International Journal of Scientific Research and Engineering Development-– Volume 5 Issue 5, Sep- Oct 2022

Available at www.ijsred.com

RESEARCH ARTICLE OPEN ACCESS

Design and Construction of a Solar Thermal Absorber Pot Suitable for Use in Parabolic Solar Cookers

[1] Nathaniel Muwa Shawhatsu, [2] Joseph Aidan

[1]Department of Science Laboratory Technology, Federal Polytechnic Bali, P.M.B. 05 Bali, Taraba State, Nigeria

[2]Department of Physics, ModibboAdama University, P.M.B. 2076 Yola, Adamawa State, Nigeria

[1] Email: nathanmshawhatsu@gmail.com

Abstract

The mathematical approach to the design and construction of a solar thermal absorber pot and a parabolic dish solar cooker were discussed in this paper. One (1 kg) of rice was used as a measured value for calculating the volume of rice that was used to calculate the volume of pot which aided in determining the dimensions of the pot. Aluminium of thickness 0.55 mm was used for the construction because of its known thermal conductivity and specific heat capacity. Based on these, the effective area of the pot andaperture area of parabolic dish were obtained as 0.1199 m^2 and 0.9505 m^2 respectively.The geometric concentration ratio for the dish solar cooker is calculated as 7.929. The time needed to cook 1 kg of rice with this pot under this cookers at solar radiation intensity of 700 W/m^2 is 1.30 hour.

Key words: Dimension, aperture area, effective area, geometric concentration ratio, thermal conductivity and radiation.

1. Introduction

The thermal modelling of solar cookers are characterized by heat and mass transfer, effects of wind, relative humidity, relative movement of the sun, nature of food, types and size of pot fit for the cooking, characteristic of different designs and heat transfer to the surroundings. Cloudy conditions, marginal insolation, tilting position of cooker or mirror's array to capture incoming radiation and wind combined to make concentrating cookers highly difficult to use (Kundapur, 1998;Mmuthusiyagani, 2910; Yahuza*et al*2016; Tiwari, 2014 and Pidwimy, 2006). But when the pot size and its position fitted to the geometric design of the solar cookers, then challenge of effectiveness and difficulties of using solar cookers becomes minimal except for the weather conditions which are natural phenomena that is beyond human control.

The dimension of cookers and its components such as absorber pots, apertureand depth of the cookers, position of the principal focus above thethroughof the dish,etc; matter a lot in determining the effective use and delivery of heat to the intended goal of thedesigned solar cooker(Agyenum, 2009 and Joshua, 2013).

2. Methodology

The desired materials needed to achieve the designs and construction of the pot and the solar cooker are: sheet of Aluminium of thickness 0.55 mm (to be used for the construction of both the bodies of the parabolic dish), mirrors and metallic stand for the dish. All these materials are to be used based on the recommended dimensions given in the design procedures of each of them.

2.1 Design of the absorber pot

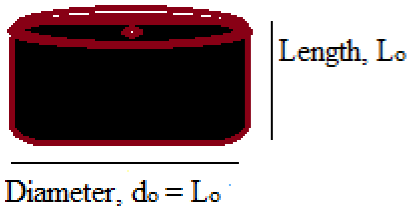

Figure 1: Schematic diagram of the pot

For a cylindrical pot shape with the following dimensions: d_o as the external diameter, L_o effective length/height (assumed to be equal to d_o), d_i internal diameter, L_i internal length (assumed to be equal to d_i) and w the thickness of the pot, then the volume $V_{pot}$of the pot which is also assumed to be equal to the volume of the food to be cooked is given as:

$$V_{pot} = \frac{\pi d_i^2 L_i}{4} \quad (1)$$

2.2Thermal performance of solar cooker.

