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Design and Development of a Parabolic Dish Solar Thermal Cooker

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ABSTRACT

A parabolic dish solar thermal cooker having aperture diameter 1.8 m, depth 29.0 cm and focal length 69.8 cm was designed and constructed. The cooker was designed to cook food equivalent of 12 kg of dry rice per day, for a relatively medium size family. For effective performance, the design required that the solar cooker track the sun frequently, and a linear actuator (superjack) was adopted for this purpose. Preliminary test results show that the overall performance of the solar thermal cooker is satisfactory. The cooker is capable of cooking 3.0 kg of rice within 90 – 100 minutes, and this strongly agrees with the predicted time of 91minutes.

***Keywords* –** Cooker, design, development, dish, thermal parabolic, solar

I. INTRODUCTION

Cooking is one of the very important and necessary household chores in every society of the world. Energy consumption for cooking in developing countries is a major component of the total energy consumption, including commercial and non-commercial energy sources [1], [2]. In the rural areas of most developing countries cooking is usually done in open fires fuelled by firewood. In the cities, stoves are more common, fuelled by wood, charcoal, kerosene of sometimes fuel gas. In many regions, especially East Africa and West Africa (including Nigeria), oil-derived fuels are expensive, and wood-based fuels are becoming increasingly scarce, as rising demand presses hard on dwindling number of trees. In developing countries like Nigeria, cooking is the main source of demand for firewood, and is an important cause of deforestation.

There are four possible ways of remedying an insufficient supply of firewood for cooking. The first is to increase supply by promoting the planting of trees. The second is to decrease demand by introducing more energy-efficient stoves. The third is to develop indigenous alternative sources of fuel, such as biogas. The fourth is to promote the replacement of fuel-using techniques by solar cooking, the subject of this technical presentation.

Solar cookers are divided into four main categories [3]: (i) concentrator cooker; (2) box cookers; (3) solar ovens, and (iv) indirect solar cookers.

The concentrating type of solar cookers is further sub-divided into parabolic dish/trough, cylindrical, spherical, and Fresnel. This type of cookers usually employs 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. Parabolic dish cooker has the highest efficiency in terms of the utilization of the reflector area because in 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 [4]. Additional advantages include higher cooking temperatures, as virtually any type of food can be cooked. , and short heat-up times.

In the present work a parabolic dish solar thermal cooker, PDSTC, was designed and constructed. The cooker was required to cook food equivalent of 12 kg of dry (uncooked) rice per day for a relatively medium size family, with a designed efficiency of about 50%.

II. PARABOLIC GEOMETRY FOR THE DESIGN OF THE PDSTC

The surface formed by rotating a parabolic curve about its axis is called a *paraboloid* of *revolution*. Solar concentrators having a reflective surface in this shape are often called parabolic dish concentrators.

The equation for the paraboloid of revolution, as shown in Fig. 1, in rectangular coordinates with the z axis as the axis of symmetry is [5]:

$$x^2 + y^2 = 4fz \qquad (1)$$

where the distance f is the focal length VF. In cylindrical coordinates, where a is the distance from the z axis, this becomes:

$$z = \frac{a^2}{4f} \qquad (2)$$

In spherical coordinates, the equation of a paraboloid of revolution with its vertex V at the origin and r, ϕ, and θ defining the location of point R on the paraboloid, is:

$$\frac{\sin^2\theta}{\cos^2\theta} = \frac{4f}{r} \qquad (3)$$

Parabolic dish concentrators use a truncated portion of the surface generated by rotating a parabolic curve. The extent of this truncation is usually defined in terms of the rim angle ψ_{rim} or the ratio of the focal length to aperture diameter f/D_a.

