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DEVELOPMENT AND EVALUATION OF AN ECONOMICAL CYLINDRICAL SOLAR COLLECTOR FOR STEAM PRODUCTION

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ABSTRACT

This study describes the development and evaluation of a reliable low-cost cylindrical collector that would be capable of operating at reasonable efficiencies for steam production. The theoretical analysis of the elastic shape of the components used to properly design the reflector is also presented. The cylindrical reflector component of the collector was fabricated using galvanized iron sheets coated with aluminum foil, while the absorber was made from a galvanized iron pipe and coated with a black paint. The system is such that it can be adjusted in two axial directions. Some sample performance tests of the system are also reported.

1. Introduction

A number of industrial, commercial and agricultural processes require medium temperature (80^0c – 150^0c) thermal energy which is currently being obtained by the use of coal, wood or electricity. Solar energy provides a readily available and easily integrated alternative to supply the required heat energy using concentrating collectors [1].

A project for the development of concentrating collectors has been started at the Obafemi Awolowo University Energy Research Centre Ile-Ife, Osun State. One of the major cost factors with concentrating collectors is the focusing component.

The design developed during the course of this work using low-cost, robust materials does not require very special tools or processes to form the collector profile and can be easily transported and assembled on site.

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The collector field focuses sunlight onto the solar boiler. The solar boiler plays a crucial role in harnessing solar energy and converting it into a usable form, making it an essential component of the cylindrical solar system for steam generation. The efficient generation of steam at industrial pressures and 180^0c requires tracking concentrating collectors to maximize annual light collection and minimize heat losses proportional to receiver surface area. [2]

2.0 Materials and Method

2.1 Collector Design

Concentrating collectors basically consists of two components: reflector and absorber.

The design of reflector is based on the fact that the shape taken on a piece of sheet material, when buckled elastically as a result of the application of equal and opposite sides of the sheet, is an approximation to a parabola.

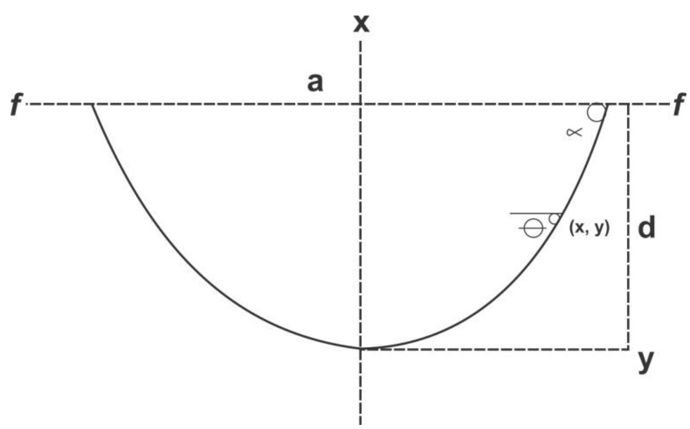

Fig. 1 Elastical Contour

Figure 1 above is the elastical contour (assumed to be a side view of a reflector). Using the theory of 'elastic stability' it may be shown that the l, and the d', may be expressed in terms of α and $\propto$ as [2].

$$l = \frac{aK(P)}{2E(P) - K(P)} \quad (1)$$

$$d = \frac{a \sin\left(\propto/2\right)}{2(2E(P) - K(P)} \quad (2)$$

where p = $\sin(\propto/2)$.

l = length of the reflector (contour) from the fixed point to the point where the angle $\propto$ is measured.

d = depth or distance from the fixed point to the point where the angle θ is measured.

$\propto$ = angle between the reflector (contour) and the horizontal plane at the point where the length is measured.

θ = angle between the reflector (contour) and the vertical plane at the point where the depth d is measured.

The co-ordinates of any point (x,y) on the curve are given by [3]

$$x = \frac{I}{n}(2E(\emptyset, p) - F(\emptyset, p) \qquad (3)$$

$$y = \frac{2p}{n}(I - \cos\theta), \text{ for } \theta < \propto \qquad (4)$$

Where θ is defined by $\sin\theta = \frac{a\sin({}^{\theta}/_{2})}{\sin{}^{\propto}/_{2}}$,

for $< \propto$, and n = 2(2E(p) – K(p)/α

Equations 1 to 4 have been used to produce reflector contours and ray traces [4]. It has been observed that for a rim angle of 40^0, an excellent focus is achieved for rays incident on the central three - fourths of the aperture. Rays incident on sides of the aperture are not well focused because the curvature decreases to zero at the edge of the reflector. With increasing rim angle, the focus becomes more dispersed.

