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DESIGN AND DEVELOPMENT OF A PARABOLIC DISH SOLAR WATER HEATER

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ABSTRACT

The design and development of a parabolic dish solar water heater for domestic hot water application (up to 100^{o}C) is described. The heater is to provide 40 litres of hot water a day for a family of four, assuming that each member of the family requires 10 litres of hot water per day. For effective performance the design requires that the solar water heater track the sun continuously, and an automatic electronic control circuit was designed and developed for this purpose. Experimental test runs carried out showed that the overall performance of the solar water heater was satisfactory. Thermal efficiencies of 52% - 56% were obtained, and this range of efficiencies is higher than the designed value of 50%. The use of a linear actuator (Superjack) to track the sun eliminates the need for constant monitoring by a human operator and, thus, reduces the cost of labour.

NOMENCLATURE

A_a – aperture area
A_{abs} – absorber area
C –concentration ratio
c_{pw} – specific heat capacity at constant pressure of water
D_a – aperture diameter
D_{abs} – outside diameter of absorber
d_{abs} – internal diameter of absorber
F_R – heat removal factor
f – focal length
I_b –beam radiation
$\bar{I}_D$ - long-term average direct radiation
l – height of absorber
M_w – mass of water
$\dot{m}_w$ - rate of heating water
P_{abs} - rate of energy absorbed by the absorber
Q_u – estimated useful energy for one cycle of the designed heater
q_u – useful thermal energy delivered
T_1 – temperature of heat transfer fluid entering the collector
T_2 – temperature of heat transfer fluid leaving the collector
T_a – ambient temperature
T_{abs} – absorber temperature
T_w – temperature of water
t – time (seconds)
t_x – thickness of absorber wall
U_L – overall heat loss coefficient
V_w - volume of water
η – instantaneous thermal efficiency
η_o – optical efficiency
ψ_{rim} - rim angle

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INTRODUCTION

In the past two decade there has been a significant increase in the use of domestic solar water heaters around the world, with solar water heater production now a major industry in China, Australia, Greece, Israel and the USA {Morrison et al, 1999} Solar water heaters are simple solar thermal applications that convert solar radiation into heat that is used to warm water for bathing, washing, cleaning, and cooking (Hankins, 1995). Solar water heating is now recognised as a reliable practice that saves substantial amounts of electricity or other conventional fuels, leads to peak load reduction and prevents emission of carbon dioxide. A domestic solar water heating system can provide close to 60% of the energy required annually for water heating in a household (Dintchev, 2006).

Solar water heaters generally fall into two broad categories: concentrating type and non-concentrating type. Flat plate collectors and evacuated tube collectors are the two most widely used non concentrating type of solar water heaters. The concentrating type of heaters usually employs parabolic/concave mirrors/reflectors to concentrate the total solar energy incident on the collector surface. So the collector surface is usually very wide and the temperature achieved is very high. Some of the collectors in this category are parabolic trough, compound parabolic concentrator, parabolic dish, and cylindrical parabolic concentrator. Parabolic dish has the highest efficiency in terms of the utilization of the reflector area because in a fully steerable dish system there are no losses due to aperture projection effects. Also radiation losses are small because of the small area of the absorber at the focus (Rai, 2005).

Back home in Nigeria, several researches on heating water using solar energy have been carried out, mainly by using flatplate collectors (DRERDAN, 1999). Other solar thermal collectors have been used as well, though on a smaller scale,. Mohammed (2001) constructed and used a parabolic trough collector for sensible heat water heating. Daudu (2002) designed and developed a solar conical concentrator which was tested by heating water up to 99^o C. Manukaji and Akinbode (2002) constructed a parabolic-dish solar concentrator which was then tested for various applications which included water-heating and cooking food items. Pelemo et al (2003) designed and constructed a parabolic solar concentrator which was then used and tested for water distillation. A more recent effort was undertaken by Folaranmi (2009) who designed, constructed, and tested a parabolic solar concentrator for steam generation.

In this present work, a parabolic-dish solar water-heater (PDSWH), as shown in Fig. 1, was designed and constructed. The heater was required to heat up to 40 litres of water a day for a family of four assuming that each member of the family would require 10 litres of hot water a day.

