CONSTRUCTION OF A PARABOLIC SOLAR COLLECTOR AND COMPARATIVE STUDY OF THE PERFORMANCE OF ALUMINUM-COATED PELLICLE FILM AND ALUMINUM FOIL AS REFLECTING SURFACES

OHAJIANYA, A. C.
Department of Physics, Federal University of Technology, P.M.B 1526, Owerri, Nigeria
anthony.ohajianya@futo.edu.ng

Abstract - Most of the concentrators used in solar thermal systems are made from mirrors or metals with mirror or other highly reflective surfaces. Because mirror is the best reflecting surface for solar collectors and parabolic mirrors are expensive, people in the developing nations resort to cutting of plain mirrors into small square or rectangular units and placing them to cover the surface and serve as reflecting surface for metal parabolic solar collectors. Due to the stress and risk involved in doing this, it is worthwhile to research on other cheap and easy to get materials as reflecting surface for metal parabolic collectors. In this light, a metal parabolic collector with aperture diameter of 1.0 m, depth of 0.5 m and focus of 12.5 cm was constructed. The collector's surface was pasted with aluminum-coated pellicle film and tested for performance using 500 cm^3 of water as the content of a black pot placed at the focus of the collector. The test was repeated with aluminum foil in place as the reflecting surface. The maximum water temperature realized when the aluminum-coated pellicle film was in place was 59 ^{0}C while that of aluminum foil was 85 ^{0}C. Aluminum foil is therefore a better reflecting surface for parabolic solar collectors than aluminum-coated pellicle film.

Keywords: concentrator, parabolic solar collector, aluminum-coated pellicle film, aluminum foil.

1. INTRODUCTION

Solar energy has been harnessed by humans since antiquity using a range of ever-evolving technologies. The technologies to harness solar energy are broadly classified into passive solar and active solar systems depending on how they capture, convert and distribute solar energy. Active solar technologies use photovoltaic modules and solar thermal collectors to harness the solar energy while passive solar techniques include orienting a building to the Sun, selecting materials with light dispersing properties, and designing a space that naturally circulates air [1]. Solar photovoltaic systems use photovoltaic modules made up of solar cells connected in series and parallel (popularly called solar panels) to convert solar radiation straight to electricity while solar thermal systems first convert the solar radiation to heat before the heat energy is converted to other forms of energy if the needed output energy of the system is not thermal energy.

Solar thermal energy (STE) technologies involve the use of collectors to harness heat energy from solar radiation. Solar thermal collectors are classified as low-, medium-, or high-temperature collectors. Low-temperature collectors are flat plates generally employed in the heating of swimming pools. Medium-temperature collectors are also flat plates but they are employed in the heating of water or air for domestic or commercial use. High-temperature collectors achieve high temperatures by using mirrors, curved reflective surfaces or lenses to concentrate solar radiation and they are generally used in solar thermal power plants for electric power generation [2]. Examples of solar thermal energy devices include solar oven, solar cookers, and boilers with different kinds of concentrators, solar dryers, etc.

A solar concentrator is a device that collects sunlight from a large area and focuses it on a smaller receiver or exit thereby generating concentrated solar power [3]. The kind of solar concentrator and material used to fabricate it varies depending on the usage. Most of the concentrators used in solar thermal systems are made from mirrors or metals with mirror or other highly reflective surfaces. Examples of solar concentrators include Parabolic Concentrator, Hyperboloid Concentrator, Fresnel Lens Concentrator, Compound Parabolic Concentrator (CPC), Dielectric Total Internal Reflecting Concentrator (DTIRC), Flat High Concentration Devices, and Quantum Dot Concentrator (QDC) [4].