It may also be observed that increasing the rim angle results in lowering of the focus so that it lies below the edge of the reflector for rim angles 41^0.

From the above analysis, one can deduce that there are two independent parameters necessary for a reflector: α and $\propto$. In this study $\propto$ has been assumed as 40^0 and α has been taken as one metre (1m).

So, P = sin$\propto$/2 = sin 20^0 = 0.3420

The incomplete elliptic integral of the first kind is defined as [5]

$$F(p,\emptyset) = \int_0^{\emptyset} \frac{d\theta}{1-p^2 sin^2\theta}, o < p < l \qquad (5)$$

If $\emptyset = {}^{\pi}/_{2}$, it is called the complete elliptic integral of the first kind.

The incomplete elliptic integral of the second kind is defined as [6].

$$G(P, \emptyset) = \int_0^{\emptyset} \frac{d\theta}{1-p^2 sin^2\theta \, d\theta}, o < p < I \quad (6)$$

and, again, if $\emptyset = \frac{\wedge}{2}$, it is called the complete elliptic integral of the second kind

Hence, $K(P) = \int_0^{\pi/2} (-p^2 sin^2\theta)^{-1/2} \, d\theta$

ie $K(p) = \int_0^{\pi/2} \left(1 + \frac{p^2}{2} sin^2\theta + \cdots\right) d\theta$

= 1.62

And $E(p) = \int_0^{\pi/2} 1 - p^2 sin^2\theta)^{-1/2} \, d\theta$

= 1.52

From equation (1)

$$L = \frac{a\,K(p)}{2\,E(p) - K(p)}$$

$$= 1.14\text{m}$$

and, from equation (2)

$$d = \frac{a \sin(\propto/_2)}{2\,(2E(p) - K(p)}$$

$$= 0.12\text{m}$$

A practical method has been used to determine the focal line, as given in the next session.

2.2 Fabrication

The reflector has been fabricated from a galvanized iron sheet of 114cm x 104cm and the reflective part has been carefully coated with aluminum foil. The absorber has been made from a galvanized iron pipe of 7.10cm internal diameter, 0.25cm thickness and 126cm length.

The collector can be adjusted manually for tracking the sun. The collector has further been kept at inclination angle of 12.5^0 (approximately equal to the latitude of the location) facing towards South.

The focal line was determined after the collector has been fabricated and properly mounted. At solar noon with all proper adjustments, this position has been found to be 40.9cm above the reflector base and of effective width 8.2cm. This matches with the size of the absorber pipe. [7].