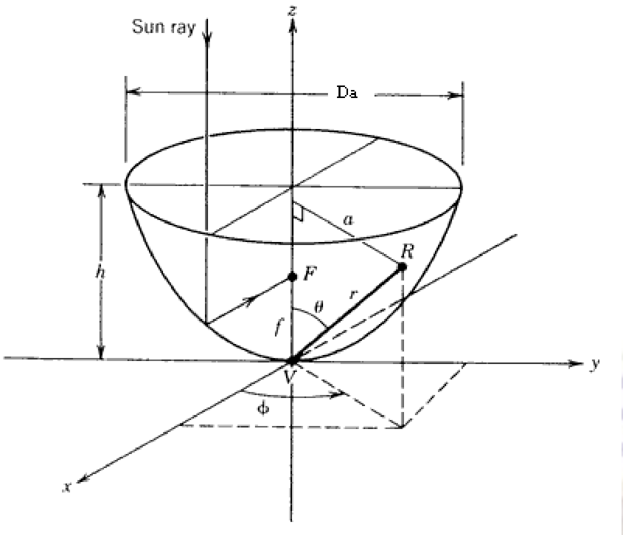

Figure 1: Paraboloid of revolution

The size of a parabolic dish is often specified terms of a linear dimension such as the aperture diameter, D_a, or the focal length, *f*. A parabolic dish with a small rim angle is relatively flat and the focal length is long compared to its aperture diameter. The height of the parabolic dish, *h*, is defined as the maximum distance from the vertex to a line drawn across its aperture. In terms of focal length and aperture diameter, the height of the dish is:

$$h = \frac{D_a^2}{16f} \tag{4}$$

The rim angle, ψ_{rim}, can be found in terms of the dish dimensions [ibid]:

$$\tan\psi_{rim} = \frac{1}{\left(\frac{D_a}{8h}\right) - \left(\frac{2h}{D_a}\right)} \tag{5}$$

The parabolic dish aperture area, of most importance to the solar energy designer, is simply the circular area defined by the aperture diameter D_a and is given by:

$$A_a = \frac{\pi D_a^2}{4} \tag{6}$$

The equation for the aperture area is also casted in terms of the focal length and rim angle:

$$A_a = 4\pi f^2 \frac{\sin^2\psi_{rim}}{1+\cos\psi_{rim}} \tag{7}$$

III. PARAMETERS CHARACTERISING THE THERMAL PERFORMANCE OF THE PDSTC

The basic function of a parabolic dish solar cooker is to collect solar radiation over a large area and concentrate it onto a smaller area, the focal point, where the absorber containing the food is located. The temperature of the absorber and the food rises, and after some time the food is cooked.

Concentrators can be defined by the following two methods [3]: geometric concentration and flux concentration. *Geometric concentration* is defined as the ratio of aperture area to absorber area:

$$C_{area} = \frac{A_a}{A_{abs}} \tag{8}$$

The flux concentration is defined as the ratio of intensity at the aperture to intensity at the absorber:

$$C_{flux} = \frac{I_b}{I_{abs}} \tag{9}$$

This involves an absorption effect in addition to geometry. In solar concentrator cookers geometric flux is the most widely used method [ibid].

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 [6]. It includes the effect of mirror/lens surface, shape and reflection/transmission losses, tracking accuracy, shading, absorber cover transmittance, absorptance of the of the absorber, and solar beam incidence effects. The optical efficiency is given as:

$$\eta_o = \frac{P_{abs}}{A_a I_b} \tag{10}$$

The *optical efficiency* of most solar concentrators lies between 0.6 and 0.7 [7]. In a solar thermal cooker, a combination of a working fluid and food substance is used to extract energy from the absorber.

The *thermal efficiency* is defined as the ratio of the useful energy delivered, to the energy incident at the concentrator aperture. For solar thermal cookers, the thermal efficiency (including evaporation of water to steam) is given as:

$$\eta_{th} = \frac{\dot{m}_f c_{pw}(T_{f2} - T_{f1}) + \dot{m}_{wl} L_w}{A_a I_b} \tag{11}$$

The incident solar radiation consists of beam and diffuse radiation. However, the majority of concentrating collectors can utilise only beam radiation.