The heat demand loads of the cooker is such that it can cook a given mass of rice M_{rice} at once at a given time.For these designs (potand parabolic dish), 1 kg of rice is used, same method can be applied to anyfood once their densities and optimum expansionsin terms of food–to–water ratio by volume are given. The only variation to be experiencedmay be the cooking time duration, one may take longer time than the other based on their nature. If the density of rice to be cooked is ρ_{rice} , the volume of rice, V_{rice} is given as:

$$V_{rice} = \frac{M_{rice}}{\rho_{rice}} \quad (2)$$

According to Bhattachary(1972), cited in Okoro (2015), density of rice varies between 777 - 847 kgm^{-3} due to the different varieties of rice. Usingan average value of 812 kgm^{-3} and noting that M_{rice} is 1 kg, then

$$V_{rice} = \frac{M_{rice}}{\rho_{rice}} = \frac{1}{812} = 1.2315 \times 10^{-3} m^3 \quad (3)$$

According to Green (2013) and Nguyenn (2009), volume of cooked rice including water expand by 3.2 – 3.5 times the volume of uncooked dry rice.

By taken 3.35 as an average expansion ratio, the volume of potrequired to accommodate the cooked rice will be:

$$V_{cff} = 3.35 V_{rice} = 4.1256 \times 10^{-3} m^3 \quad (4)$$

Thus volume of pot is$V_{pot} = V_{eff}$and the internal diameter of the pot can be determined from equation (5):

$$V_{pot} = \frac{\pi d_i^2 L_i}{4} = 4.1256 \times 10^{-3} m^3 \quad (5)$$

This implies that the internal diameter of the pot $d_i = 0.17382$ m, the external diameter d_o and the pot's height L_o can be determined as:

$d_o = d + 2w = 0.17382 + 2 \times 0.00055 = 0.1749$ mand

$L_o = L_i + w = 0.17382 + 0.00055 = 0.1744$ m (6)

where$w$ is the thickness (0.55 mm) of the pot.

Therefore, effective area A_{eff}:

$$A_{eff} = \frac{\pi d_o{}^2}{4} + \pi d_o L_o = \frac{3.142(0.17492)^2}{4} + 3.142 \times 0.17492 \times 0.17437 = 0.1199 \text{ m}^2 \quad (7)$$

Area of the rim $A_{P-rim}$of the pot and its lid coverA_{lcov} are obtained as:

$$A_{p-rim} = \pi r_o{}^2 - \pi r_i{}^2 = 3.0133 \times 10^{-4} \text{m}^2 \quad (8)$$

$$A_{l\,cov} = \pi r_o{}^2 = 0.02403 m^2 \quad (9)$$

According to Dilip*et al* (2014), the optimum rice–to–water ratio by volume is given as 2:3.2. Thus the volume of water V_w required to cook the given volume of rice V_{rice} is:

$$V_w = \frac{3.2}{2} V_{rice} = 1.6 \times 1.23153 \times 10^{-3} = 1.9705 \times 10^{-3} \text{m}^3 \quad (10)$$

Total volume of uncooked foodV_{uf} is given as:

$$V_{uf} = V_w + V_{rice} = 2.6 V_{rice} = 2.6 \times 1.23153 \times 10^{-3} = 3.2020 \times 10^{-3} \text{m}^3 \quad (11)$$

Mass of water required M_w(From appendix A,$\rho_w = 995.8$ kg/m^3 at 27^{o}C) is:

$$M_w = \rho_w V_w = \rho_w \frac{3.2}{2} V_{rice} = 995.8 \times 1.6 \times 1.23153 \times 10^{-3} = 1.9622 \text{ kg} \quad (12)$$

Therefore the total mass of uncooked food is given by:

$$M_{uf} = M_w + M_{rice} = 1.96217 + 1 = 2.9622 \text{ kg} \quad (13)$$

Ratio of cooked food to uncooked food is

$$\frac{V_{eff}}{V_{uf}} = \frac{3.35\, V_{rice}}{2.6\, V_{rice}} = 1.2885$$

$$V_{eff} = 1.2885\, V_{uf} \quad (14)$$

This means that after cooking, the volume of food increased by 29 %.

In conventional methods of cooking, about 25 % of water required for cooking is lost to the surrounding through evaporation (Mahavar, 2013).

