. Conclusions

1. A natural circulation solar heating system for general home cooking has been designed and could be integrated easily within the building kitchen.
2. A simple manually tracked Compound Parabolic Concentrator collector has been selected and heat transfer oil was used as a working fluid.
3. From the system performance analysis, the maximum useful heat gain and the thermal efficiencies were estimated to be

(1428W, 47.02%), (827W, 36.8%) and 1411W, 45.9%) for three typical days in Khartoum for the months March, July and November respectively.

4. The temperature of the cooker hot plate ranged from 100°C to 180°C throughout the hours of these days which will facilitate convenient cooking at any time.
5. It is recommended that the whole solar heating system to be manufactured by using local materials, integrated within the building kitchen and proper field tests to be carried out.

Nomenclature

- A-Cross sectional area, m²
- b- Absorber width, m
- f_1, f_2, f_3, f_4 - frictional factors in section 1,2,3 and 4 respectively
- k_1, k_2, k_3, k_4 - Shock factors in section 1,2,3 and 4 respectively
- V_1, V_2, V_3, V_4 - Fluid velocity in section 1,2,3 and 4 respectively, (m/s)
- d_1, d_2, d_3, d_4 - Inside tube diameter in section 1,2,3 and 4 respectively (m)
- $\rho_1, \rho_2, \rho_3, \rho_4$ - Fluid density in section 1,2,3 and 4 respectively (kg/m³)
- v - Specific volume of fluid (m³/kg)
- L_{1v}, L_{2v}, L_{3v} - Vertical length of section 1,2 and 3 respectively (m)
- F_R - Heat removal factor
- M_f - Fluid mass flow rate, (kg/s)
- C_p -Specific heat of fluid, (kJ/kgK)
- F - Collector efficiency factor
- U_L - Heat transfer loss coefficient, kW/m²K
- h_f - Fluid heat transfer coefficient, kW/m²K
- Q_u - Useful energy gain, kW
- C - Concentration ratio
- S - Absorber energy, kW/m²
- T_{fi} - Fluid inlet temperature to collector, °C
- T_{fo} - Fluid outlet temperature from collector, °C
- T_a - Ambient air temperature, °C
- T_p - Hot plate temperature, °C
- η_i - Instantaneous efficiency using both beam and diffuse radiation
- G_b - Solar intensity, kW/m²



G_d – Diffuser intensity kW/m^2
 R_b, R_d – Beam, diffuse radiation
 θ – Incidence angle, degree
 θ_z – Zenith angle, degree
 β – Tilt angle of the CPC collector, degree

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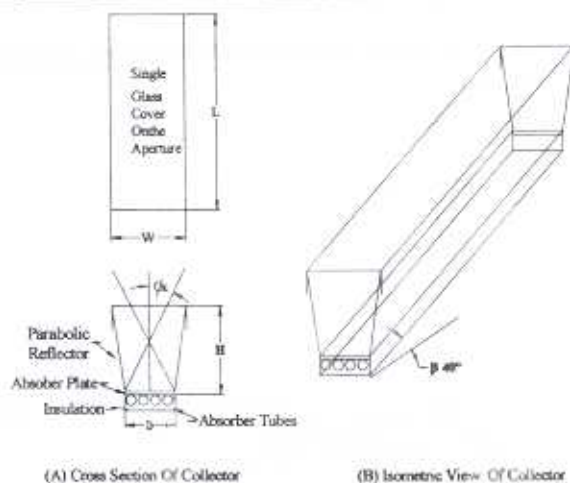


