DESIGN, CONSTRUCTION AND STUDY OF THE PERFORMANCE OF A CONICAL SOLAR CONCENTRATOR

O. I. Popoola* and J. D. Ayanda+

*Department of Physics, University of Ibadan, Ibadan, Nigeria

+Department of Physics Tai Solarin University of Education, Ijebu Ode, Nigeria

Abstract

The design, construction and study of conical solar concentrator was carried out using locally available materials such as conical shaped concentrator made from fabricated iron sheet of 2mm, (0.2cm) thickness. The inner side of the cone shape was lined with strips of plane mirror cemented to the surface using araldite mix with sawdust. The conical concentrator has an aperture area equal to 8142.19cm², while the two solar absorber used for the study has surface area 795.64cm² and 713.53cm² with the concentration ratio being 9.82 and 10.96 respectively. The conical solar concentrator was tested under various operation conditions, such as; different concentration ratio, static and none static condition of the absorber fluid. The relationship between the working (absorber) fluid temperatures against local time of the day showed that higher temperatures of the fluid were obtained on bright sunny days when the collector received beam radiation (highest temperature recorded = 166°C) and a rapid decline of the fluid temperatures when a cloudy interception of the sun occurred. The theoretical calculations of the heat energy gained and overall thermal efficiency of the collector based on Hottel-whiller equations shows that the collector's efficiency increased as the concentration ratio increased.

Keywords: *Concentration ratio, solar absorber, thermal performance, working fluid, solar concentrator, Aperture.*

Introduction

The conventional sources of energy being presently utilized by man for domestic and industrial uses are the fossil fuels, coal, gas and oil. These energy sources came indirectly from the sun in that they were formed some thousands of years ago from decayed plants and animals that once depended on the sun for life and growth. These fossil fuels may accurately be thought of as 'stored' solar energy.

The recent energy crisis which resulted from high energy demand coupled with rising cost of crude oil which accounted for the largest convectional energy source, has led to a considerable interest in solar energy for additional source of energy in highly industrialized and some developing countries. This energy crisis has prompted scientists and engineers into the study of sun, its radiations and possibilities of obtaining energy from it by employing different types of sun collecting system and methods of orientation and designing these collectors for maximum trappings of sun's energy for domestic and industrial uses.

The amount of energy radiated from the sun annually is estimated at 5.4×10^{24} Joule per year, which is equivalent to at least 1000 times the amount of energy used presently in the whole world for the same period of time (Dixon & Leslie, 1978). The annual total horizontal solar radiation in Nigeria as determined from mean annual sunshine hours varies from 5000MJ/m^2 in the humid Niger Delta to over 9400MJ/m^2 in the extreme north-east of Nigeria (Arinze and Obi, 1984). This energy from the sun is transmitted through space to the earth by means of Electromagnetic radiation in form of heat and high energy at a relatively low intensity. Many researchers in Nigeria (Garba *et al* 1997, Falade *et al* 1985, Arinze, 1986) have shown considerable interest in the sun and have researched into different methods of harnessing its energy for domestic purposes such as solar cooking, water pumping and drying of food item in rural areas. A device, which utilizes this incident flux by concentrating it on a definite energy absorbing material for heat energy trapping purposes, is called solar concentrator.

There are various types of focusing collector each having different approaches in design and each being an improvement on the former. These include rotatory paraboloid mirror, cylindrical parabolic mirror, spherical mirror, cone mirror and Fresnel mirror (Ren *et al*, 1997). Out of the various types of focusing collector mentioned, the conical solar concentrator was chosen for this study based on (i) The geometry of deign is less complex than other solar concentrators (ii) The energy received by the absorber is greater than any other concentrator /focusing collector of equal aperture area. (iii) Availability of local materials and relatively lower labour cost needed for the construction of the concentrator.