If the amount of water lost is taken as a direct proportion to the amount of water required, then the amount of water lost during cooking with solar cooker is 25 %. Thus, mass of water remaining $M_{w,rem}$ and mass of water lostM_{lost} during cooking with solar are equal to:

$$M_{w,rem} = (1 - 0.25) M_w = 0.75 \times 1.96217 = 1.4716 \text{ kg} \quad (15)$$

Mass of water lost:

$$M_{lost} = 1.96217 - 1.4716 = 0.4906 \text{ kg} \quad (16)$$

Therefore,total mass of cooked food, $M_{TCF}$is:

$$M_{TCF} = M_{rice} + M_{w,rem} = 1 + 1.4716 = 2.4716 \text{ kg} \quad (17)$$

Ratio of cooked food to uncooked food is:

$$\frac{M_{TCF}}{M_{uf}} = \frac{2.4716}{2.96217} = 0.8344 \quad (18)$$

Mass of initial uncooked food decreased by: $(1 - 0.83439) \times 100\% = 16.56\%$

Estimated rate of energy to be absorbed by the food under the solar cooker is:

$$Q_{ab} = \eta_{th} I_b A_{ap} \quad (19)$$

whereA_{ap} is the aperture area and I_b the average solar intensity at the location. Assuming thermal efficiency of solar cookers to be 50 – 70 %, therefore average thermal efficiency will be 60 %, I_b is 700 W/m^2 (ASAE, 2013 & Funk, 2000). In this work a parabolic dish of depth h = 25 cm and aperture diameter D = 1.1 m (110 cm) is used.

Hence, aperture area $A_{ap}$is given as:

$$A_{ap} = \frac{\pi D^2}{4} = 0.9505 \text{ m}^2$$

$$Q_{ab} = 0.6 \times 700 \times 0.9505 = 399.1911 \text{ W} \quad (20)$$

Rate of energy absorbed by pot is given as:

$$Power = \eta_o I_b A_{ap} = \frac{\eta_o}{\eta_{th}}(\eta_{th} A_{ap} I_b) = \frac{\eta_o}{\eta_{th}} . Q_{ab} \quad (21)$$

Taking optical efficiency to be 0.6 as the lower fraction of 0.6 and 0.7, thus

$$power = \frac{0.7}{0.6} \times 399.1911 = 465.7230 \text{ W} \quad (22)$$

In this design, the latent heat of vaporization of water is considered as part of the useful energy. The useful energy, Q_u required for the cooking is given as:

$$Q_u = Q_1 + Q_2 \quad (23)$$

where Q_1 is the heat required to rise the sensible temperature of food to 100 ^oC, and Q_2 is the heat energy required to convert (0.4905 kg) the loss mass of water at 100 ^oC to steam and given as:

$$Q_1 = (M_w + M_{rice}).C_w(T_{w2} - T_{w1}) = \eta_{th} I_b A_{ap}.t_1 \quad (24)$$

where t_1 is the time required to raise the temperature of the food from T_{w1} (assumed 27^oC) to T_{w2} (100 ^oC). Thus

$$t_1 = \frac{M_{TCF} C_w (T_{w2} - T_{w1})}{\eta_{th} I_b A_{ap}} = \frac{2.4716 \times 4186 \times (100-27)}{0.6 \times 700 \times 0.9505} = 1{,}891.9030 \text{ s} = 0.5255 \text{ hr} \quad (25)$$

$$Q_2 = M_w.L_w = \eta_{th}.I_B.A_{ap}.t_2 \quad (26)$$

where L_w is the latent heat of vaporization of water at 100 °C and t_2 is the time required to convert 0.4905 kg mass of water to steam (Agyenum, 2009). Thus

$$t_2 = \frac{M_{wL}L_w}{\eta_{th}I_bA_{ap}} = \frac{0.4905\times2.26\times10^6}{0.6\times700\times0.9505} = 2{,}776.8092 \text{ s} = 0.7713 \text{ hr} \quad (27)$$

Total time t required for cooking is therefore given as:

$$t = t_1 + t_2 = 0.5255 + 0.7713 = 1.2968 \text{ hr} \quad (28)$$

2.3 Design of Parabolic Dish

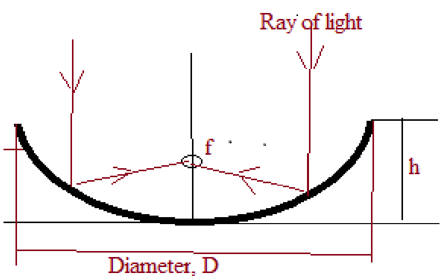

Figure 2: Sketch of parabolic dish

The dimension of symmetrical parabolic solar cooker can be estimated (Aidan 2014 and Okoro 2015) as:

$$h = \frac{R^2{}_{rim}}{4f} \quad (29)$$

where h is the depth of the parabolic dish, R_{rim} is the rim radius ($R_{rim} = \frac{D}{2}$), D is the aperture diameter of the parabolic cooker and f is the focal length.

