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Design and Fabrication of Parabolic Trough Solar Water Heater for Hot Water Generation

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Abstract

Solar Energy is a renewable source of energy. Its uses do not contribute to emission of green house gases and other pollutants to the environment. It is sustainable since it cannot be depleted in a time relevant to the human race. In this paper, the potential for a solar- thermal system for hot water generation has been studied. A parabolic trough concentrator (PTSC) is made of an aluminium sheet which is covered by a cloth on which rectangular mirror strips (1.20mx 0.05m) are pasted. Two different absorber tubes were taken and the efficiencies of the PTSC where compared without glass cover on the absorber tubes. They were designed with principal focus at 0.3m so that the receiver heat loss was minimized.

Keyword: *Reflector, Absorber Tube, Reflector Support Structures, Water Container, Inlet Pipe, Outlet Pipe, Pump*

1. INTRODUCTION

Recent increase in energy demand and constraints in supply of energy becomes a priority for the different industry [1]. Very few research attempts have been done to estimate the significance of energy required for the different process. In this experimental study alternative use of solar energy has been studied. Solar energy is a high-temperature, high-exergy radiant energy source, with tremendous advantages over other alternative energy sources. It is a reliable, domestic, robust renewable resource with large undeveloped potential, and it emits essentially none of the atmospheric emissions that are of growing concern. The design and fabrication of parabolic trough solar water heater for water heating was executed. The procedure employed includes the design, construction and testing stages. The equipment which is made up of the reflector surface (curved mirror), reflector support, absorber pipe and a stand was fabricated using locally sourced materials. This work presents a reproducible parabolic trough solar water heater as a suitable renewable technology for reducing water-heating costs and solar water heating systems with optical concentrating technologies as important entrants for providing needed bulk solar energy [2]. Parabolic trough power plants are the only types of solar thermal power plant technology with existing commercial operating systems.

Parabolic- trough collectors ($PTCs$) are frequently employed for solar steam- generation because temperatures of about 300 $^{\circ}C$ can be obtained without any serious degradation in the collector's efficiency. The incident solar-radiation falling on the collector is utilized for pipe heating. Inside the pipe, the thermal fluid flows and its temperature increases due to the incoming radiation. A vacuum was created around the pipe and a thermal insolent was placed at its rear. The developed simulation program calculates the outlet fluid temperature and shows the efficiency of the proposed parabolic trough collector as a function of the outlet temperature, the pipe diameter, the intensity of the incoming solar radiation and the active diameter of the parabolic collector.

In spite of efforts to promote and develop renewable sources of energy and other new sources, fossil fuels (coal, oil & natural gas) continue to dominate the energy scene [3]. While the need for alternative sources of energy is recognized, no set of alternatives has emerged which can take over the role played by fossil fuel. In India the energy problem is very serious. In spite of discoveries of oil and gas off the west coast, the import of crude oil continues to increase and the price paid for it now dominates all other expenditure. One of the promising options is to make more extensive use of renewable sources of energy derived from the sun. Solar energy can be used both directly and indirectly. It can be used directly in a variety of thermal applications like heating water of air, drying, distillation, and cooking.

2. DESCRIPTION OF PARABOLIC TROUGH CONCENTRATOR

A parabolic trough concentrator consists of a reflecting surface mounted on a reflector support structure having the profile of a parabola. A receiver assembly comprising a circular absorber tube with suitable selective coating and enclosed in a concentric glass envelope is centered along the reflector focal line. Maintain focusing of solar radiation on the receiver assembly. The incident energy is absorbed by a working fluid circulating through the absorber tube.

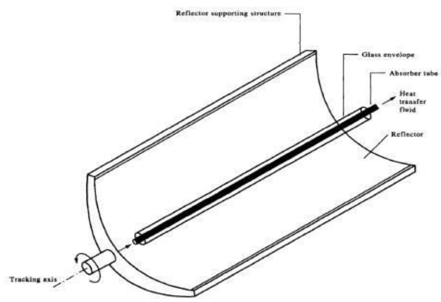

Fig. 1 Parabolic trough concentrator.