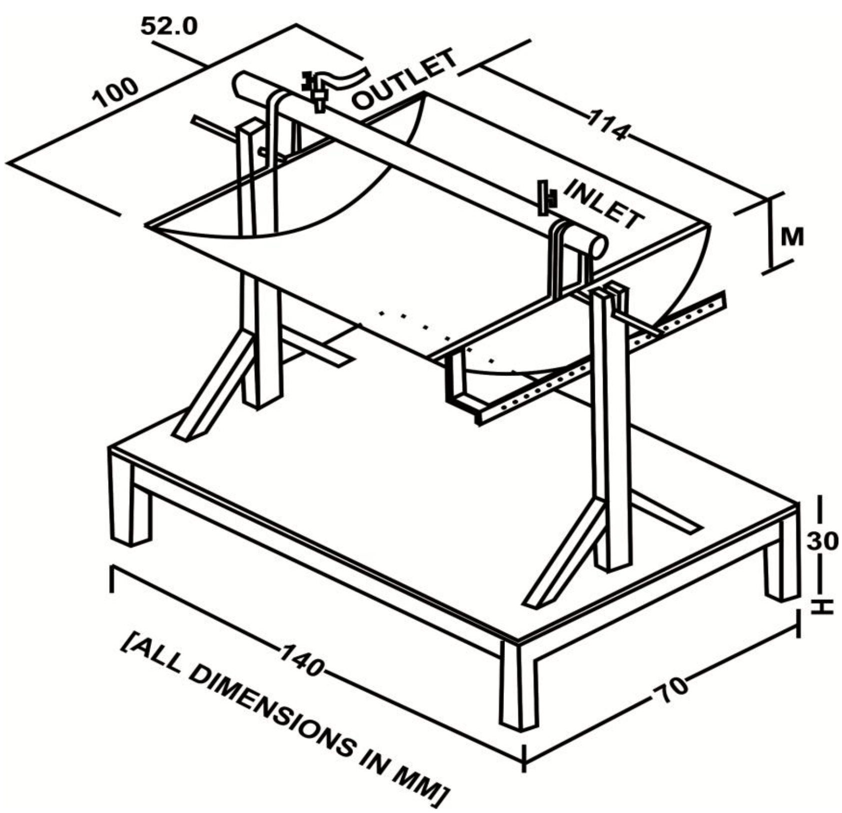

Figure 2. Full cylindrical Collector

The concentration ratio (the ratio of the width of the reflector to the width of the absorber) is about 13. [8].

Results and Discussion

A number of sets of observations were taken with the system at varied starting time during August – October 2024 period. Readings of the temperature of water inside the absorber and the global solar radiation were recorded with two different values of the volume of the water inside the absorber, at regular intervals of time until the maximum temperature of water was achieved for that day, (the practical limit) with manual tracking of the sun by adjusting the collector at half an hour intervals. [9]

If the initial temperature of a known quantity of water in the absorber is T_1 and after a time, the temperature changes to T_2, then the heat gained by the water is equal to mc ($T_2 – T_1$). Total energy falling on the collector during this time is AIt

So, the efficiency of the system during this time interval would be

$$\frac{mc\,(T_2 - T_1)}{AIt}, [10]$$

where

- m = working fluid mass flow rate in kg/s;
- T_1 and T_2 are temperatures of fluid entering and leaving the receiver in ^oC.
- c = specific heat at constant pressure in J/Kg.K.
- A = Area
- I = current
- t = Time

This analysis was used to compute the efficiency of the system for various interval of time for each test.

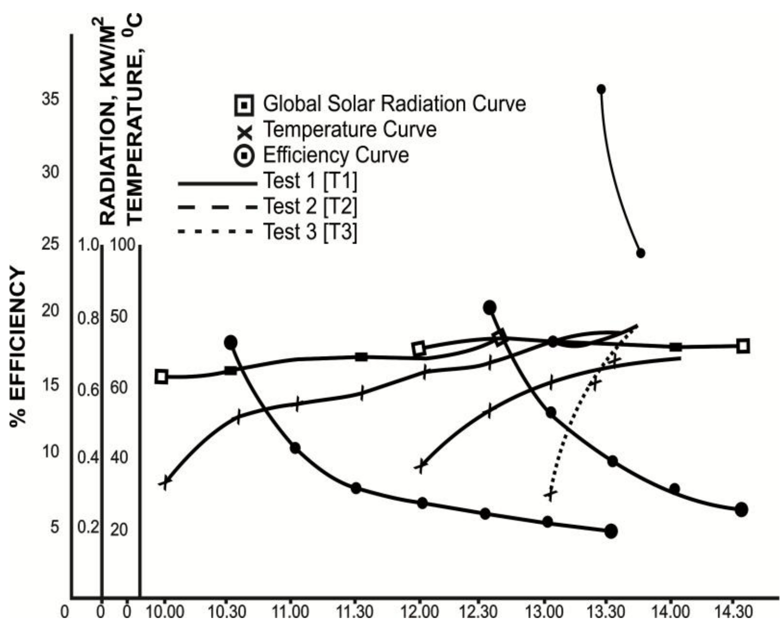

Figure 3: Variation of global solar radiation, temperature of water inside the absorber and time interval efficiency with time. (Volume of water = 3000cm^3)

Figure 3 above shows the variation of temperature of water in the absorber, global solar radiation, the time – interval efficiency of the system with time for 3 typical tests, T1, T2 and T3 having 3000cm^3 of water in the absorber.