$$f = \frac{R^2{}_{rim}}{4h} = \frac{(55)^2}{4\times25} = 30.25 \text{ cm} \quad (30)$$

The rim angle θ_{rim} can be estimated as:

$$\theta_{rim} = tan^{-1}\left(\frac{1}{\frac{D}{8h}-\frac{2h}{D}}\right) = tan^{-1}\left(\frac{1}{\frac{110}{8\times25}-\frac{2\times25}{110}}\right) = tan^{-1}(10.476190) = 84.55^o \quad (31)$$

The geometric concentration ratio of the dish with respect to the effective area of the pot is given as:

$$C_{dish-g} = \frac{A_{ap}}{A_{eff}} = \frac{\pi D^2}{4A_{eff}} = \frac{3.142(1.1)^2}{4\times0.11987} = 7.93 \quad (32)$$

The surface area of the parabolic dish can be determined (Quedermi et al 2009) from:

$$A_s = \frac{4\pi f^2 \sin^2\theta_{rim}}{1+\cos\theta_{rim}} \cong \frac{8\pi}{3}f^2\left[\left(\left(1+\left(\frac{D}{4f}\right)^2\right)^{3/2}-1\right)\right]$$

$$= \frac{8\times3.142(30.25)^2}{3}\left[\left(\left(1+\left(\frac{110}{4\times30.25}\right)^2\right)^{3/2}-1\right)\right] = 11{,}258.00233\ \text{cm}^2 = 1.1258\ \text{m}^2 \quad (33)$$

3. Conclusion

From the above analysis, the geometric concentration ratio for the parabolicsolar cookersto the effective area of the pot ($A_{eff} = 0.1199m^2$)is calculated to be 7.929. The time needed to cook 1 kg of rice with this pot when used in this cookers based on its thermal performance at solar radiation of 700 W/m^2 is 1.30 hour. This shows that the cooker and the pot of such dimensions can achieve cooking within the short possible period of time when all controlled and uncontrolled variables are not interrupted during their usage in cooking.

Reference

Agyenum, F. (2009). A Review of Materials, Heat Transfer and Phase Change Problem Formulation for Latent Heat Thermal Energy Storage Systems. *Renewable and Sustainable energy reviews*,14(2),615-628. Cited in Okoro, C. (2015). Design and Performance Evaluation of a Parabolic Solar Cooker. Federal University of Technology, Owerri - Nigeria

Aidan, J. (2014). Performance evaluation of a parabolic solar dish cooker in Yola, Nigeria. IOSR Journal of applied physics (IOSR-JAP). Vol. 6(5). Pp46-50

ASAE (2013). ASAE S-580.1: Testing and Reporting Solar Cooker Performance

Bhattacharya, K.R. (1972). Some physical properties of paddy and rice and their interrelations. Jounal of the science of food and Agriculture, Vol. 23. Issue 2, John Wiley and sons Ltd. Cited in Okoro, C. (2015). Design and Performance Evaluation of a Parabolic Solar Cooker. Federal University of Technology, Owerri - Nigeria

Dilip, K. D., Muwa, N. S. and Olukunle, O. (2014). Cooking with Minimum Energy and Protection of Environment and Health. *JERI Procedia 9*(2014) 148-155

Funk, P. A. (2000). Evaluating the International Standard Procedure for Testing Solar Cookers and Reporting Performance of *Solar Energy Vol. 68 No. 1* pp. 1-7

Green, O.A.(2013). The green optimistic. Htt://www.greenoptimistic.com/2013/08/07

Kundapur, A. (1998). Review of solar cooker designs. http;//solarcooking.wikia.com/wiki/compendium of solar cooker desgns.