3. METHODOLOGY

For this research, a different integrated approach are used, different theory are integrated by experimental study.

3.1 DESIGN PARAMETERS

The design parameter of a parabolic trough collector can be classified as geometric and functional. The geometric parameters of a PTC are its aperture width and length, rim angle, focal length, diameter of the receiver diameter of the glass envelope and the concentration ratio.

The functional parameters of a PTC are optical efficiency, instantaneous and all day thermal efficiency and receiver thermal losses. These parameters are largely influenced by the absorptive of the absorber [4,5].

3.1 DESIGN ANALYSIS

The instantaneous efficiency of a PTC (η_i) can be calculated from an energy balance on the receiver tube. The instantaneous efficiency is defined as the rate at which useful energy is delivered to the working fluid per unit aperture area (q_u) divided by the beam solar flux (at the collector aperture plane

$$\eta_i = \frac{q_u}{I_b} = F_R \eta_0 - \frac{F_R A_C U_C (T_i - T_a)}{A I_b} \quad (4.1)$$

Where, F_R = Heat removal factor, η_0 = Optical efficiency, U_C = Heat loss coefficient, A_C = Absorber area, A = Aperture area, T_i = Inlet fluid temperature.

In equation (1.1) , F_R , U_C and η_o can be identified as the three major design parameters which can be used to construct a three-parameter collector model for the preliminary design of PTC.

3.2 OPTICAL ANALYSIS

The optical efficiency η_o can be expressed as

$$\eta_o = \rho(\tau\alpha)_{eff} \gamma_\theta \cos\theta \quad (4.2)$$

Where

ρ = average specular reflectance of the reflective surface

$(\tau\alpha)_{eff}$ = effective transmittance-absorptance factor

θ = angle of the incidence of the sun's rays on the collector aperture measured from the normal to the collector

γ_θ = instantaneous intercept factor (defined as the fraction of rays incident upon the aperture that reach the receiver for a given incidence θ)

The optical efficiency, η_o, given by equation (4.2), varies with angle of incidence between the aperture surface normal and the incoming radiation.

3.3 THERMAL ANALYSIS

The primary function of the receiver subsystem of a PTC is to absorb and transfer the concentrated energy to the fluid flowing through it [6]. The knowledge of heat loss from the receiver is important for predicting the performance and, hence, designing PTC_s .

The cross-section of the receiver subsystem is shown in Fig.2. As shown, three different heat exchangers exist between the components of the receiver.

These are:

(1) Heat transfer from the absorber tube to the working fluid.

(2)Heat transfer between the absorber tube and the glass jacket (glassing).

(3)Heat exchange between the glass jacket and the surroundings.

Since PTC will be optimized based on instantaneous or all-day efficiency, a steady-state thermal analysis of the receiver will sufficient for design studies.

Then, the total heat loss from the collector module can be calculated by:

$$q_{0-L} = \int_0^L U_{loss}(x) \left[T_{glass}(x) - T_a\right] dx \quad (4.3)$$

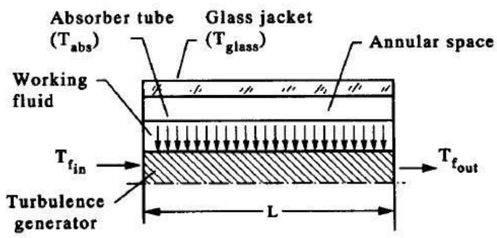

Fig.2 Two-dimensional energy exchange to the working fluid.

Where $U_{loss}(x)$ is the heat transfer coefficient for combined convection and radiation heat losses from the outer surface of the glass jacket.

3.4 MIRROR MATERIALS

In solar energy applications, back silvered glass plates, anodized aluminum sheets and aluminized plastics films serve as reflectors. Of the various commercially available reflector materials, Corning 0317 glass 1.5 mm thick, having evaporated silver coating, is the best reflector, since its reflectivity is high at all acceptance angles. The composite glass mirror having reflectivity of the order of 92% in the solar spectrum has been used in several industrial process heat systems.