IV. DESIGN CALCULATIONS

IV.1 Gravimetric and Volumetric Rice--Water Ratios

The heat demand load of the cooker is such that it will cook about 12 kg of rice in a day. In order to reduce space requirement, the cooker is designed in such a way that it will cook only about 3 kg of rice at a time. Thus at an average uniform rate of solar radiation intensity, the cooker will make 4 cycles of almost equal length in time to cook the quantity of food required. The volume of rice, v_{r1}, to be cooked is given as:

$$v_{r1} = \frac{m_{r1}}{\rho_{r1}} \tag{12}$$

The density of rice, ρ_{r1}, varies between 777 – 847 kg/m^3, due to the different varieties of rice [8]. Average value of 812 kg/m^3 is adopted for the design. Applying Eq. (12) and noting that $\boldsymbol{m_{r1}}$ = 3 kg:

$$v_{r1} = 0.0037 \text{ m}^3$$

For the cooking process, the optimum rice-to-water ratio by volume is 1:2 [9], [10]. The volume of water, $\boldsymbol{v_{w1}}$, required to cook $\boldsymbol{v_{r1}}$ volume of rice is:

$$v_{w1} = 2v_{r1} = 2\left(\frac{m_{r1}}{\rho_{r1}}\right) \tag{13}$$

$$v_{w1} = 0.0074 \text{ m}^3$$

Total volume of food to be cooked, $\mathbf{v}_{f1}$, is:

$$v_{f1} = v_{r1} + v_{w1} = 3v_{r1} \tag{14}$$

$$v_{f1} = 0.0111 \text{m}^3$$

The mass of water, $\boldsymbol{m_{w1}}$, required for the cooking is:

$$m_{w1} = \rho_{w1} \times v_{w1} = \rho_{w1} \times \frac{2m_{r1}}{\rho_{r1}} \tag{15}$$

Where $\boldsymbol{\rho}_{w1}$ **is** the density of water evaluated at 25 °C and has the value of 997.01 kg/m^3 [11].

$$m_{w1} \approx 7.4 \text{ kg}$$

Total mass of food to be cooked, $\boldsymbol{m_{f1}}$, is:

$$m_{f1} = m_{r1} + m_{w1} \tag{16}$$

$$m_{f1} = 10.4 \text{ kg}$$

After the cooking process, the volume of cooked rice (including water) expands to about 3.2 – 3.5 times the volume of dry (uncooked) rice [12], [13]. An average factor of 3.35 is taken for this design. Hence:

$$v_{f2} = 3.35 v_{r1} \tag{17}$$

$$v_{f2} = 0.0124 \text{m}^3$$

The ratio, by volume, of cooked food to uncooked food is:

$$\frac{v_{f2}}{v_{f1}} = \frac{3.35 v_{r1}}{3 v_{r1}}$$

$$v_{f2} = 1.1167\, v_{f1} \tag{18}$$

Therefore, after the cooking process the volume of the food increases by about 11.7%.

Cooking of rice using conventional methods requires five volume of water to one volume of rice, while cooking using solar cooker requires two volume of water to one volume of rice [9]. In conventional methods, about 25% of the water required for cooking is lost to the surrounding by evaporation. If the amount of water lost is taken as directly proportional to the amount of water required, then the amount of water lost during cooking using solar cookers is 10%. Hence, the mass of water, $\boldsymbol{m_{w2}}$, remaining in the cooked food is:

$$m_{w2} = 0.9 m_{w1} \tag{19}$$

$$m_{w2} \approx 6.7 \text{ kg}$$

Mass of water lost, $m_{wl} = m_{w1} - m_{w2} = 0.7 \text{ kg}$ (20)

Mass of cooked food,

$$m_{f2} = m_{r2} + m_{w2} = m_{r1} + m_{w2} \tag{21}$$

$$m_{f2} = 9.7 \text{ kg}$$

The ratio, by mass, of cooked food to uncooked food is:

$$\frac{m_{f2}}{m_{f1}} = \frac{9.7}{10.4}$$

$$m_{f2} = 0.9327\, m_{f1} \tag{22}$$

After the cooking process, the mass of the initial uncooked food decreases by about 6.7%.

For four cycles of cooking in a day the total mass of cooked food is (4×9.7) kg = 38.8 kg.