The two-dimensional design of a parabolic concentrator is a parabola. It is widely employed as a reflecting solar concentrator for solar cookers. A distinct property that it has is that it can focus all the parallel rays from the sun to a single focus point, *F* as shown in Figure 1. It is not essential to utilize the whole part of the parabola curve in the construction of the concentrator. Most of the parabolic concentrator employs only a truncated portion of the parabola. Currently, there are two available designs of the parabolic concentrator. One is by rotating the two-dimensional design along the x-axis to produce a parabolic dish, and the other way is by having a parabolic trough. Both of the designs act as reflectors and are used mostly in concentrating solar power systems in big solar power plants. The EUCLIDES-THERMAE Plant in Tenerife, Canary Island employs the parabolic trough concentrators in the 480 kW concentrator project

[4]. Parabolic trough solar concentrators can achieve temperatures of around 400 ^{0}C [5].

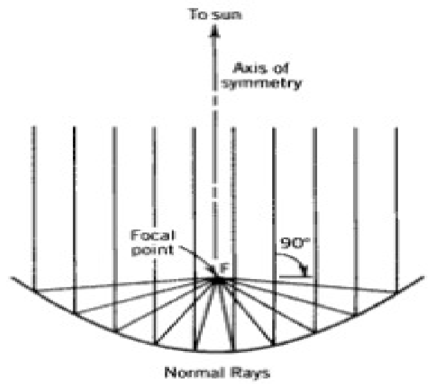

Fig. 1. A parabolic concentrator with normal rays focused at the focal point [4]

A parabola is the locus of a point that moves such that its distances from a fixed line and a fixed point are equal. This is shown in Figure 2, where the fixed line is called the *directrix* and the fixed point *F,* the focus. The length *FR* equals the length *RD.* The line perpendicular to the directrix and passed through the focus, *F* is called the *axis of the parabola.* The parabola intersects its axis at a point *V* called the *vertex,* which is exactly midway between the focus and the directrix.

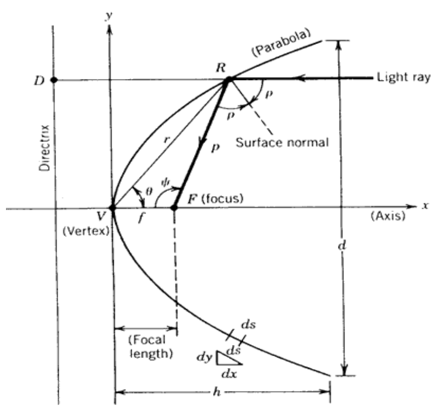

Fig. 2. The parabola [4]

If the origin is taken at the vertex *V* and the *x*-axis along the axis of the parabola, the equation of the parabola is

$$y^2 = 4fx \qquad (1)$$

where *f*, the focal length, is the distance *VF* from the vertex to the focus. When the origin is shifted to the focus *F* as is often done in optical studies, with the vertex to the left of the origin, the equation of a parabola becomes

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

The surface formed by rotating a parabolic curve about its axis is called a paraboloid of revolution. Solar concentrators in this shape and with reflective surfaces are called parabolic dish concentrators. The equation for the paraboloid of revolution as shown in Figure 3, in rectangular coordinates with the *z*-axis as the axis of symmetry, is

$$x^2 + y^2 = 4fz \qquad (3)$$

where the distance, *f* is the focal length *VF.*

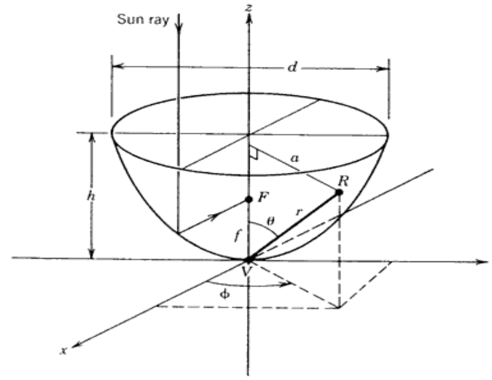

Fig. 3. Paraboloid of revolution [4]

The paraboloid surface area, A, can be calculated from the formula [6]:

$$A = \frac{8\pi f^2}{3}\left[\left(\left(\frac{d}{4f}\right)^2 + 1\right)^{\frac{3}{2}} - 1\right] \qquad (4)$$