The design, construction of the concentrator using locally available materials and study of its thermal performance are presented thus:

Theoretical Background

Solar concentrator are types of focusing collectors which utilize optical system reflectors (Mirrored or reflecting surfaces) or refractors (lenses) to increase the intensity of solar radiation on an energy absorbing surface for applications requiring high temperatures such as is required for refrigeration, power generation and space heating. In focusing collectors the refracting or reflecting surface are used to channel natural concentration of solar energy falling on an area into a significantly smaller area i.e. the focus of the system. Thus, the energy intensity at the focus is much greater than that of the natural sunlight (see fig 1.0). The area that receives this augmented insolation is called the "hot spot" and may be a small circle, a rectangle, a thin wire or cylindrical shape, depending on the techniques used. The extent to which concentration is achieved is called the concentration ratio (C) and is generally expressed as the ratio of effective aperture area (A_a) to the area of the solar energy absorber (A_r). It is an important factor in determining the amount of heat intercepted by the solar absorber. As C increases the heat loses per aperture decreases. At optimal concentration ratio, an incremental heat loss equals the incremental loss of intercepted solar radiation.

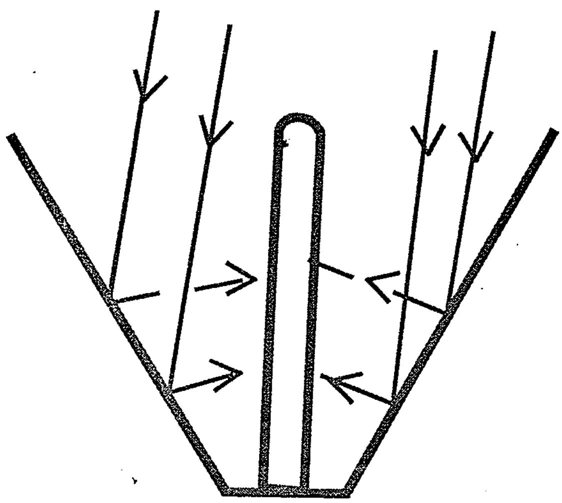

Figure 1 : Reflection by a conical surface

Most of these concentrators have certain essential features in common, these are

(i) reflecting or refracting surface
(ii) absorbing surface and fluid
(iii) tracking system
(iv) storage system

Reflectors that are surface of revolution generally must be oriented so that the focus vertex and the sun are in line (position whereby no shadow of the absorber is cast on the wooden base of the collector). For these types of solar collectors to deliver a constant flow of heat, they must 'track' the sun as it moves across the sky, otherwise, sunlight will not be constantly focused on the absorber. To achieve this objective, the collector must be able to move about two axes. These axes may for example be horizontal and vertical or one axis of rotation may be inclined so that it is parallel to the earth's axis of rotation (i.e. a polar axis) and the other perpendicular to it.

Design and Construction of the Concentrator

The collector is essentially a frustum of a right circular cone (slant angle = 45^0) upper circular diameter equal to 102cm and lower circular diameter equal to 20.4cm. The slant height of the frustum is 57.6cm while the vertical height is 40.7cm.

The frustum was rolled into shape as shown in fig 2a using iron sheet of 2mm thickness and braced at the adjoining ends by welding.

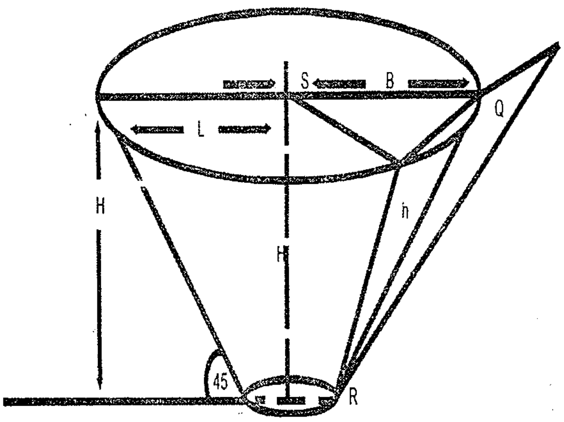

Fig 2.a Frustum of A right-circular cone

Two iron rods P&Q (Sec fig.) made of mild steel of length 30cm and diameter 1.5cm each were welded to the sides of the cone along an axis passing through its centre of gravity.