IV.2 Sizing of the Parabolic Dish Solar Thermal Cooker

The absorber of the cooker will be a cylinder of external diameter D_{abs}, external height L_{abs}, internal diameter d_{abs}, internal height l_{abs}, and thickness t_x = 0.8 mm. The internal volume of the cylinder is the same as the volume of food, $\boldsymbol{v_{f2}}$, after cooking. Therefore:

$$\frac{\pi d_{abs}^2}{4} \times l_{abs} = v_{f2} \tag{23}$$

For simple solution of the equation and optimum design of the absorber, the height $\boldsymbol{l_{abs}}$ is made to be the same as the diameter $\boldsymbol{d_{abs}}$. Therefore:

$$\frac{\pi d_{abs}^3}{4} = 0.0124 \text{ m}^3$$

$$d_{abs} = \sqrt[3]{\frac{4 \times 0.0124}{\pi}}$$

$$d_{abs} = 0.2509 \text{ m} \approx 25.1 \text{ cm}$$

$$l_{abs} = d_{abs} = 25.1 \text{ cm}$$

$$D_{abs} = d_{abs} + 2t_x = 0.251 + 2(0.0008) \tag{24}$$

$$D_{abs} = 0.253 \text{ m} = 25.3 \text{ cm}$$

$$L_{abs} = l_{abs} + t_x = 0.251 + 0.0008 \tag{25}$$

$$L_{abs} \approx 0.252 \text{ m} = 25.2 \text{ cm}$$

The effective surface area of the absorber is given as:

$$A_{abs} = \frac{\pi D_{abs}^2}{4} + \pi D_{abs} L_{abs} \tag{26}$$

$$A_{abs} \approx 0.2506 \text{ m}^2$$

The shell of the parabolic dish is adopted from a commercially-available, satellite dish of aperture diameter D_a = 1.8 m, and height *h* = 29.0 cm.
The geometric concentration ratio is given as per Eq. (8) as:

$$C_{area} = \frac{A_a}{A_{abs}} = \frac{\pi \times D_a^2}{4 \times A_{abs}}$$

$$C_{area} = 10.2$$

The focal length, ***f***, of the dish is obtained from Eq. (4) as:

$$f = \frac{D_a^2}{16h}$$

$$f = 0.6983\,\mathrm{m} \approx 69.8\,\mathrm{cm}$$

V. EXPECTED THERMAL PERFORMANCE OF THE PDSTC

The estimated rate of useful energy absorbed by the food for one cycle of the designed PDSTC is given by:

$$\dot{q}_u = \eta_{th} I_b A_a \tag{27}$$

The efficiency range of most solar concentrators is 40%-60% [14]. The standard solar radiation intensity is 700 W/m^2 [15], [16]. Hence:

$$\eta_{th} = 0.5\,(\text{average of } 0.4 \text{ and } 0.6)$$

$$\mathrm{I_b} = 700\ \mathrm{W/m^2}$$

$$A_a = \frac{\pi D_a^2}{4} = 2.545\ \mathrm{m^2}$$

$$\dot{q}_u = 0.5 \times 700 \times 2.545$$

$$\dot{q}_u = 890.8\ \mathrm{W}$$

The rate of energy absorbed by the absorber, P_{abs}, is obtained from Eq. (10):

$$\eta_o = \frac{P_{abs}}{A_a I_b}$$

$$P_{abs} \frac{\eta_o}{\eta_{th}} \left(\eta_{th} A_a I_b\right)$$

η_O = 0.6 (lower of the factors of 0.6 and 0.7) and the bracketed term is the same as $\dot{q}_u$

$$P_{abs} = \frac{0.6}{0.5}\dot{q}_u = 1.2\dot{q}_u$$

$$P_{abs} = 1.2 \times 890.8 = 1069.0\ \mathrm{W}$$

In this design, the latent heat of vapourisation of water is considered as part of the useful energy. The useful energy, $\boldsymbol{q_u}$, for one cycle of cooking is calculated as:

$$q_u = q_{u1} + q_{u2} \tag{28}$$

where $\boldsymbol{q_{u1}}$ is the heat energy required to raise the sensible temperature of the food to 100 °C, and $\boldsymbol{q_{u2}}$ is the heat energy required to convert 0.7 kg of water at 100 °C to steam.