One of the standards for the performance evaluation of solar cookers was developed by the American Society of Agricultural Engineers (ASAE). This testing standard specifies that the change in water temperature for each ten-minute interval shall be multiplied by the mass and specific heat capacity of the water contained in the cooking pot and the product shall be divided by the 600 seconds contained in the ten-minute interval to obtain the cooking power for the solar cooker [7]. That is

$$P_i = \frac{(T_2 - T_1)MC_v}{600} \qquad (5)$$

where P_i is the cooking power (W) for interval i, T_1 is the initial water temperature for the interval (^{0}C), T_2 is the final water temperature for the interval (^{0}C), M is the mass of water in the pot, and C_v is the heat capacity of water [4186 J/(kg.^{0}C)]. It also requires that the average insolation, average ambient temperature, and average water temperature be found for each interval. The standardized cooking power for each of the intervals is then obtained by correcting P_i to standard insolation of 700 W/m^2. This is achieved by multiplying the interval observed cooking power by 700 W/m^2 and dividing by the interval average insolation recorded during the corresponding interval as follows:

$$P_s = P_i\left(\frac{700}{I_i}\right) \qquad (6)$$

where P_s is the standardized cooking power (W), P_i is the interval cooking power (W), and I_i is the interval average solar insolation (W/m^2). The ambient temperature, T_a for each interval is to be subtracted from the average water temperature, T_w for each corresponding interval to obtain the temperature difference, T_d.

$$T_d = T_w - T_a \quad (7)$$

The ASAE standard S-580 also requires that the standardized cooking power, P_s (W) be plotted against the temperature difference, T_d (°C), for each time interval and linear regression used to find the relationship between the cooking power and temperature difference in terms of intercept, a (W), and slope, b (W/ °C):

$$P_s = a + bT_d \quad (8)$$

In the end, the value for standardized cooking power, P_s (W), should be computed for a temperature difference, T_d, of 50 °C. The minimum number of observations to be used here should be 30 for three different days. The coefficient of determination (r^2) or the proportion of variation in cooking power that can be attributed to the relationship found by regression should be higher than 0.75. This testing standard has been used and reported by many researchers [8][9][10].

2. MATERIALS AND METHODS

Materials for the construction were sourced locally and they include: mild steel sheet for the construction of the wall of the paraboloid, ¾ inch steel flat bar used for the skeletal design of the solar collector to give it adequate rigidity and also aid in achieving accurate parabolic shape, 3/2 inches angle iron used in the construction of the stand and frame, swinging shaft made of sprockets and used to aid the rotation of the collector for manual solar tracking, 17 bolts and nuts used to fasten the various components of the collector, 3/2 inches steel square pipe used for the stand, oil paint for the painting of the collector, and aluminum foil and aluminum-coated pellicle film for the reflecting surface of the parabolic collector. The equipment and machine tools used for the construction include hack saw, vernier caliper, angle grinders (small and big), steel tape, tri-square, pinch roller machine, arc welding machine, vice, drilling machine, and filing machine.

The parabolic collector was to have an aperture diameter (d) of 1.0 m and height (h) of 0.5m. Using the parabolic equation $y^2 = 4fx$, and taking $y_{max} = \frac{d}{2}$ and $x_{max} = h$, the focus of the parabolic collector was calculated as 12.5 cm. With the focus and a design directrix, flat steel bars were formed into parabolas of diameter, 1.0 m. The parabolic steel bars were welded together to form a skeletal paraboloid. A hole was dug into the ground, and with the help of the skeletal paraboloid, concrete was used to fill the hole and to make it take the inner shape of the parabolic collector to be constructed. The formed parabolic hole was left for one week so as to allow it set and become strong enough for the construction impact. For the actual construction, the skeletal paraboloid was fit into the hole and the mild steel sheet placed on it. By pressing and continuous hammering, the steel plate was made to take the shape of the parabolic hole. With filing, a near-perfect parabolic collector was obtained. The collector stand and pot stand were constructed and the different units were welded together and painted. Aluminum coated pellicle film was pasted on the inner surface of the collector to serve as the reflecting material. Pictures of the constructed parabolic solar concentrator are shown in Figure 4.