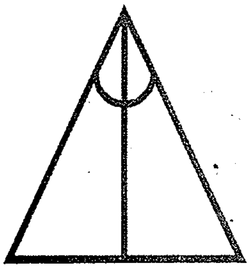

Fig: 2b

A section of lower polygon

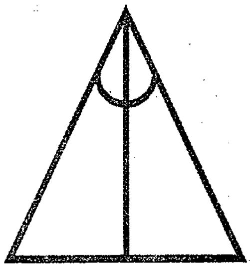

Fig: 2c

A section of upper polygon

These two rods were joined through the centre of the collector to rectangular frame in such a way that the rods P&Q will have free axis of rotation along RS direction. They were bracketed to the frame using a bolts and nuts arrangement to allow for easy tracking of the sun energy along North-south direction and also to ensure for a fixed position for trapping of the sun energy. The rectangular frame upon which the conical collector rests is made of an angle iron on the sides of which two mild steel rods R and S of length 30cm and diameter 2.5cm are welded. These two rest the entire weight of the angle iron frame and the conical collector on the wooden planks A and B which act as the main support, thus enabling the collector to track the sun along East-west direction. Two scales for measuring the angle of inclinations of the sun to the horizontal along the North-south direction and East-west direction were attached to rod R and plank A respectively.

Reflecting surface

The reflecting surface of the collector is made of finite numbers of mirror strips gummed to the inner surface of the collector using Araldite mixed with sawdust to ensure proper stickiness to the surface. The mirror strips each has an upper and lower with equal to 5cm and 1cm respectively and length equal to the slant height of the conical collector which is 57.57cm. The upper and lower width form a regular polygon of sixty-four sides each of which constitutes the base side of sixty-four isosceles triangles (Fig: 2b & 2c) forming both the upper and lower aperture of the conical collector. A total of 64 mirror strips were used for the reflecting surface.

The Absorbing surface

The absorber is a tubular structure made from a copper sheet. The copper sheet was rolled into a cylindrical form, then braced at the adjoining end by a zinc metal alloy, it is then painted with a black paint to act as a black body absorber. Two copper pipes of lengths 52.7cm and 12.2cm and having equal diameter serves as the inlet and outlet fluid flow sources respectively as shown in fig 3.0.

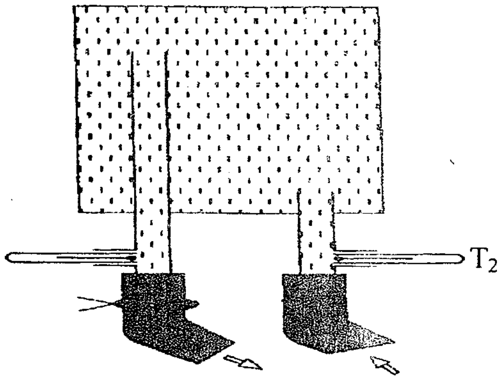

Fig 3: Cross sec onal view of solar concentrator abso r

Thermometer junction were attacked to each of the pipes using a mixture of Araldite and sawdust, these junctions are created for measuring inlet and outlet temperatures.

Experimental Procedures and Measurements

The working fluid used in the absorber for the research work was a black engine oil of low specific heat capacity, with a high boiling point temperature.

In this research work, two perpendicular axes of rotation were adopted with continuous adjustment by hand, such that, the sun image is constantly reflected to the absorber. The hourly orientation of the concentrator is along PQ axis. A semi-circular scale attached to the wooden stand at the pivot position P, gives the angle of inclination of the sun to the horizontal in its daily motion in East-West direction (fig. 4). It was observed that the inclination of the sun to the horizontal maintains a value of 15^0 in one hour. Another axis of orientation of the concentrator is the North-South direction, meant for tracking of the sun in its seasonal movement. A circular scale is also attached to the frame at point R to measure the inclination of the sun to the horizontal along this axis.

The experimental recordings of the sun energy trapped by the absorber took a total of seven days, with the recordings starting from 9.30 a.m and ending at 5.30 p.m on each of the days at an interval of 30 minutes except on days 5 and 7 as shown in Tables 3 and 4. Days 1 to 4 recordings were taken with both inlet and outlet fluid flow sources closed. A thermometer was inserted through a hole punched at the flat end of the absorber to measure the temperature (T_3 ^{0}C) of the working fluid. On days, 5, 6 and 7, observations were recorded with the different flow rate of the working fluid.

