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Analysis of Locally Fabricated Parabolic Trough Solar Concentrator System at Obafeni Awolowo University, Ile-Ife, Nigeria Region for Thermal Energy Applications

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ABSTRACT

Performance evaluation of a Parabolic Trough Solar Collector (PTSC) efficiently utilized for water heating in a natural climate condition was investigated in the present work. The fabrication and design of (PTSC) were done with a combination of reflector surface, reflector support, absorber pipe and wooden stand. The absorber pipe painted black while the trough manually operated. The flow of water in the system follows the recycling process repeated during data acquisition between 10.30 to 16.00 h. The collector design parameters are; focal distance of 0.115 m, width of 0.56 m, 2.44 m length of the collector and collector depth of 0.110 m. The parametric study of the PTSC was investigated based on the effect of variation of mass flow rate of water by using equation m=v/t, solar intensity was measured using general solar power meter DBTU1300 and water inlet and outlet temperature by using a thermometer. The temperature of water in the storage tank increased from 30 °C at 10.30 h to 65 °C at 16.00 h. The total heat gain by the coated metallic receiver found to be 772.8 W and the most heat losses occur through storage tank. The average thermal efficiency of the collector is approximately 30%. The total radiation during the collection ranges between 561 and 721 W/m^2. The results of the performance of collector showed that the maximum outlet water temperature attained was 72 ^{o}C that is acceptable for pasteurization of water. This show that fabricated PTSC is suitable for hot water processing. The useful heat gain and the collector efficiency found to follow the variation of incident beam radiation, which is strongly influenced by the incident beam radiation. The value of each parameter observed is higher around noon, when the incident beam radiation is at maximum.
Keywords: *Absorber pipe, Efficiency, Parabolic trough collector, Reflector surface and Storage tank.*

1. Introduction

Solar energy is one of the most promising renewable energies for applications in thermal energy generation in sea water, ground water and rain water. PTSC is employed for a variety of applications such as power generation [1], industrial steam generation [2] and hot water Production [3]. Parabolic Trough Collector (PTC) is preferred for steam generation because high temperatures can be obtained without any serious degradation of the collector's efficiency [4]. Solar thermal power plants based on PTC are presently the one of the successful solar technologies for electricity generation, as shown by the Solar Electric Generating Systems (SEGS) plant at Kramer Junction in California, USA [5]. A feasibility study of the use of PTC in a hotel for hot water production was reported [3]. It was shown that PTC could be more cost effective than the conventional flat plate collectors. Design and simulation analysis of a PTC hot water generation system has been made by [6]. The simulation analysis was in agreement with the test results reported by [7]. The present work focuses on the performance study of a locally fabricated PTSC hot water generation.

2.0 Materials and Methods of the study

A parabolic trough solar collector model was developed and installed in an open field near Chemical Engineering Department, Obafemi Awolowo University, Ile-Ife. The designed consists of a wooden support frame, galvanized sheet, reflector sheet, solar radiation absorbing system (stainless pipe), and driving system.

2.1 Trough Dimension

The simple parabolic equations were adopted in collector design. The reflector is designed to set the focal length *(f)* 0.11479 m from the vertex (V), the aperture width of the system (*W*) is 0.56 m. The Cartesian equation of the designed system was based on equations (1) below [8].

$$x^2 = 4fy \quad (1)$$

From equation (1), the height of the parabola in terms of the focal length and aperture diameter was calculated from the equation (2) below.

$$h_c = \frac{w^2}{16f} \quad (2)$$

While the rim angle ψ_{rim} is given by equation (3);

$$Tan\frac{\psi rim}{2} = \frac{w}{4f} \quad (3)$$

A geometrical relation of the parabolic section from equation (1), the cross section for the parabolic trough was traced as shown in fig. (1). The sheet was curved to form a parabolic trough module of 2.44 m length and 0.56 m aperture width with effective aperture area of 1.37 m^2.