Muthusivagami, R.M. (2010). Solar cooker with and without thermal storage-a review.Renewable and sustainable energy reviews,Pp. 691-701.

Mohammed, I.I. (2013). Design and development of a parabolic dish Solar Water Heater. *Int. J. of Engineering Research and Application,* Vol. 2 issue 1 Pp.822-830

Mahavar, S. (2013). Modelling and on-field testing of solar rice cooker. Energy, Vol. 49. Pp404- 412

Nguyen, A. (2009). How to cook perfect rice.viet rice kitchen. www.vietworldkitchen.com/blog/2009/03/how-to-cook-perfect-rice.html

Okoro, C. (2015). Design and Performance Evaluation of a Parabolic Solar Cooker. Federal University of Technology, Owerri– Nigeria

Pidwimy, M. (2006). Earth-Sun Geometry. Fundamental of Physica Geography. In Yahuza, I., Rufai, YA. And Tanimu, L. (2016). Design, Construction and Testing of Parabolic Solar Oven. *J. of Applied Mechanical Engineering,* Vol.5, No. 4. DOI: 10.4172/2168-9873.1000212

Quedermi, E.L, Ben, A.R, Saleh, Askri, M, Ben, F, Narallah, M and Aloui, F. (2009). Experimental study of parabolic solar concentrator. Revue des Engineering Reneuvelables12:395-404. Cited in Yahuza et al (2016).Design, construction and testing of parabolic solar oven. *J. of applied mechanical engineering*

Tiwari, G.N. (2014). Solar Energy. Fundamentals, design, modelling and application. Delhi, India. Narosat publishing house pvt. Ltd.

Appendix A

Table 1: Properties of water (saturated liquid)

°F	°C	c_p kJ/kg°C	P Kg/m³	μ kg/m sec	K W/m°C	Pr	V = μ/ρ m²/s
32	0	4.225	999.8	$1.79x10^{-3}$	0.566	13.25	$1.79x10^{-6}$
40	4.44	4.208	999.8	$1.55x10^{-3}$	0.575	11.35	$1.55x10^{-6}$
50	10	4.195	999.2	$1.31x10^{-3}$	0.585	9.40	$1.31x10^{-6}$
60	15.56	4.186	998.6	$1.12x10^{-3}$	0.595	7.88	$1.12x10^{-6}$
70	21.11	4.179	997.4	$9.8 x 10^{-4}$	0.604	6.78	$9.82x10^{-7}$
80	26.67	4.179	995.8	$8.6 x 10^{-4}$	0.614	5.85	$8.63x10^{-7}$
90	32.22	4.174	994.9	$7.65x10^{-4}$	0.623	5.12	$7.69x10^{-7}$
100	37.78	4.174	993.0	$6.82x10^{-4}$	0.630	4.53	$6.87x10^{-7}$
110	43.33	4.174	990.6	$6.16x10^{-4}$	0.637	4.04	$6.22x10^{-7}$
120	48.89	4.174	988.8	$5.62x10^{-4}$	0.644	3.64	$5.68x10^{-7}$
130	54.44	4.179	985.7	$5.13x10^{-4}$	0.649	3.30	$5.20x10^{-7}$
140	60	4.179	983.3	$4.71x10^{-4}$	0.654	3.01	$4.63x10^{-7}$
150	65.55	4.183	980.3	$4.3 x 10^{-4}$	0.659	2.73	$4.39x10^{-7}$
160	71.11	4.186	977.3	$4.01x10^{-4}$	0.665	2.53	$4.10x10^{-7}$
170	76.67	4.191	973.7	$3.72x10^{-4}$	0.668	2.33	$3.82x10^{-7}$
180	82.22	4.195	970.2	$3.47x10^{-4}$	0.673	2.16	$3.58x10^{-7}$
190	87.78	4.199	966.7	$3.27x10^{-4}$	0.675	2.03	$3.38x10^{-7}$
200	93.33	4.204	963.2	$3.06x10^{-4}$	0.678	1.90	$3.18x10^{-7}$
210	104.4	4.216	955.1	$2.67x10^{-4}$	0.684	1.66	$2.79x10^{-7}$

Courtesy: G.N. Tiwari (2014). Centre for Energy Studies, New Delhi 110016, India