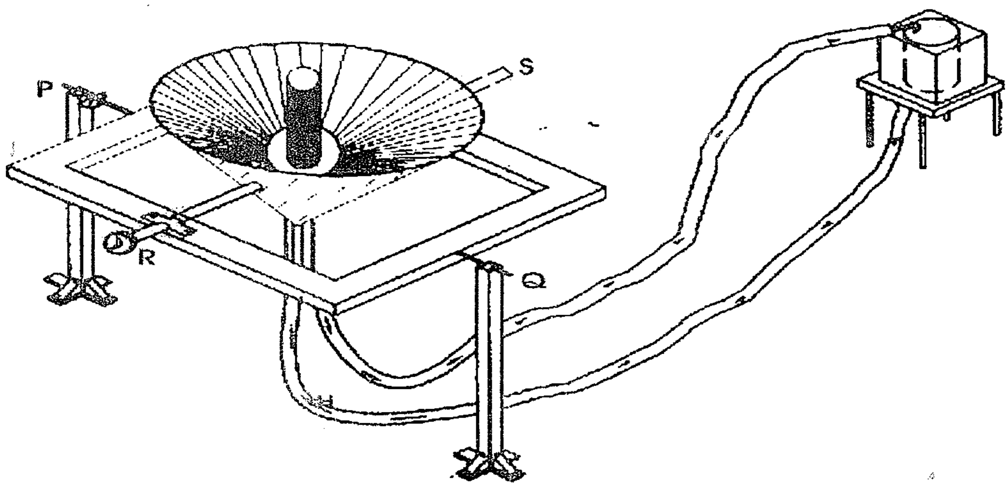

Fig 4: Pictorial view of the conical solar concentrator

Results and Discussion

A summary of the measurement for all the days on which these readings were recorded shows that higher working fluid temperatures were obtained on sunny day when the collector received full beam radiation (highest temperature recorded was 166^{o}C). This can be observed from Tables 1-4 and from the graphs of Figures 5 and 6. A rapid decline in working fluid temperatures occurred when there were cloudy interceptions of the sun. Two solar absorbers used for the observation have concentration ratios Cr_1=10.96 and Cr_2=9.82. The highest temperature of 166^{o}c was obtained with the absorber with higher concentration ratio (Cr= 10.96) on the 4th day of the recording at 1.30pm.

Table 1: Temperatures of the absorber working fluid against local time of the day for static condition of the working fluid for day 1 and day 2.

Day 1			Day 2		
Local time of the day	T_a^{0}C	T_3^{0}C	Local time of the day	T_a^{0}C	T_3^{0}C
9.30am	28.4	78.0	10:00am	27.5	74.0
10.00am	28.6	110.0	10:30am	28.0	90.0
10.30am	30.0	125.0	11:00am	28.4	122.0
11.00am	30.2	128.0	11:30am	28.8	120.0
11.30am	32.4	122.0	12:00 noon	30.0	108.0
12.00 noon	32.2	120.0	12:30p.m	30.1	134.0
12.30p.m	32.5	110.0	1.00p.m	30.6	150.0
1.00p.m	33.5	98.0	1.30p.m	31.1	148.0
1:30p.m	33.0	90.0	2.00p.m	32.0	158.0
2.00pm	33.1	72.0	2.30p.m	32.7	134.0
2.30p.m	33.0	66.0	3.00p.m	33.0	156.0
3.00p.m	33.0	62.0	3.30p.m	33.1	126.0
3.30p.m	33.2	62.0	4.00p.m	33.3	120.0
4.00p.m	33.6	62.0	4.30p.m	33.5	80.0
4.30p.m	33.6	62.0	5.00p.m	33.7	82.0
5.00p.m	33.6	94.0			
5.30p.m.	33.6	62.0			

T_a ^{0}C - *ambient temperature*
T_3 ^{0}C - *temperature for static condition of working fluid*

Table 2: Temperatures of the absorber working fluid against local time of the day for static condition of the working fluid for day 3 and day 4.