3.5 DIFFERENT SOLAR POWER TECHNOLOGIES

Solar power technology has been great advances over the past decade. Both photovoltaic (PV) and concentrating solar power (CSP) technologies now constitute feasible commercial options for large scale power plants as well as for smaller electricity and heat generating devices. The principle of CSP (also referred to as solar thermal power), on the other hand, is the use of heat generated by direct solar radiation concentrated onto a small area with the purpose of producing electricity. There are currently four basic commercially available CSP technologies. From the available CSP technologies, parabolic trough is the most widespread today, with around 29 plants in operation and around 1220 MW_e of installed power in the world, corresponding to 96.3% of the total operational concentrating solar power as the beginning of 2011.

4 CONCENTRATING COLLECTORS EXHIBIT CERTAIN ADVANTAGES AS COMPARED WITH THE CONVENTIONAL FLAT-PLATE TYPE

The main ones are:

(1) The working fluid can achieve higher temperature in a concentrator system when compared with a flat-plate system of the same solar-energy collecting surface area. This means that a higher thermodynamic efficiency can be achieved.

(2) It is possible with a concentrator system to achieve a thermodynamic between temperature level and task.

(3) The thermal efficiency is greater because of the smaller heat-loss area relative to the receiver area.

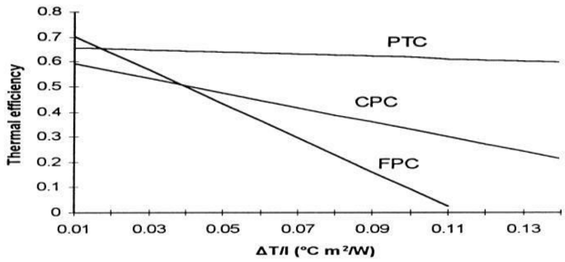

Fig.3 Variation of efficiency with ratio of temperature difference and solar intensity.

This Fig. shows that the efficiency in the PTC_s remains high at high inlet-water temperatures. Therefore, at a temperature of 100$^{\circ}C$, which occurs at a $\Delta T/I$ value of about 0.1, CPC_s work at an efficiency of about 62%, FPC_s at about 32% and the FPC at about 10%. This clearly suggests that the PTC is the best type of collector for this application.

5 FABRICATION OF SOLAR CONCENTRATOR TROUGH

Carefully prepared aluminum sheet 0.635 cm (1/4in.) thick, were shaped consistent with the equation,

$$Y = \frac{x^2}{4f} \qquad (6.1)$$

Where in this case f = 0.30m. An aluminum sheet of aperture width 1.2m was bent into parabola with a focus at 0.3m using the formula the common equation for plotting parabola.

The paint coat was kept as thin as possible so that there was minimum resistance of flow of heat through the coat through the pipe and to the heat transfer fluid. The collector was covered with a 0.001m thick glass cover.

The fabricated collector parameters were:

Aperture area = 1.387
Collector area = 1.44 m^2
Aperture width = 1.2m
Focal length = 0.3m
Collector length = 1.2m
Outer diameter of absorber pipe = 0.0325m
Inner diameter of absorber pipe = 0.0315m
Concentration ratio = 11.3

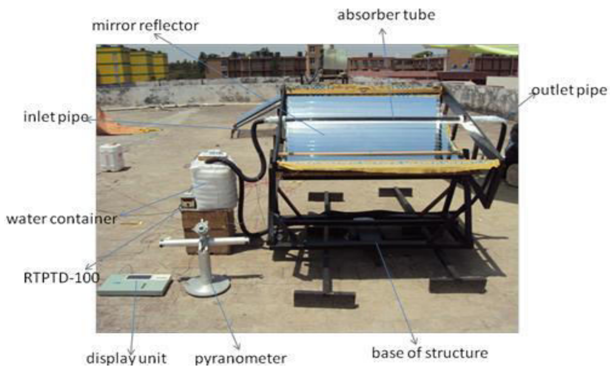

Fig.4 Fabricated parabolic trough solar concentrator for hot water generation.