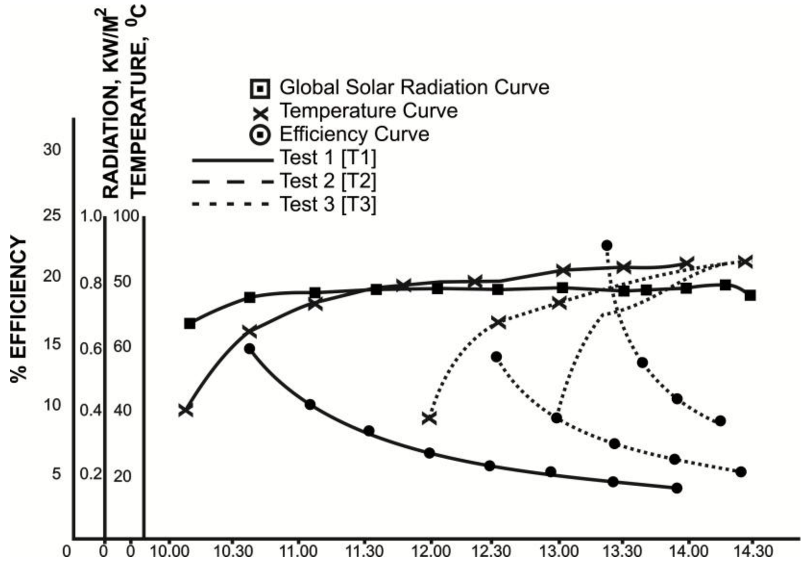

Figure 4: Variation of global solar radiation, temperature of water inside the absorber and time interval efficiency with time. (Volume of water = 1500cm^3)

Figure 4 above shows similar curves for other tests, T4, T5, T6 having 1500cm^3 of water in the absorber.

Table 1: Average global solar radiation and performance parameters of the six (6) tests carried out.

Table 1

PERFORMANCE PARAMETERS OF THE SIX TESTS

Test Number	Average Global Solar Radiation during the period of test (kW/m)	Sky Clearness condition for the duration of the test	Max. temperature of water obtained (C)	Time taken to reach the max. temperature and its range.
T1	0.7021	Some clouds during 11.00 am - 12noon period	76.5	3 hours [10.00am - 1.30pm]
T2	0.7432	clear	74.5	2 hours [12.00pm - 2.30pm]
T3	0.7667	very clear	79.5	40 minutes [1.00am - 1.40pm]
T4	0.7068	some clouds during 12noon - 12.30pm period	84	4 hours [10.00am - 2.00pm]
T5	0.7437	clear	85	2 hours [12.00pm - 2.30pm]
T6	0.7490	some clouds during 1.00pm - 1.30pm period	84.5	1 hours [1.00pm - 2.20pm]

Table 1 above presents the values of average global solar radiation and some performance parameters for all the six tests that were carried out and reported.

The above tests can be compared in pairs such as T1 and T4, T2 and T5, T3 and T6 because each pair has almost equal range of time and approximately same average global solar radiation during the period of testing, although volume of water is different.

It can be seen that higher temperatures can be reached with lesser volume of water, although thermal losses from the absorber are also supposed to be higher in such cases. [11]

From figures 3 and 4 and table 1, the following points are observed with respects to the performance of the system:

- The performance of the system strongly depends on the clearness of the sky (or the amount of direct solar radiation)
- It is better to operate the system when the solar radiation is high, ie between 12.00 noon and 2.30pm period.
- High temperatures can be reached in much shorter durations in this period.

It should be noted that the system did not produce steam in any of the tests. This is due to the mismatch between the size of the absorber and the reflective area. The volume of the absorber pipe is much bigger than the required value with the present size of reflecting area.

A higher concentration ratio can lead to increased energy density, but also increase the complexity and cost of the system. Mismatches between the absorber and reflective area can result in energy losses due to spillage, shading and optical losses [12]. Optimizing the concentration ratio and minimizing energy losses can improve the overall system efficiency.

Conclusion

This study successfully demonstrated the development and evaluation of an economical cylindrical solar collector for steam production.

The results showed that at high solar radiation and between 12.00noon and 3.30pm and temperature 74.5^0C, the performance of the system is better together with its efficiency, making it a viable alternative for industrial steam generation. The proposed design offers a cost effective and sustainable solution for harnessing solar energy, contributing to a reduction in greenhouse gas emissions and dependence on fossil fuels.

However, the following modifications are suggested to achieving much more better results.

- The reflector had a coating of aluminum foil which did not spread smoothly with the use of available adhesives.
- Replacement with a paint (like silver or chromium) or glass strips will reduce the width of focal line and increase the reflectance coefficient.
- Absorber can be made from a material which has a better thermal conductivity like copper instead of the galvanized iron and could be coated with a selective material rather than the black paint for increased value of absorbance coefficient

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