Day 3			Day 4		
Local time of the day	T_a^{0}C	T_3^{0}C	Local time of the day	T_a^{0}C	T_3^{0}C
11.30am	30.0	80.0	9.30am	25.0	78.0
12.00 noon	30.0	122.0	10.00am	28.5	109.0
12.30p.m	30.5	126.0	10.30am	29.0	116.0
1.00p.m	31.4	140.0	11.00am	29.5	127.0
1.30p.m	31.4	152.0	11.30am	30.0	128.0
2.00pm	31.4	92.0	12.00 noon	31.0	124.0
2.30p.m	31.8	144.0	12.30p.m	31.7	138.0
3.00p.m	32.6	158.0	1.00p.m	32.0	162.0
3.30p.m	32.7	130.0	1.30p.m	32.9	166.0
4.00p.m	32.9	150.0	2.00pm	33.3	104.0
4.30p.m	32.6	162.0	2.30p.m	33.5	127.0
5.00p.m	32.6	150.0	3.00p.m	34.0	143.0
			3.30p.m	34.1	122.0
			4.00p.m	34.3	98.0
			4.30p.m	34.0	72.0
			5.00p.m	33.5	65.0

T_a ^{0}C - *ambient temperature*
T_3 ^{0}C - *temperature for static condition of working fluid*

Table 3: Temperatures of the absorber working fluid against local time of the day for non-static condition of the working fluid for day 5.

Day 5							
Local time of the day	Ta^{0}C	T_1^{0}C	T_2^{0}C	Estimated Value of Solar Radiation HbRb (WHR/m^2) Received Half/Hour	Heat Energy Gained By the Collector (WHR)	Efficiency of Collector	Percentage Efficiency of the Collector %
9.00a.m	25.4	30.0	68.0	1400	760.08	0.667	66.7
9.30 a.m	26.8	33.0	80.0	1400	755.03	0.662	66.2
10.00 a.m	27.8	35.0	90.0	1700	917.06	0.663	66.3
10.30a.m	28.0	38.0	98.0	1900	1023.99	0.662	66.2
11.00a.m	28.6	38.5	80.0	2000	1087.80	0.668	66.8
11.30a.m	29.3	40.0	78.0	2000	1078.70	0.0669	66.9
12.00noon	29.9	40.0	80.0	1900	988.69	0.639	63.9
12.30p.m	30.6	39.0	85.0	1300	697.36	0.659	65.9
1.00p.m	31.1	38.0	52.0	1200	655.90	0.671	67.1

Working fluid rate of flow = 1.5cm ^{3}/s, M_1 = 1.3086g/s, FR_1 = 0.7909275

T_a^{0}C - *ambient temperature*
T_1^{0}C - *inlet temperature* ***T_2^{0}C*** - *outlet temperature*

Table 4: Temperature of the absorber working fluid against local time of the day for non-static condition of the working fluid for day 6 and 7.

Day 6							
Local time of the day	Ta^{0}C	T_1^{0}C	T_2^{0}C	Estimated Value of Solar Radiation HbRb (WHR/m^2) Received Half/Hour	Heat Energy Gained By the Collector (WHR)	Efficiency of Collector	Percentage Efficiency of the Collector %
10.30am	26.0	37	66.0	1800	1021.58	0.697	69.7
11.00am	26.0	41.0	72.0	1800	1019.20	0.695	69.5
11.30am	26.0	46.0	52.0	2100	1201.38	0.703	70.3
12.00 noon	28.3	40.0	50.0	1300	740.67	0.700	70.0
12.30p.m	Break						
1.00p.m	29.2	38.0	75.0	2100	1190.89	0.697	69.7
1.30p.m	30.2	39.0	80.0	2100	1188.51	0.695	69.5
2.00pm	31.0	41.0	93.0	1900	1067.36	0.690	69.0
2.30p.m	31.0	43.0	80.0	1800	1014.90	0.692	69.2
3.00p.m	31 0	41.0	78.0	1600	900.44	0.691	69.1
3.30p.m	31.3	46.0	84.0	1500	340.35	0.688	68.8
4.00p.m	31.9	45.0	72.0	1400	787.88	0.691	69.1

Working fluid rate of flow = 2.87cm^3/s, M_2 = 2.5g/s, FR_2 = 0.8218444

T_a^{0}C - *ambient temperature*
T_1^{0}C - *inlet temperature* *T_2^{0}C* - *outlet temperature*