Fig.1 THE CPC COLLECTOR

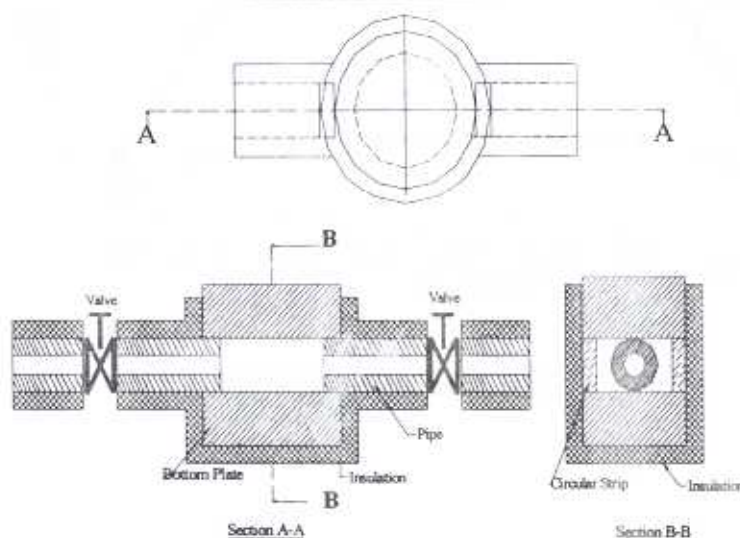


Fig.2 THE SYSTEM COOKER



Section 1 - ABCD of length L_1
 Section 2 - DE of length L_2
 Section 3 - EFGH of length L_3
 Section 4 - HA of length L_4

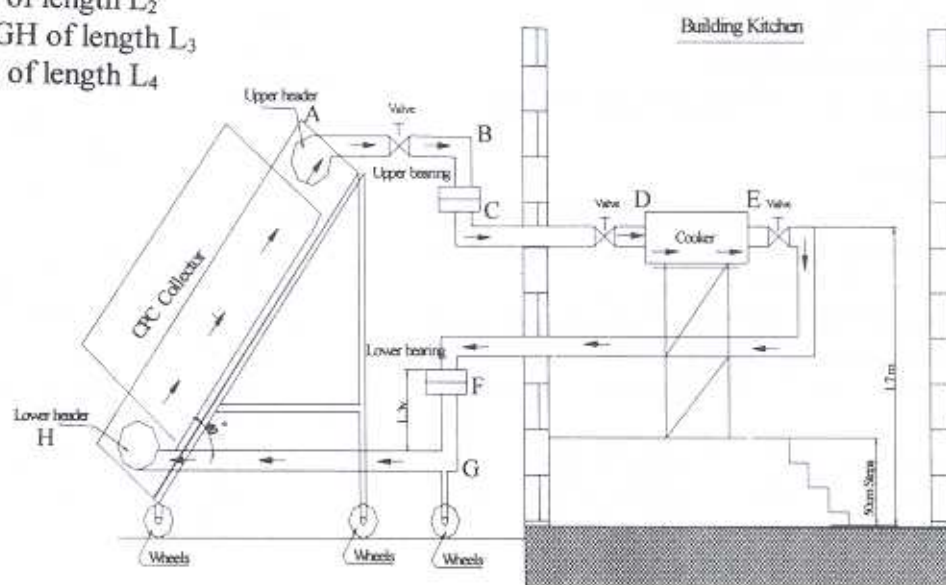
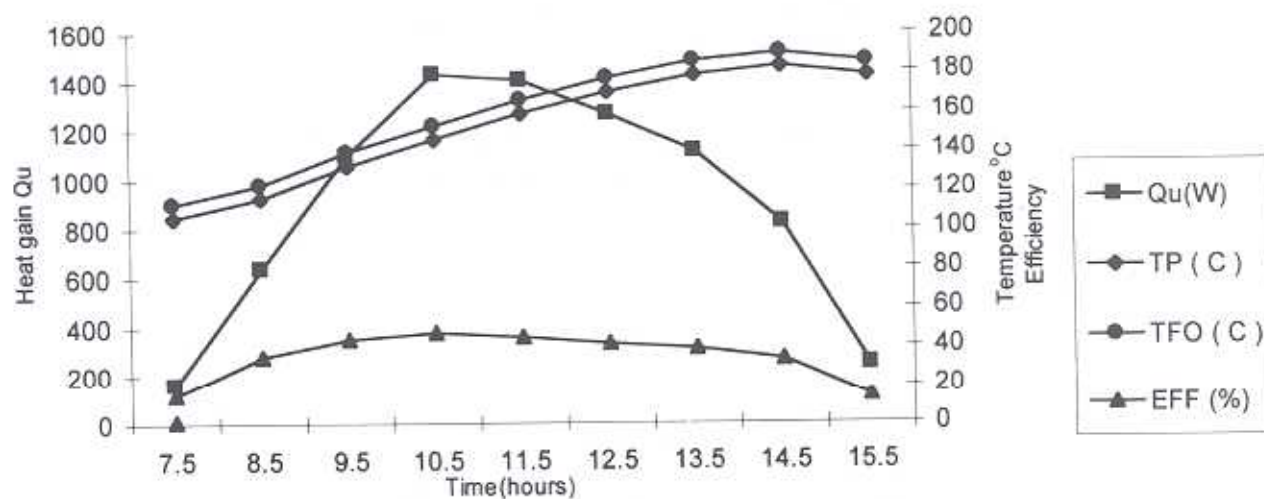
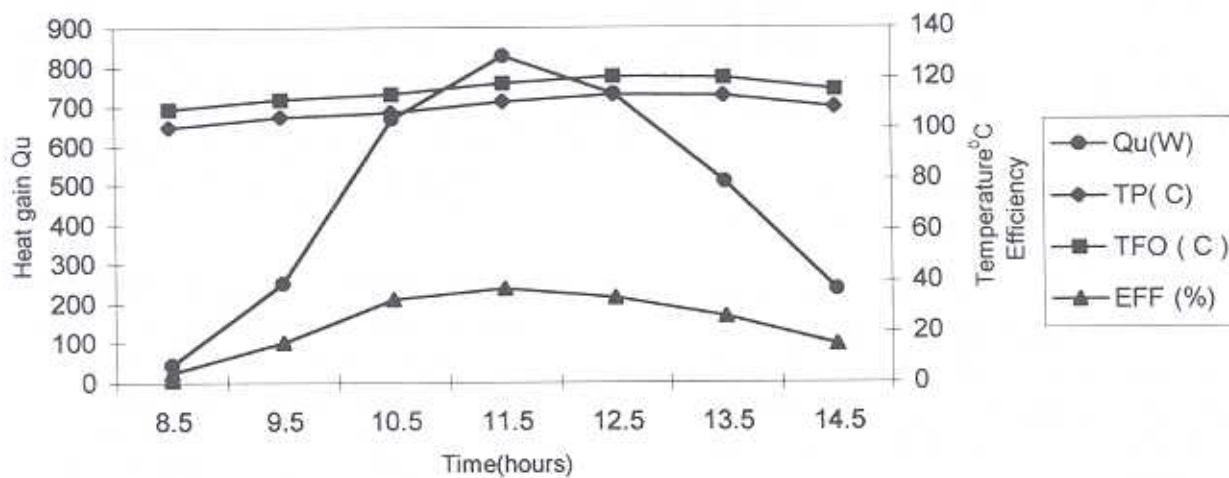