5.1 MEASURING DEVICES AND INSTRUMENTS:

Measurement Of Solar Intensity

Solar radiation flux is usually measured with the help of a pyranometer. A pyranometer is an instrument which measures either global or diffuse radiation falling on a horizontal surface over a hemispherical field of view [7,8].

Fig.5 Solar intensity measurement: Pyranometer

Measurement Of Temperature

For measurement of temperature we used RTPTD-100.

Fig. 6 Temperature measurement device: RTPTD-100.

5.2 TRACKING SYSTEM OF SOLAR CONCENTRATOR TROUGH:

Fig.3.4 shows the manual tracking system of solar concentrator trough in which we track the concentrator from E to W direction by 10° in every 30 minutes interval [9].

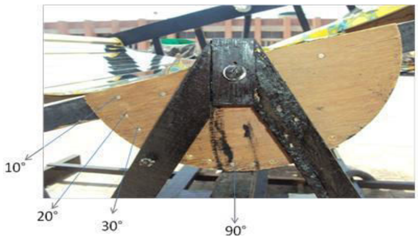

Fig.7 Manual tracking system of solar concentrator trough.

6 ANALYSIS OF EXPERIMENTAL DATA:

The useful energy collected per unit time in a solar collector system employing solar concentrators may be written as [10,11] :

$$Q_u = A_a F_R \left[\eta_o I_c - \frac{U_L(T_i - T_a)}{c}\right] \quad (7.1)$$

It can also be expressed as

$$Q_u = mC_p(T_o - T_i) \quad (7.2)$$

The heat removal factor is given by

$$F_R = \frac{mC_p}{A_r U_L}\left[1 - \exp\left(-A_r U_L F' / m C_p\right)\right] \quad (7.3)$$

From equations (7.1)-(7.3),

$$mC_p(T_o - T_i) = \frac{A_a m C_p}{A_r U_L} \times \left[1 - \exp\left(-A_r U_L F' / \dot{m} C_p\right)\right] \times \left[\eta_o I_c - \frac{U_L(T_i - T_a)}{c}\right] \quad (7.4)$$

Which may be solved to give

$$T_o = T_a + \frac{C\eta_o I_c}{U_L} + \left(T_i - T_a - \frac{C\eta_o I_c}{U_L}\right) \times \exp\left(-F' U_L A_r / \dot{m} C_p\right) \quad (7.5)$$

The efficiency of the concentrating solar collector may now be calculated as

$$\eta_c = \frac{mC_p(T_o - T_i)}{I_c A_a} \quad (7.6)$$

Whereas, using equation (7.6),

$$\eta_c = F_R\left[\eta_o - \frac{U_L}{CI_c}(T_i - T_a)\right] \quad (7.7)$$

When thre is no flow of fluid (i.e. efficiency is zero), the stagnation temperature of the absorber may be written, using equation (7.7), as

$$T_{st} = T_a + \frac{\eta_o C I_c}{U_L} \quad (7.8)$$

In order to calculate T_o, η_c and T_{st} on the basis of the equations (7.6)-(7.8), it is necessary to have an appropriate expression for the heat loss coefficient U_L. When U_L is known, the outlet temperature, efficiency and stagnation temperature of the collector can be calculated.

7 RESULTS AND DISCUSSION

A cylindrical parabolic collector located in Kurukshetra operating in tracking mode (III) is used for heating water. The concentrator has an aperture of 1.20m and a length of 1.20m, while the absorber tube (3.15cm inner and 3.25cm outer diameter). Values of other design parameters of the collector are as follows:

Specular reflectivity of the concentrator surface = 0.94

Glass cover transmittivity for solar radiation = 0.88

Absorber tube emissivity/absorptivity = 0.96

Intercept factor = 0.95

Values of the operational and metrological parameters are as follows:

Date = 15 April

Time = 1230 h (LAT)

I_b = 705W/m^2

Ambient temperature = 31.9 °C

Mass flow rate of water = 0.09kg/s

°C

Inlet temperature = 60

Calculate:

(1) The absorbed flux S.