Day 7							
Local Time of the Day	Ta^{0}C	T_1^{0}C	T_2^{0}C	Estimated Value of Solar Radiation HbRb (WHR/m^2) Received Half/Hour	Heat Energy Gained By the Collector (WHR)	Efficiency of Collector	Percentage Efficiency of the Collector %
9.30 am	24.5	31.0	80.0	1500	820.93	0.670	67.0
10.00 am	26.0	34.5	76.0	1500	822.79	0.694	67.4
10.30am	26.0	41.0	108.0	2000	1087.77	0.669	66.9
11.00	26.0	39.0	98.0	2300	1262.79	0.674	67.4
11.30am	27.2	43.0	110.0	2300	1269.67	0.671	67.1
12.00noon	28.3	50.0	108	2100	1146.04	0.670	67.0
12.30pm	29.0	44.5	98.0	2300	1262.79	0.674	67.4
1.00 pm.	29.2	43	86.0	2300	1268.37	0.677	67.7

Working fluid rate of flow = 1.8cm^3/s, M_3 = 1.57g/s, FR_3 = 0.8014896

T_a^{0}C - *ambient temperature*
T_1^{0}C - *inlet temperature* *T_2^{0}C* - *outlet temperature*

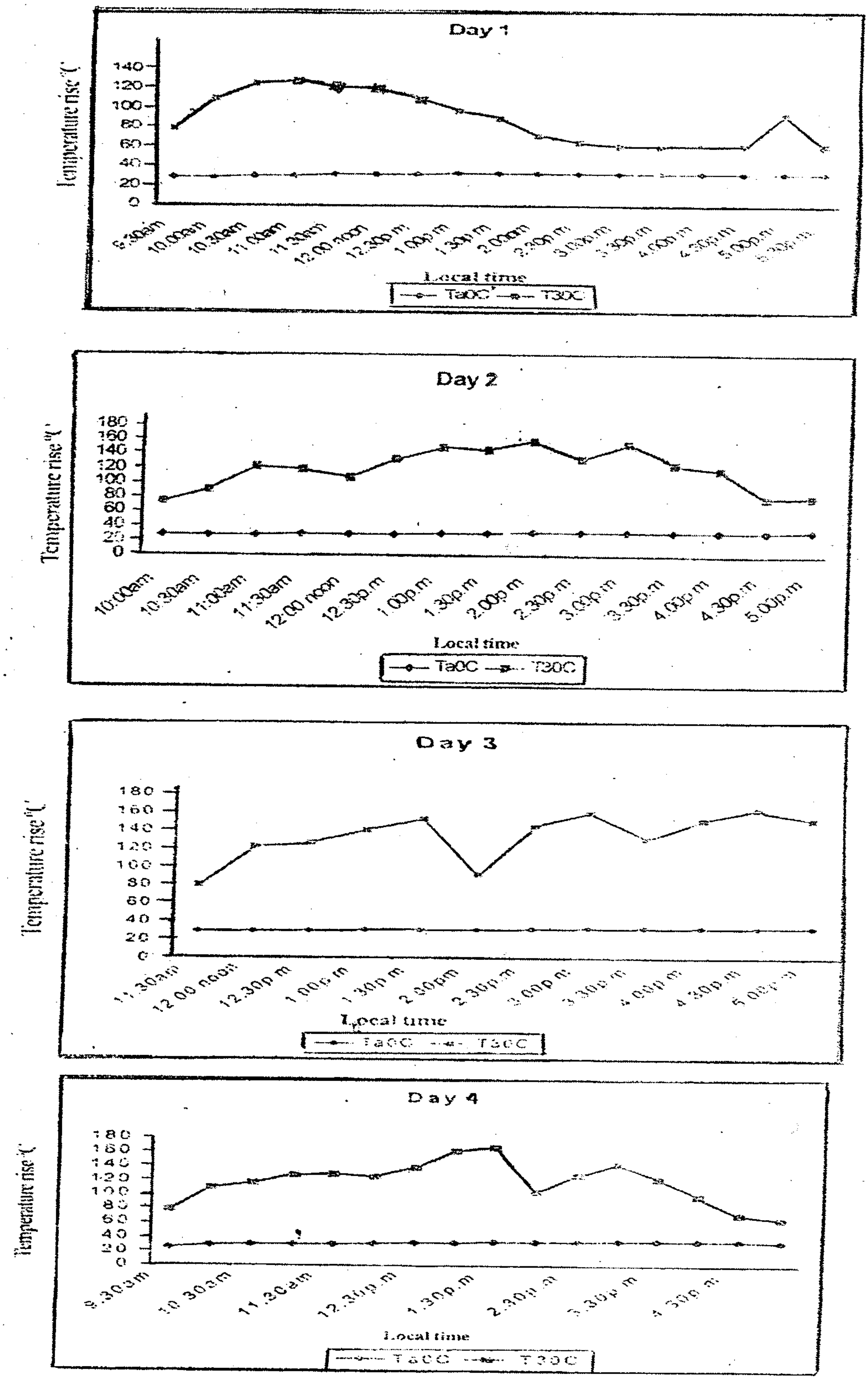

Fig. 5: Graphs of working fluid temperature (static conditions) against local time of the day for days 1,2,3 & 4