THEORETICAL BACKGROUND

Several parameters are used to describe solar concentrating collectors. Given below are brief descriptions of some of these parameters:

The *aperture area* A_a is the area of the collector that intercepts solar radiation.

The *Acceptance angle* is defined as the angle through which a source of light can be moved and still converge at the receiver (Hsieh, 1986). A concentrator with small acceptance angle is required to track the sun continuously while. a concentrator with large acceptance angle needs only seasonal adjustment.

The *absorber area* A_{abs} is the total area of the absorber surface that receives the concentrated solar radiation. It is also the area from where useful energy can be extracted.

The *Concentration ratio* C is defined as the ratio of the aperture area to the absorber area i.e.

$$C = \frac{A_a}{A_{abs}} \quad (1)$$

The *optical efficiency* η_o is defined as the ratio of the energy absorbed by the absorber to the energy incident on the concentrator aperture (Garg and Prakash, 2000). It includes the effect of mirror/lens surface, shape and reflection/transmission losses, tracking accuracy, shading, receiver-cover transmittance, absorptance of the absorber and solar beam incidence effects. The optical efficiency is given as:

$$\eta_o = \frac{P_{abs}}{A_a \overline{I_D}} \quad (2)$$

The optical efficiency of most solar concentrators lies between 0.6 and 0.7. In a thermal conversion system a working fluid is used to extract energy from the absorber. The thermal performance of solar concentrator is determined by their thermal efficiency.

The *thermal efficiency* is defined as the ratio of the useful energy delivered to the energy incident at the concentrator aperture:

$$\eta_{th} = \frac{\rho V c_{pf}(T_2 - T_1)}{I_b A_a} \quad (3)$$

The incident solar radiation consists of beam (direct) and diffuse radiation. However, the majority of concentrating collectors can utilize only beam radiation.

The *instantaneous thermal efficiency* of a solar concentrator may be calculated from an energy balance on the absorber. The useful thermal energy delivered by a concentrator is given by

$$q_u = \eta_o I_b A_a - U_L(T_{abs} - T_a)A_{abs} \quad (4)$$

Therefore, the instantaneous thermal efficiency may be written as

$$\eta = \frac{q_u}{I_b A_a} = \eta_o - \frac{U_L(T_{abs} - T_a)}{I_b C} \quad (5)$$

At higher operating temperatures the radiation loss term dominates the convection losses and the energy balance equation may be written as

$$q_u = \eta_o I_b A_a - U_L(T_{abs}^4 - T_a^4)A_{abs} \quad (6)$$

instead of Eq. (4).

In Eq. (6) U_L takes into account the accompanying convection and conduction losses also. The instantaneous thermal efficiency η is now given by

$$\eta = \eta_o - \frac{U_L(T_{abs}^4 - T_a^4)}{I_b C} \quad (7)$$

Since the absorber surface temperature is difficult to determine, it is convenient to express the efficiency in terms of the inlet fluid temperature by means of heat
removal factor F_R as:

$$\eta = F_R\left[\eta_o - \frac{U_L(T_L - T_a)}{I_b C}\right] \quad (8)$$

The instantaneous thermal efficiency is dependent on two types of quantities, namely the concentrator design parameters and the parameters characterising the operating conditions. The optical efficiency, heat loss coefficient and heat removal factor are the design dependent parameters while the solar flux, inlet fluid temperature and the ambient temperature define the operating conditions.

DESIGN CALCULATIONS

Sizing of the Parabolic Dish Solar Water Heater

The heat demand load of the heater is such that it will heat about 40 litres of water in a day, from ambient temperature to 100^0C. However, in order to reduce space requirement, the heater will be designed in such a way that it will heat about 10 litres of water only at a time. Thus at an average uniform rate of solar insolation, the heater will make 4 cycles of almost equal lengths in time to heat the quantity of water required.

The absorber of the heater will be a cylinder of outside diameter D_{abs}, internal diameter d_{abs}, height *l*, and thickness t_x = 2mm.