$$q_{u1} = \left(m_{w1} + m_{r1}\right)c_{pw}\left(T_{f2} - T_{f1}\right) = \eta_{th} I_b A_a t_1 \tag{29}$$

where $\boldsymbol{t_1}$ is the time required to raise the temperature of the food from T_{f1} (= 25 °C) to T_{f2} (= 100 °C).

$$t_1 = \frac{m_{f1} \times c_{pw}\left(T_{f2} - T_{f1}\right)}{\eta_{th} I_b A_a} = \frac{10.4 \times 4186(100 - 25)}{0.5 \times 700 \times 2.545}$$

$$t_1 = 3655.5\,s \approx 61.1\,\text{minutes}$$

$$q_{u2} = m_{wl} L_w = \eta_{th} I_b A_a t_2 \tag{30}$$

where L_w is the latent heat of vapourisation of water at 100 °C and $\boldsymbol{t_2}$ is the time required to convert 0.7 kg of water to steam.

$$t_2 = \frac{m_{wl} \times L_w}{\eta_{th} I_b A_a} = \frac{0.7 \times 2.26 \times 10^6}{0.5 \times 700 \times 2.545}$$

$$t_2 = 1776.0\,s \approx 29.6\,\text{minutes}$$

The cooking time, $\boldsymbol{t_c}$, is given as:

$$t_c = t_1 + t_2 \tag{31}$$

$$t_c \approx 91\,\text{minutes}$$

For four cycles of cooking in a day, the total cooking time, $\boldsymbol{t_{tc}}$, is:

$$t_{tc} = 4 \times 91 = 364\,\text{minutes}$$

$$t_{tc} \approx 6\,\text{hours}\,4\,\text{minutes}$$

VI. SELECTION OF MATERIALS FOR THE CONSTRUCTION OF THE PDSTC

VI. 1 Material for the Body of the Dish

Steel was selected over aluminium because of its strength, durability, and energy effectiveness in use of material. Energy consumed to produce steel is estimated to be16500 kJ/kg compared to that of aluminium of 141,000 kJ/kg [6] commercially-available dish was adopted so as to reduce errors in the process of manufacture: its smooth contour shape minimizes the sloping error of the reflective, glass material.

VI.2 Material for the Reflecting Surface

A light glass mirror of high surface quality and good specular reflectance was selected. A glass mirror of 2 mm thickness was selected over 3mm- and 4mm-thick glasses to reduce the overall weight of the PDSTC. Glass mirror was selected over polished aluminium surface because its reflectivity of 95% is better than that of aluminium (85%).

VI.3 Material for the Absorber

Aluminium was selected over copper and steel because of its lower cost, light weight, and ease of fabrication. Its light weight reduces the overall weight of the solar cooker and also reduces the amount of work to be done by the superjack in turning the dish on its axis.

VI.4 Material for the Absorber Surface Coating

Black paint was selected for the absorber coating. It was 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.

VI.5 Food Material and Heat Transfer Fluid

Rice was selected as a representative food to be cooked because it is a staple food for about two-third population of the world [17]. It is also a non-perishable food item and can be cooked simply without adding any additive. Water was selected as the heat transfer fluid 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.