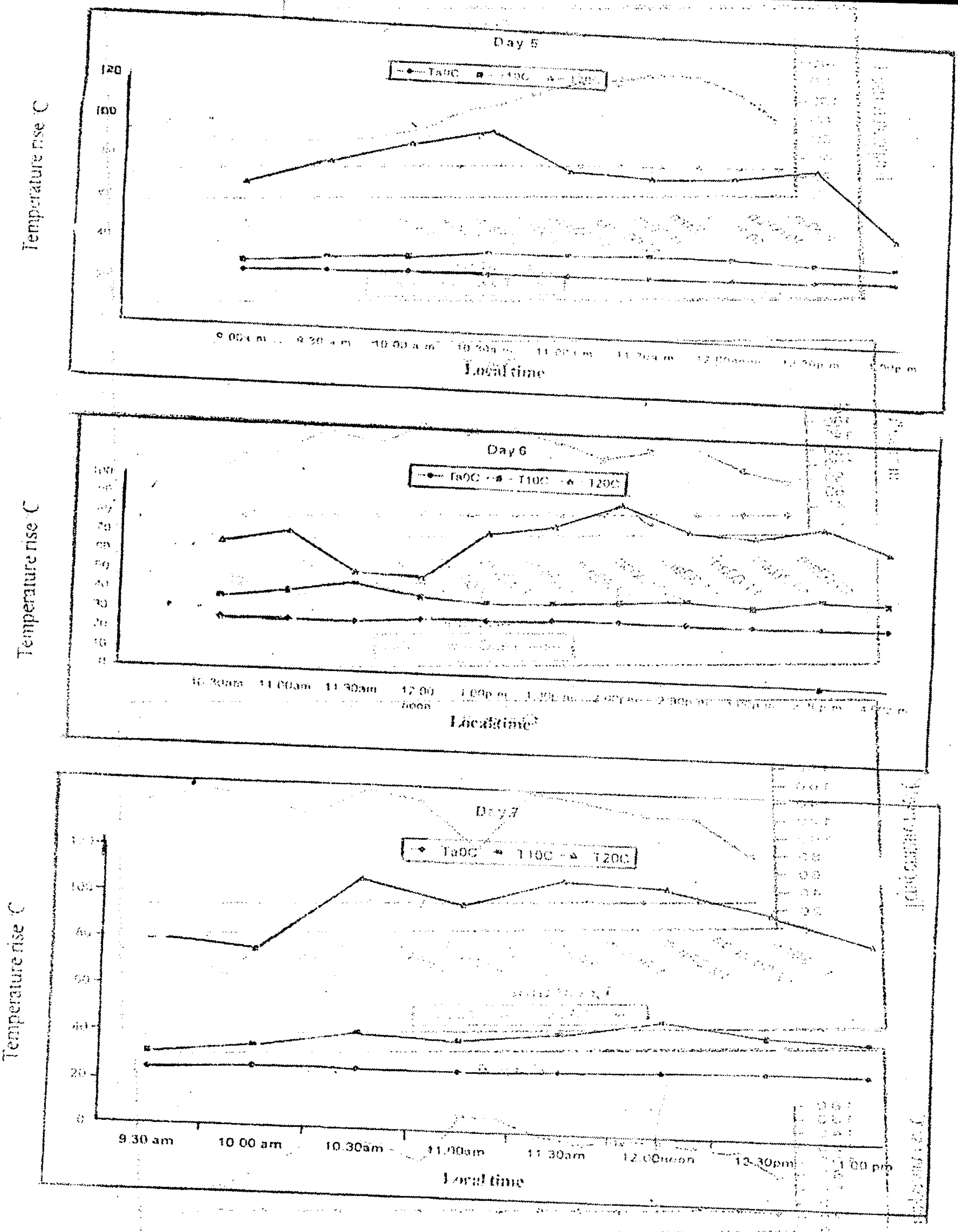

Fig. 6: Graphs of working fluid temperatures (different rate of flow) against local time of the day for days 5, 6, & 7.

Thermal Performance of the Concentrator and Calculations

The thermal performance of the conical solar concentrator can be determined using the basic equation widely known as the Hottel-Whillier-Bliss equations, which expresses the useful heat collected, Q, per unit area, in terms of two operating variable i.e the incident solar radiation normal to the collector surface Gc and the temperature difference between the mean temperature of the heat removal fluid in the collector, T_m and the surrounding air temperature, T_a as (Mcveigh, 1977)

$$Q = F(\tau\alpha)[G_c - U(T_m - T_a)] \quad (1)$$

where F is a factor related to the effectives heat transfer from the absorber to heat removal fluid. The above equation is then modified to another form for non static condition of the working fluid as (Duffie and Beckman, 1974)

$$Q_u = A_a F_R \left[S - \frac{A_r}{A_A} U_L (T_m - T_A) \right] \quad (2)$$

while the collector flow factor is given as:

$$= \frac{F_R}{F^1} = \frac{MC_0}{A_r u_L F^1}\left(1 - e^{-A_r U_L F^1 / MC_0}\right) \quad (3)$$

where

$$F^1 = \frac{U_0}{U_L} \quad (4)$$

and U_o the overall heat transfer coefficient based on the outside tube diameter for a tubular solar absorber) from the surrounding to the fluid is given as (Duffie and Beckman, 1974) =6.0 W/m^2 °C. U_L =7.0 W/m^2 (°C) (the thermal losses per unit area from absorber outer surface to the surrounding).

∴ F^1 = 6/7 = 0.857, Cȯ- The specific heat capacity of the engine oil was estimated by method of mixtures to be 2.263x10^3 Jkg^{-1}K^{-1}.

M-mass of working fluid following per second