The internal volume of the cylinder is the same as the volume of water, V_w, to be heated. Therefore:

$$\frac{\pi d_{abs}^2}{4} \times l = V_w \quad (9)$$

For simple solution of the equation and optimum design of the absorber the height *l* is made to be the same as the diameter d_{abs}.

$$\frac{\pi d_{abs}^3}{4} = 0.01$$

$$d_{abs} = \sqrt[3]{\frac{4\times 0.01}{\pi}} = 0.234m$$

d_{abs} = 23.4cm

l = d_{abs} = 23.4cm

D_{abs} = d_{abs} + 2t = 0.234 + 2 (0.002) (10)

D_{abs} = 0.238m = 23.8cm

The effective surface area of the absorber is given as:

$$A_{abs} = \frac{\pi D_{abs}^2}{4} + \pi D_{abs} l \tag{11}$$

$$= \frac{\pi \times 0.238^2}{4} + \pi \times 0.238 \times 0.234$$

A_{abs} = 0.219m^2

From Eq. (1), the concentration ratio is given as:

$$C = \frac{A_a}{A_{abs}}$$

To reduce the frequency of tracking the sun C is set at 10 (Magal, 1993).

A_a = C ×0.219 = 2.19m^2

The aperture diameter D_a is given by

$$\frac{\pi D_a^2}{4} = 2.19$$

$$D_a = \sqrt{\frac{4\times 2.19}{\pi}} = 1.67\text{m}$$

D_a = 167cm

The half-acceptance angle ϕ is given by (Garg and Prakash, 2000):

$$C = \frac{1}{\sin^2 \phi} \tag{12}$$

$$\phi = \sin^{-1}\sqrt{\frac{1}{C}} = \sin^{-1}\sqrt{\frac{1}{10}}$$

ϕ = 18.43°

The optimum rim angle ψ_{rim} is:

ψ_{rim} = 90° - ϕ (13)

= 90° – 18.43° = 71.57°

The focal length, *f*, of the dish is obtained from (Stine and Harrigan, 1985):

$$\frac{f}{D_a} = \frac{1+\cos\psi_{rim}}{4\sin\psi_{rim}} \tag{14}$$

$$f = \frac{D_a(1+\cos\psi_{rim})}{4\sin\psi_{rim}} = \frac{1.67(1+\cos 71.57)}{4\sin 71.57}$$

f = 0.579m = 57.9cm

The height, h, of the dish is given by:

$$h = \frac{D_a^2}{16f} \qquad (15)$$

$$= \frac{1.67^2}{16 \times 0.583} = 0.3010$$

h =30.1 cm

EXPECTED THERMODYNAMIC PERFORMANCE OF THE PDSWH

The estimated useful energy for one cycle of the designed PDSWH is given by

$$\dot{q}_u = \eta I_b A_a$$

The efficiency range of most solar concentrators is 40% - 60% (Magal, 1993). Hence for Kaduna (Mohammed,2009):

$I_b = \bar{I}_D$ = 716.6 W/m^2

η = 0.5 (average of 0.4 and 0.6)

$\dot{q}_u$ = 0.5 × 716.6 × 2.19

$\dot{q}_u$ = 784.68W

For four cycles, the total useful energy is

$\dot{Q}_u$ = 4 $\dot{q}_u$ = 4 × 784.68

$\dot{Q}_u$ = 3138.72W

The useful energy is also given by

$$\dot{q}_u = \dot{m}_w c_{pw}(T_w - T_a) = \eta.\bar{I}_D.A_a \qquad (16)$$

where $\dot{m}_w$ is the rate of heating the water and c_{pw} is the specific heat capacity at constant pressure of the water. c_{pw} is obtained from tables of properties of water (Rogers and Mayhew, 1981) as 4186J/kgK (at 25 ^{o}C).

$$\dot{m}_w = \frac{\eta.\bar{I}_D.\pi D_a^2}{4c_{pw}(T_w - T_a)}$$

$$= \frac{0.5 \times 716.6 \times \pi \times 167^2}{4 \times 4186 \times (100 - 25)}$$

= 2.49982 × 10^{-3} kg/s

= 9.00 kg/hr

$\dot{m}_w$ is also given by

$$\dot{m}_w = \frac{\rho_w V_w}{t} \qquad (17)$$

where ρ_w is the density of water evaluated at the temperature of 25^{0}C, and t is the time taken to heat the water.