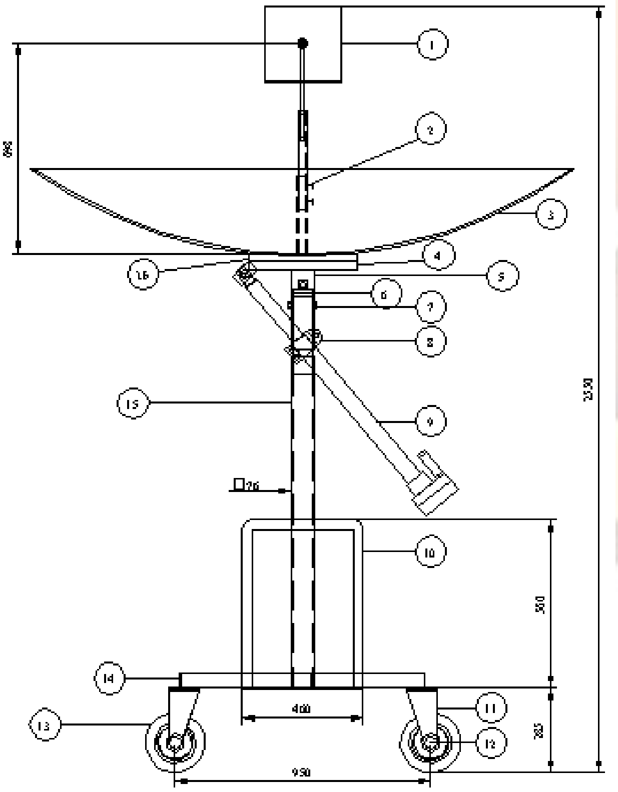

Figure 2: Assembled drawing of the PDSTC
Original scale used 1:15

S/No.	Item	Material	No. of
1	Absorber	Aluminium	1
2	Screw Lock	Mild Steel	2
3	Paraboli Dish	Mild Steel	1
4	Flat Bar of ATM	Mild Steel	1
5	Aperture Tilting Mechanism ATM	Mild Steel	1
6	Vertical Part of ATM	Mild Steel	1
7	Bolt Lock	Mild Steel	3
8	Clamp	Brass	1
9	Superjack	-------	1
10	Handle	Mild Steel	1
11	Wheel Bracket	Steel	4
12	Wheel Axle	Steel	4
13	Wheel	Rubber	4
14	Base Support	Mild Steel	1
15	Trunk	Mild Steel	1
16	Ring Connector	Mild Steel	1

VI.6 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 PDSTC

Figure 3: Photograph of the PDSTC

Table 1: Results of cooking 3.0 kg of parboiled rice

Date (Time Period)	Food Items	Length of Time (Minutes)	Mass of water lost during cooking (kg)	% mass of water lost during cooking	Atmospheric condition during cooking
16/04/2013 11.55am - 13.35pm	3.0 kg of rice + 7.4 kg of water	100	0.6	8.1	Clear sky condition
16/04/2013 14.15pm - 16.25pm	3.0 kg of rice + 7.4 kg of water	130	0.3	4.1	Fairly cloudy sky condition. Average solar radiation fell below the design value of 700 W/m^2
29/04/2013 11.20am - 12.50pm	3.0 kg of rice + 7.4 kg of water	90	0.4	5.4	Clear sky condition
29/04/2013 13.20pm - 14.55pm	3.0 kg of rice + 7.4 kg of water	95	0.4	5.4	Clear sky condition
30/04/2013 12.15pm - 13.55pm	3.0 kg of rice + 7.4 kg of water	100	0.4	5.4	Fairly clear sky with intermittent interruption of solar radiation by thin layers of cloud

VI.7 Material for the Base of the PDSTC

A combination of angle and channel-section steel bars were selected for the base which support the whole solar cooker structure. Channel-section and angle bars were chosen to provide solid and rigid support for the rectangular, vertical-axis steel bar which supports the parabolic dish.

VI.8 Tracking Mechanism

A linear actuator (superjack) was selected over the manual-adjust tracking mechanism. The superjack consists of a hydraulic arm, and a 12V – 36V electric motor fitted at one end of the jack. The hydraulic arm consists of two cylinders, one fitted into the other in a telescopic manner. When fully extended the total length of the two cylinders is approximately 96 cm. The extension and contraction of the inner cylinder within the outer cylinder gives a slow, steady motion to the parabolic dish as it turns on its axis from east to west, for the daily tracking of the sun. The superjack works in conjunction with an aperture-tilting mechanism, which is used to change the orientation of the dish for seasonal tracking of the sun. The outer cylinder is anchored to the vertical part of the aperture-tilting mechanism using a fastening device, which holds the superjack at an angle of about 45^o relative to the vertical support. The superjack is connected to the aperture-tilting mechanism at a second point using nut and bolt, which passes through a hole on a piece of metal at the top of the inner cylinder. The lower part of the aperture-tilting mechanism is connected to the cylindrical part of the vertical support while its upper part is connected to the body of the dish via a flat bar.