Aa = Effective aperture area of the collector for this research work = .814219m^2

Ar = Recover effective area = 0.0795639m^2

$$S = H_b R_b \rho\tau\alpha \quad (5)$$

Where $H_b R_b$ represent the total solar radiation falling on an horizontal surface, ρ - represent specular reflectance of the reflector surface = 0.88. τ - transmittance coefficient (When the glass cover is present) and α-absorptance coefficient of the receiver =0.98 hence τα = 0.98 (since there is no glass cover) Aa/Ar = concentration ratio = 9.82. The thermal efficiency η of the collector is express by the equation

$$\eta = \frac{Q_u}{H_b R_b A_a} \quad (6)$$

thus the thermal efficiency calculated using the above equations was given as η =0.662=66.2%. Other calculated values of the heat energy gained by the solar collector and the overall efficiency for days 5, 6 and 7 are shown in Tables 1,2, and 3. These values of thermal efficiency calculated agrees with the thermal efficiencies recommended for these categories of solar collectors, which should be greater than 50% (Ren *et al'* 1997).

Conclusion

The thermal efficiency and overall heat energy gained by the solar concentrator calculated using Hottel-whillier-Bliss equation for non-static conditions of the working fluid shows that the solar concentrator, when equipped with a receiver of high concentration ratio can be used to achieve a high temperature applications such as refrigeration and air conditioning purposes, where high temperature of the working fluid is required. Also concentrator with wider aperture area, equipped with electronic sun tracking devices for constant trapping of the sun energy can be used to heat water to generate steam to drive turbine, in generating electricity.

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