$$t = \frac{\rho_w V_w}{\dot{M}_w} = \frac{997.01 \times 0.01}{2.49982 \times 10^{-3}}$$

t = 3988.3s ≈ 66.5 minutes

For 4 cycles the total time is

t_t = 4 × t = 4 × 66.5

t_t = 266 minutes

The energy, P_{abs}, absorbed by the absorber is obtained from Eq. (2):

$$\eta_0 = \frac{P_{abs}}{A_a \bar{I}_D}$$

$$P_{abs} = \frac{\eta_o}{\eta}\left(\eta A_a \overline{I_D}\right)$$

η_o = 0.65 (average of 0.6 and 0.7) and the bracketed term is the same as $\dot{q}_u$

$$P_{abs} = \frac{0.65}{0.5}\dot{q}_u = 1.3\dot{q}_u$$

For $\dot{q}_u$ = 784.68 W

P_{abs} = 1.3 × 784.68 = 1020.08 W

SELECTION OF MATERIALS FOR THE CONSTRUCTION OF THE PDSWH.

Material for the Body of the Dish:
Aluminium was selected over steel because of its lightness, lower cost, ease of fabrication and energy effectiveness in use of material. Its light weight reduces the overall weight of the PDSWH, and also reduces the amount of work to be done by the SuperJack in turning the dish from east to west and vice versa.

Material for the Reflecting Surface.
To reduce the overall weight of the solar water heater, a light glass mirror of 2mm thickness, of high surface quality and good specular reflectance was selected. A glass mirror was selected over polished aluminium surface because its reflectivity of 95% is better than that of aluminium (85%). Also, glass surface is easier to clean than aluminium surface.

Material for the Absorber
Aluminium was selected over copper and steel because of its lower cost, light weight, ease of fabrication and energy effectiveness in use of material. Its light weight reduces the overall weight of the solar water heater and also reduces the amount of work to be done by the SuperJack in turning the dish about its horizontal axis.

Material for the Absorber Surface Coating
Black paint was selected for the absorber coating. It is selected over other coatings because of its higher absorptivity at angles other than normal incidence, adherence and durability when exposed to weathering, sunlight and high stagnation temperatures, cost effectiveness and protection to the absorber material.

Heat Transfer Fluid
Water was selected as the heat transfer fluid for the solar heater because of its stability at high temperatures, low material maintenance and transport costs, safe to use, and is the most commonly used fluid for domestic heating applications.

Material for the Vertical Support of the Dish
A rectangular, hollow, steel bar was selected for the support of the dish and the SuperJack. This is because of its strength, rigidity, resistance to deflection by commonly encountered winds, and its ability to withstand transverse and cross-sectional loads of the entire heating portion of the PDSWH.

Material for the Base of the PDSWH
A combination of angle and flat, steel bars were chosen for the base which supports the whole solar water heater structure. Flat and angle bars were chosen to provide solid and rigid support for the rectangular, vertical axis steel bar which supports the parabolic dish.

Tracking Mechanism

An automatic linear actuator (SuperJack) typical of the one in use in the satellite dish industry was selected over the manual tracking mechanism. The Superjack gives a slow, steady motion to the parabolic dish as it turns on its axis from East to West. The hydraulic arm is controlled by a 36V-Motor fitted at one end of the jack. Solar energy radiation sensors (see Plate 1) fitted on the aperture of the dish send electric signals to the motor which, in turn, adjust the position of the dish until maximum solar radiation intensity is received at the aperture.

Development of the Electrical Control Circuit for the Tracking Mechanism

The Superjack consists of a hydraulic arm, an electric motor, and solar photosensors circuit.