Fig. 4. Pictures of the constructed parabolic collector

A thermal performance test was carried out on the collector following the American Society of Agricultural Engineers Standard, ASAE S580. 500cm^3 (0.5 kg) of water was put into a small aluminum pot which has an outer black painted surface. With the help of the collector's pot stand, the pot was placed at the focus of the collector and the collector was turned to face the Sun. At this moment, the temperature of the water, T_w, ambient temperature, T_a and solar irradiance, I were measured and recorded. This was at 9:00 hours, Nigerian time. The measurements were repeated at 10 minutes intervals and a total of forty readings were taken. The last measurement was made at 15:30 hours. The results were recorded. This test was repeated on three different days in the month of February and the average was computed and recorded. The solar collector's picture with pot inside is given in Figure 5.

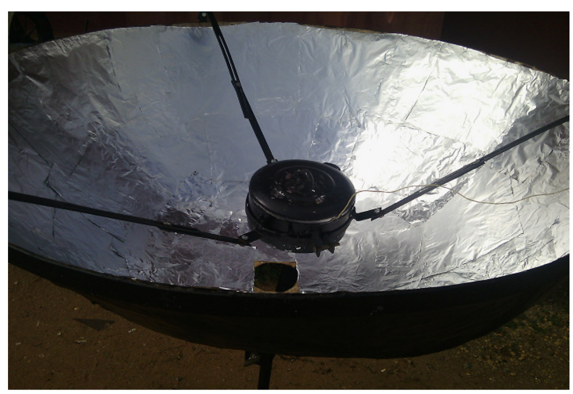

Fig. 5. The Collector with pot of water inside

After the first series of tests, the aluminum-coated pellicle film on the inner surface of the collector was replaced with aluminum foil. The thermal performance test was repeated on three different days as before and the average was computed and recorded.

3. RESULTS AND DISCUSSION

Results of the thermal performance tests carried out on the constructed parabolic solar concentrator when the reflecting surface was made of aluminum-coated pellicle film and when it was replaced with aluminum foil, are presented in the form of graphs of water temperature against time for pellicle film, water temperature against time for aluminum foil, solar irradiance against time, and ambient temperature against time as shown in Figures 6 and 7.

From the graphs, it is obvious that aluminum foil performed better as a parabolic collector reflecting surface than aluminum-coated pellicle film. But the solar collector was not able to achieve a temperature of 100 ^{0}C with any of them. This means that they can only be used as a reflecting surface for this size of solar collectors not meant for cooking of food or water boiling.

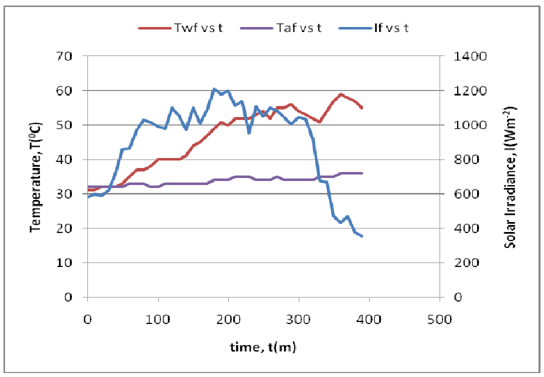

Fig. 6. Graphs of water temperature (T_{wf}), ambient temperature (T_{af}), and solar irradiance (I_f) against time, with pellicle film in place as reflecting surface for the solar concentrator