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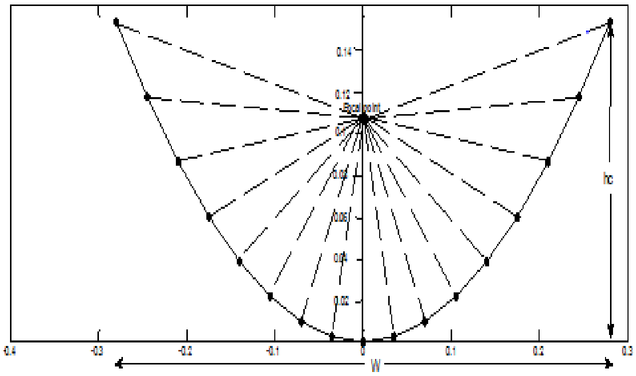

Fig. 1: Geometric Dimensions of the Trough

The values of the aperture area, curve surface area, the focal length, height of the parabola, the aperture width, the receiver outside diameter and the length of the concentrator were calculated using equation (1) and (3). The collector height h_c is almost equivalent to the focal length f. The specifications of the fabricated system are given in table (1) below.

Table 1: Parabolic Trough Collector System Specifications

Parameter	Sample	Value
Length (m)	L	2.4
Aperture area (m^2)	A_a	1.49
Curve area (m^2)	A_s	1.3655
Focal length (m)	f	0.11479
Receiver diameter (mm)	d	19
Width (m)	W	0.61
Height (m)	h_c	0.110

From the solar constant first introduced by the French scientist Pouillet in 1837 [9] and current accepted value from [10] is said to be 1353 W/m^2 and the mean earth sun distance is 1.496 x 10^{11} m respectively [11].

Extraterrestial solar radiation I_o is calculated with equiation (5) below;

$$I_o = I_{sc}\left[\frac{D_m}{D_{e-s}}\right]^2 \quad (5)$$

Where D_{e-s} is the distance between the earth and the sun. The value of I_o for a given day of the year is approximated by empirical equation in (6) [9];

$$I_o = I_{sc}\left[1 + 0.034\cos\left(\frac{360 d_n}{365.25}\right)\right] \quad (6)$$

The beam radiation, I_b is the solar radiation on a surface that has passed through the atmosphere without being appreciable scattered [9]. And is calculated with equation (7) below;

$$I_b = I_o\left[a_o + a_1 e^{-(kAM)}\right] \quad (7)$$

The diffused solar irradiance, I_d is the solar radiation that reaches the surface after being significantly scattered by the atmosphere on a horizontal surface may be calculated by using the following equation (8) [12].

$$I_d = I_o \cos\theta_z\left[0.2710 - 0.2939\left(a_o + a_1 e^{-(kAM)}\right)\right] \quad (8)$$

2.2 Thermal Efficiency of a Parabolic Trough Solar Collector

The instantaneous thermal efficiency η_{th} of a solar concentrator was calculated from an energy balance on the receiver. The useful heat gain is related to the flow rate and can be defined on the base of fluid difference temperature as shown in equation (9) [13];

$$Q_u = mc_p(T_{out} - T_{in}) \quad (9)$$

Where T_{out}, and T_{in} represent the inlet fluid and outlet fluid temperature respectively.

The thermal efficiency of the solar thermal collector simplified and defined as the ratio of useful heat Q_u, delivered per Area A_a, and the isolation I_b, which is incident on the aperture as seen from equation (10);

$$\eta_{th} = \frac{Q_u}{A_a I_b} \quad (10)$$

The thermal efficiency depends upon two types of quantities namely the concentrator design parameters and the parameters characterizing the operating conditions. The exit fluid temperature, T_{out} the temperature rise, ($T_{out} - T_{in}$) and the efficiency can be calculated using equation (11) [13].

$$\eta_{th} = \frac{mc_p(T_{out} - T_{in})}{A_a \cdot I_b} \quad (11)$$

2.3 Principle of Operation

The experimental setup used for testing the PTSC consists of the constructed collector, 25liters storage tank and throttling valve. The principle adopted in the construction was parabolic reflecting surface, which takes the advantage of all parallel rays of light from the sun that incident on a parabolic shaped mirror and converge after reflection to a point focus. The storage tank is fixed above the receiver's pipe level to allow the heating fluid to flow naturally without pumping system. The storage tank is filled with water from the main supply through an open flow system. The natural force (gravitational) is used to circulate water from the collecting tank through the absorber tube of the solar collector back to the collecting tank. The water temperatures at the inlet and outlet of the absorber tube, ambient temperature, mass flow rate, and solar radiation intensity are continuously measured during the experiment during the process. The testing area and experiment was set as shown in Fig. (2). The solar tracking was manually operated at interval to continuously position of the reflector toward sun. As the sun position change hourly, the solar device is adjusted to produce the maximum output.