The hydraulic arm consists of two cylinders, one fitted into the other in a telescopic manner. The diameter of the inner cylinder is 14cm and its length is approximately 30cm. When fully extended the total length of the two cylinders is approximately 95.5cm. The elongation and contraction of the inner cylinder within the outer cylinder gives the dish its movement from east to west. The outer surface of the inner cylinder and the inner surface of the outer cylinder are separated by an extremely thin film of lubricating oil, which make the relative movement of the two cylinders smooth. An oil seal provided at the top end of the outer cylinder prevents the lubricating oil from leaking outside. The outer cylinder is anchored to the cylindrical part of the vertical support through a fastening device, which rigidly holds the Superjack at an angle of about 45^o relative to the vertical support. The Superjack is connected to the body of the parabolic dish through a hole on a piece of metal at the top of the inner cylinder.

The hydraulic arm is controlled by a 12-36V motor fitted at one end of the outer cylinder. Electric current is supplied to the motor by a 12 volt, 12AH rechargeable dry cell of trade mark GASTON model MH19926 (see Plate 1).

The operation of the tracking mechanism can be controlled either manually or automatically. For both modes of control, an electric circuit had to be developed.

Thus when the switch is turned in one direction, the control of the dish is automatic, using the two solar sensors. When the switch is turned in the opposite direction, the control of the dish is manual,

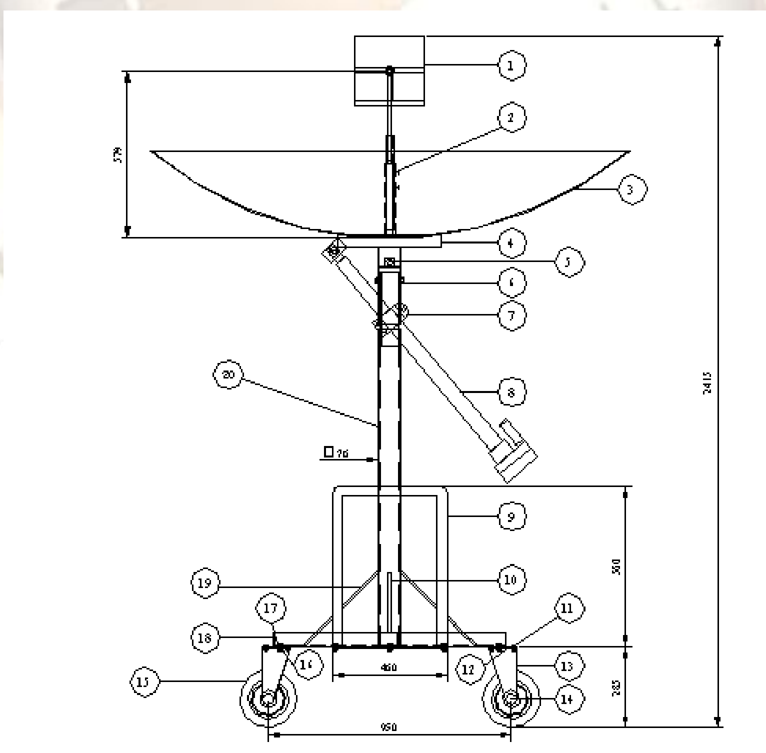

Figure 1: Assembled drawing of the parabolic dish solar water heater

Original scale used 1:15

S/NO	ITEM	MATERIAL	NO. OF
1	ABSORBER	ALUMINIUM	1
2	SCREW LOCK	STEEL	2
3	PARABOLIC DISH	ALUMINIUM	1
4	RING CONNECTOR	STEEL	1
5	SWING ROD	STAINLESS STEEL	1
6	BOLT LOCK	STEEL	3
7	CLAMP	BRASS	1
8	SUPERJACK		1
9	HANDLE	STEEL	1
10	SHORT-BAR SUPPORT	STEEL	2
11	BOLT	STEEL	16
12	NUT	STEEL	16
13	WHEEL BRACKET	STEEL	4
14	WHEEL AXLE	STEEL	4
15	WHEEL	RUBBER	4
16	NUT	STEEL	8
17	BOLT	STEEL	8
18	BASE SUPPORT	STEEL	1
19	LONG-BAR SUPPORT	STEEL	2
20	TRUNK	STEEL	1