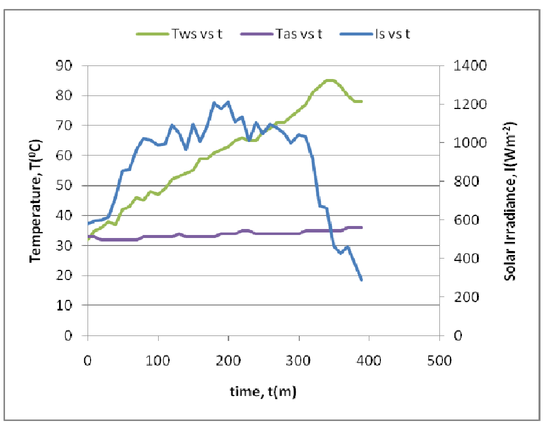

Fig. 7. Graphs of water temperature (T_{ws}), ambient temperature (T_{as}), and solar irradiance (I_s) against time, with aluminum foil in place as reflecting surface for the solar concentrator

4. CONCLUSION AND RECOMMENDATION

A parabolic solar concentrator was constructed and tested with aluminum-coated pellicle film and aluminum foil in place as reflecting surfaces. The concentrator was designed to have its focus inside the paraboloid to reduce heat loss to the surrounding due to temperature gradient. The highest water temperature realized when the aluminum-coated pellicle film was in place as a reflecting surface was 59 ^{0}C while a maximum of 85 ^{0}C water temperature was realized with aluminum foil used as a reflecting surface. Therefore, aluminum foil is a better reflecting surface for solar collectors than aluminum-coated pellicle film.

I recommend that aluminum foil be used as reflecting surface for solar collectors meant for applications where the needed temperature is less than or equal to 85 ^{0}C if the collector aperture diameter is restricted to 1.0 m and below due to low cost of the material. But for higher temperature applications, the collector should be designed to have bigger aperture diameter or better reflecting surfaces should be used.

REFERENCES

[1]. Murthy, M. S., Patil, Y. S., Ambekar, D., Patil, T., Sonawane, G., Chaudhari, R., et al. - Concrete slab solar water heating system. In: 2011 IEEE 1st Conference on Clean Energy and Technology, CET 2011, 2011, pg. 332–6.

[2]. Rogee, H. - Solar thermal [Online]. 2002 [cited 2019 Jul 15]. Available from: https://www.rogeehydronics.com/page-3

[3]. Santos, J. J. C. S., Palacio, J. C. E., Reyes, A. M. M., Carvalho, M., Freire, A. J. R., Barone, M. A. - Concentrating Solar Power. In: Advances in Renewable Energies and Power Technologies, 2018, pg. 373–402.

[4]. Muhammad-Sukki, F., Ramirez-Iniguez. R., McMeekin, S. G., Stewart, B. G., Clive, B. - Solar concentrators. Handb Clim Chang Mitig, vol. 3, no. 1, 2012, pg. 1263–94.

[5]. Vasiu, I. - SOLAR THERMAL POWER PLANTS OPERATING ON PARABOLIC TROUGHS MIRRORS, J Sustainable Energy, vol. 10, no. 2, 2019, pg. 83–92.

[6]. Ouannene, M., Chaouachi, B., Gabsi, S. - DESIGN AND REALISATION OF A PARABOLIC SOLAR COOKER. In: Int Symp On convective Heat and Mass Transfer in Sustainable Energy, 2009.

[7]. *** American Society of Agricultural Engineers. - Testing and Reporting Solar Cooker Performance. Am Soc Agric Eng ASAE S580, 2003.

[8]. Mawire, A. - Solar Thermal Energy Storage for Solar Cookers. In: Solar Energy Storage, Elsevier Ltd., 2015, pg. 327–58. Available from: http://dx.doi.org/10.1016/B978-0-12-409540-3.00014-1

[9]. Funk, P. A. - Evaluating the international standard procedure for testing solar cookers and reporting performance, Sol Energy, vol. 68, no. 1, 2000, pg. 1–7.

[10]. Yahya, D. D. - Thermal Performance Testing of Parabolic Solar, Int J Eng Res Technology, vol. 6, no. 3, 2013, pg. 323–31