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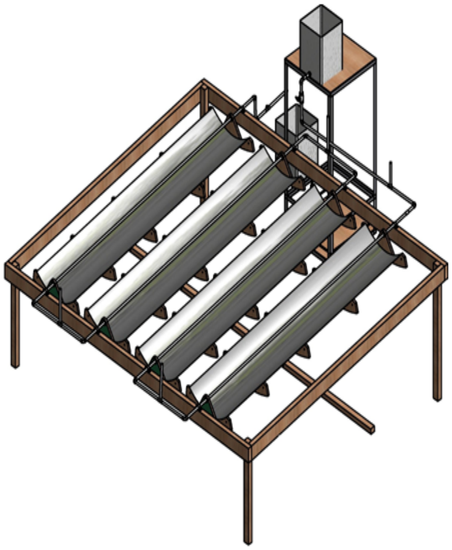

Fig. 2: Schematic Diagram of the Experimental Setup

2.4 Measuring Instruments

The fabricated PTSC system consists of, (a) PTC with tracking system; (b) Storage tank; (c) Throttle valve. The data was collected with the fabricated system between the months of January and February 2014 as representation for summer weather. The parameters listed below were measured during data collection.

(a) Water inlet temperature to the absorber T_i; Water outlet temperature from the absorber T_o; and ambient temperature T_{amb} by using thermometer

(b) Water mass flow rate m by using equation, m = $\frac{V}{t}$, where V is the volume of the water in a container and t is the time taking to run out of the system while;

(c) Solar intensity $I_{intensity}$ was measured using solar meter.

3.0 Results and Discussion

3.1 Performance Analysis of PTSC

An increase in outlet Heat Transfer Fluid (HTF) temperature was noticed during early hour of the day until it reaches maximum value around mid noon when total solar radiation value is the highest. The experiment was conducted from 10:30 am to 4:00 pm with a total solar radiation in the range of 563 W/m^2 to 723 W/m^2 and ambient temperature in the range of 29 to 32^{o}C. After that, outlet HTF temperature inside the receiver reached 72 ^{o}C in highest sun radiation where the maximum registered ambient temperature was 32.5^{o}C as shown in Table (2). It was noticed that the HTF temperature inside the receiver increasing with respect to increase in ambient temperature until when the solar radiation intensity is at highest. The rising is proportional to that of incident solar radiation until solar noon when the temperature of storage tank leaves the storage to the inlet of the receiver. The big difference in performance is due to using special black paint receiver.

No. Of day = 39 L = 7.4667° d_a = -15.5153° I_o = 1393.138 W/m^2 Flow rate = 0.023 kg/s

TABLE B-11: Experimental data for coated metallic receiver during 8th February, 2014 (point 4).

Time (hr)	T_{in} (°C)	T_{out} (°C)	T_{amb} (°C)	α_s (degree)	θ_z (degree)	I_b (W/m^2)	I_d (W/m^2)	I_{total} (W/m^2)	I_{sc} (W/m^2)	Q_u (W)	η_{th} (%)
10:30	46	50	29.3	55.84874	34.15126	505.5589	189.4751	695.034	1367	386.4	20.31193
11:00	51	56	29.9	62.63212	27.36788	510.1557	202.1306	712.2862	1367	483	25.38991
11:30	57	63	30.5	64.7734	25.2266	511.317	205.59	716.9071	1367	579.6	30.46789
12:00	57	64	30.9	67.01797	22.98203	512.4035	208.9318	721.3354	1367	676.2	35.54588
12:30	63	71	31.5	66.58955	23.41045	512.2061	208.3167	720.5228	1367	772.8	40.62386
13:00	65	72	32.5	62.63212	27.36788	510.1557	202.1306	712.2862	1367	676.2	35.54588
13:30	62	70	32.2	59.97735	30.02265	508.5326	197.4804	706.013	1367	772.8	40.62386
14:00	61	68	32	52.43193	37.56807	502.623	182.1618	684.7848	1367	676.2	35.54588
14:30	60	68	31.8	48.81606	41.18394	498.9639	173.7715	672.7354	1367	772.8	40.62386
15:00	59	65	31.7	39.85154	50.14846	486.6646	150.274	636.9386	1367	579.6	30.46789
15:30	57	63	31.4	35.85345	54.14655	479.1442	138.6502	617.7944	1367	579.6	30.46789
16:00	52	57	31	26.29118	63.70882	452.6825	108.2959	560.9784	1367	483	25.38991

3.2 Useful Heat Gain (Q_u)

The useful heat gain is calculated from the measurement of the inlet and outlet HTF temperature and mass flow rate. It is clear that the Q_u varies from 483 W to 773 W when the beam solar radiation varied from 452.68 W/m^2 to 512.40 W/m^2 as shown in Fig. (4).