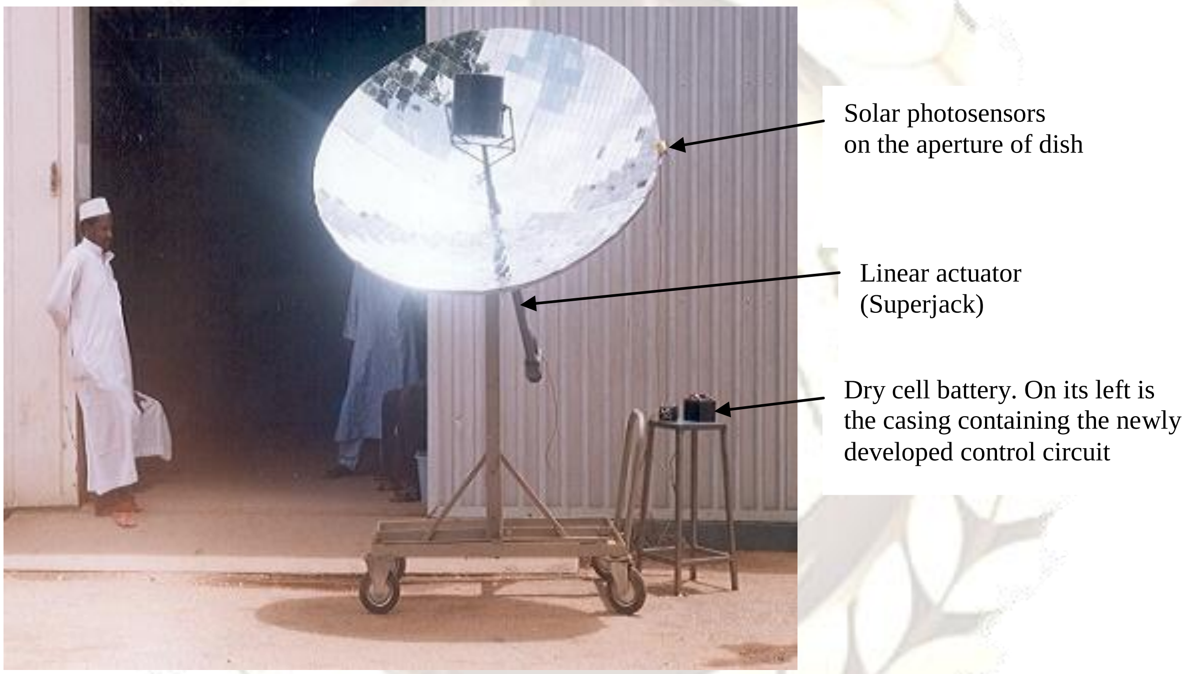

Plate 1: Front photograph of the parabolic dish solar water heater

After the solar water heater was constructed some performance test runs were carried out. The result of the experimental test runs are given in Table 1.

Table 1: Summary of useful energy, energy at aperture and efficiency of PDSWH

S/NO	MONTH/YEAR	E_u (J)	E_a (J)	η (%)
1	APR (2008)	3002407.2	5311188.0	56.3
2	MAY(2008)	3087511.2	5886720.0	52.4
3	JUN (2008)	3130113.6	5851242.0	53.5
4	JUL (2008)	3130113.6	5722470..0	54.7
5	AUG (2008)	3044930.4	5637060.0	54.0
6	SEP (2008)	3087511.2	5794740.0	53.3

All experiments were carried out within the range of ± 1 day of the mean day (Klein, 1977) of each month. From the results, it can be seen that the thermal efficiency of the heater for each month is higher than the designed value of 50.0% and, therefore, the overall performance of the heater is satisfactory.

CONCLUSION

The design and development of a parabolic dish solar water heater for domestic hot water application is presented in this paper together with the predicted and actual thermal performance of the system. The performance of the heater in terms of efficiency is higher than expected. While no detailed performance analysis is presented here, it has always been possible for the water temperature to reach 100°C in agreement with the designed requirement of the heater. The main research fields for this work are solar - collector physics, components design and development, material economy, energy cost savings, and reduction of carbon dioxide emission into the atmosphere. With the exception of the linear actuator (Superjack) all the other components were made from locally available materials. This promotes local content utilization of manufactured goods and services. The use of the tracking mechanism, Superjack, eliminates the need for constant monitoring by a human operator and this results in the reduction of the cost of labour.

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