Fig.3 THE NATURAL CIRCULATION SOLAR HEATING SYSTEM

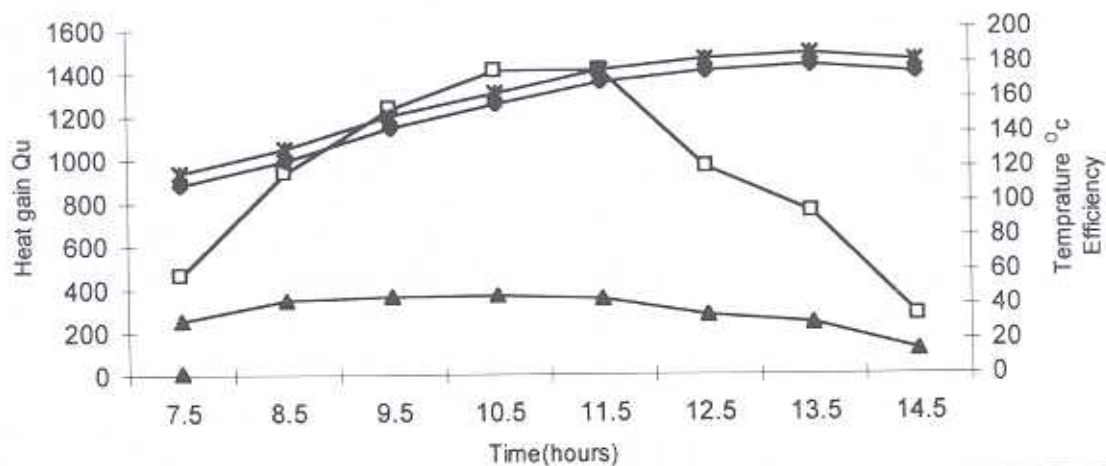


Fig(4) PERFORMANCE CHART FOR 16th March





Fig(5) PERFORMANCE CHART FOR 17th July



Fig(6) PERFORMANCE CHART FOR 14th Nov.