3.3 The Instantaneous Thermal Efficiency

The collector efficiency of a coated metallic receiver is varied from 0.25 to 0.41 and when the beam solar radiation is varied from 452 to 512 W/m^2 as shown in Fig. (5). This variation is related to the improvement in receiver and decreasing of heat losses due to using a special black paint receiver.

Generally, it will be noted that the general pattern of variation of efficiency over day is the same as that of the useful heat gain because the value of efficiency depends on both the incident beam radiation and the useful heat gain.

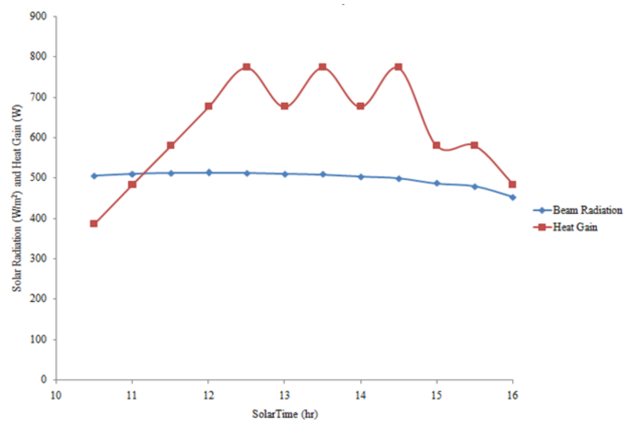

Fig. 4: Variation of beam radiation and heat gain with time for coated metallic receiver.

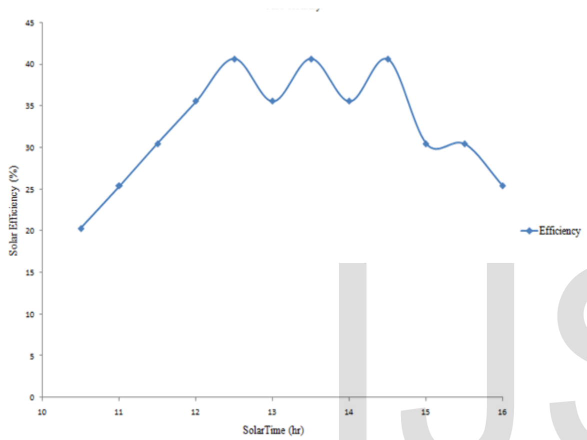

Fig. 5: Variation of Thermal Efficiency with Time

3.4 Comparison of the Results

Data was obtained from four set of thermal efficiency tests from coated metallic receiver as was demonstrated previously. It was noted clearly that the thermal efficiency of coated metallic receiver varied at interval indicated on the graph from 0.41 to 0.20 for point 1, 0.46 to 0.20 for point 2, 0.36 to 0.15 for point 3 and 0.41 to 0.20 for point 4 in 15thof February 2014 respectively when receiver temperature above the ambient temperature is varied from 29 to 32.5^{o}C.The thermal efficiency using coated metallic receiver increasing steadily. These results indicate a beneficial effect when the receiver is painted black.

4.0 CONCLUSIONS

The operating performance of the fabricated parabolic trough solar power plants has demonstrated it technology ability to be robust and excellent performer in the commercial power industry and efficiency analysis of the PTSC plant shows that solar thermal power can compete well with conventional fossil fuel and renewable energy power plants in the energy market. Practical results have shown that the maximum thermal efficiency of the mechanically controlled PTSC is 55% using coating metallic receiver. The coating metallic receiver is suitable for obtaining high temperature at the range of 60 and 100^{o}C. The uses of coating metallic receiver have shown that the collector can offer significant reductions in the overall system heat loss. The PTSC that has been fabricated is suitable for hot water because of the high temperature of storage reaches 72^{o}C with enhanced features such as economical thermal storage, utilizing standard industrial manufacturing processes, materials, power cycle equipment and the technology for rapid deployment is achievable at a low-cost solar power option.

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