VII. COOKING TEST RESULTS

After the solar thermal cooker was constructed as shown in Fig. 2, some cooking tests were carried out. The results of the tests are summarized in Table 1. The overall performance of the cooker is satisfactory. The actual coo-king times taken for four tests, out of five, strongly agree with the predicted time.

VIII. CONCLUSION

The design and development of a parabolic dish solar thermal cooker for domestic cooking applications has been presented, together with the predicted and actual performance of the system. Although no detailed thermal performance analysis is presented, the cooking test results show that the cooker is always capable of cooking food equivalent of 3 kg of dry rice at a time, within the expected length of time and solar radiation levels. The total cooked food capacity of the cooker per cycle of cooking operation is about 9.7 kg, and the total per day is about 38.8 kg. The main research points of this paper are food-water volume and mass ratios, cooker component design and development, material and labour economy, and energy cost savings. With the exception of the superjack, all the other components were made from locally available materials. This promotes local content utilisation of manufactured goods and services.

IX. NOMENCLATURE

A_a	aperture area
A_{abs}	absorber area (m^2)
a	distance from the Z – axis (m)
C_{area}	geometric concentration ratio
C_{flux}	flux concentration ratio
c_{pw}	specific heat capacity at constant pressure of water (kJ/kgK)
D_a	aperture diameter (m)
D_{abs}	external diameter of absorber (m)
d_{abs}	internal diameter of absorber (m)
F	focal point
f	focal length of dish (m)
h	height of parabolic dish (m)
I_b	beam radiation (w/m^2)
L_{abs}	external height of absorber (m)
L_w	latent heat of evaporation of water (J/kg)
$\boldsymbol{l_{abs}}$	internal height of absorber (m)
m_{f1}	mass of food before cooking (kg)
$\boldsymbol{m_{f2}}$	mass of food after cooking (kg)
$\boldsymbol{m_{r1}}$	mass of dry rice before cooking (kg)
$\boldsymbol{m_{r2}}$	mass of rice after cooking (kg)
$\boldsymbol{m_{wl}}$	mass of water lost, due to evaporation (kg)
$\boldsymbol{m_{w1}}$	initial mass of water added to uncooked rice (kg)
$\boldsymbol{m_{w2}}$	final mass of water remaining in cooked food (kg)
P_{abs}	rate of energy absorbed by the absorber (W)
$\boldsymbol{q_u}$	useful energy for one cycle of cooking (J)
$\dot{q}_u$	rate of useful energy absorbed by food for one cycle of cooking (W)
$\boldsymbol{q_{u1}}$	heat energy required to raise the sensible temperature of food to 100 ^{o}C (J)
$\boldsymbol{q_{u2}}$	heat energy required to convert water at 100 ^{o}C to steam (J)
R	arbitrary point on a paraboloid
$\boldsymbol{r}$	distance from polar origin (m)
T_{f1}	initial temperature of uncooked food (^{o}C)
T_{f2}	final temperature of cooked food (^{o}C)
$\boldsymbol{t_c}$	cooking time (s)
$\boldsymbol{t_{tc}}$	total cooking time (s)
$\boldsymbol{t_1}$	time taken for sensible temperature of food to reach 100 ^{o}C (s)
$\boldsymbol{t_2}$	time taken to evaporate water at 100 ^{o}C to steam (s)
$\boldsymbol{t_x}$	thickness of absorber material (m)
V	vertex of a parabola
$\boldsymbol{v_{f1}}$	volume of food before cooking (m^3)
$\boldsymbol{v_{f2}}$	volume of food after cooking (m^3)
$\boldsymbol{v_{w1}}$	volume of water added to uncooked rice (m^3)
$\boldsymbol{v_{w2}}$	volume of water remaining in cooked food (m^3)
$\boldsymbol{v_{r1}}$	volume of dry rice before cooking (m^3)
$\boldsymbol{v_{r2}}$	volume of rice after cooking (m^3)
η_o	optical efficiency of the solar cooker
η_{th}	thermal efficiency of the solar cooker
$\boldsymbol{\o}$	polar coordinate angle (degrees)
ψ_{rim}	rim angle (degrees)
θ	angle about vertex (degrees)

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