(2) The convective heat transfer coefficient on the inside surface of absorber tube.

(3) The collector heat removal factor and overall loss coefficient.

(4) The exit temp. of thermic fluid.

(5) The instantaneous efficiency.

(7.1) Absorbed flux S:

$$S = I_b r_b \rho \gamma (\tau\alpha)_b + I_b r_b (\tau\alpha)_b \left(\frac{D_o}{W-D_o}\right) \quad (8.1)$$

So (here r_b=1)

S = 705 $\times \left[0.94 \times 0.95 \times 0.88 \times 0.96 + \frac{0.88 \times 0.96 \times 0.0315}{(1.20-0.0315)}\right]$

= 548.42W/m^2 **Ans.**

(7.2) Convective heat transfer coefficient:

Properties will be taken at a mean fluid temp. of 60°C.

$$V_{av} = \frac{m}{\frac{\pi}{4}{D_i}^2 \rho} = \frac{0.09}{\frac{\pi}{4} \times 0.0315^2 \times 1000} = 0.1155 \text{m/s}$$

Renolds number $R_e = \frac{V D_i}{v} = \frac{0.1155 \times 0.0315}{0.475 \times 10^{-6}} = 7659$

Prandtl number $P_r = \frac{c_p v \rho}{k} = \frac{4.2 \times 0.0475 \times 10^{-6} \times 1000 \times 10^3}{...}$ =3.44

Nusselt number $N_u = 0.023 \times R_e^{0.8} \times P_r^{n}$ (8.2)

$= 0.023 \times 7659^{0.8} \times 3.44^{0.4}$

= 48.27

(where n= 0.4 for heating)

Therefore

$$h_f = N_u \times \frac{k}{D_i} \quad (8.3)$$

$= 48.27 \times \frac{0.58}{0.0315}$ = 888.8W/m^2K **Ans.**

(7.3) Collector heat removal factor and Overall loss coefficient:

Assume U_l = 12.82W/m^2K , so the collection efficiency factor

$$F' = \frac{1}{U_l\left[\frac{1}{U_l} + \frac{D_o}{D_i h_f}\right]} = 0.98 \quad (8.4)$$

So $\frac{m c_p}{\pi D_o U_l L} = \frac{0.09 \times 4.2 \times 10^3}{\pi \times 0.0315 \times 13.28 \times 1.20}$ =232.32

Therefore, heat removal factor

$$F_R = \frac{m c_p}{\pi D_o U_l L}\left[1 - \exp\left(-\frac{F' \pi D_o U_l L}{m c_p}\right)\right] = 0.9293$$

Ans. (8.5)

Here concentration ratio (C) is calculated by the following method:

$$C = \frac{Aperture\ area}{Receiver\ area} = \frac{(W-d_{co})\times L}{\pi D_o L} \quad (8.6)$$

(where d_{co} is the outer dia. of glass cover)

$= \frac{W-d_{co}}{\pi D_o}$ =11.32

The useful heat gain rate (q_u) is calculated by the following method:

$q_u = F_R (W-D_o)L\left[S - \frac{U_l}{C}(T_{fi} - T_a)\right]$ = 672.6W (8.7)

Therefore rate of heat loss = (W-d_{co})LS-(8.8) q_u

= (1.20-0.044)$\times 1.20 \times 548.42 - 672.6$

= 88.17W

(7.4) Exit Temperature:

Equating the heat gained by the fluid to the useful heat gain rate, we get

$0.09 \times 4.2 \times (T_{fo} - 60) = \frac{672.6}{1000}$

T_{fo} = 61.78 °C **Ans.**

(7.5) Instantaneous Efficiency:

$$\eta_{ib} = \frac{q_u}{I_b r_b W L} \quad (8.9)$$

$= \frac{672.6}{705 \times 1.2 \times 1.2}$ (R_b=1)

= 0.663 **Ans.**

(7.6) Optical efficiency:

$$\eta_o = \frac{I_b r_b \rho \gamma (\tau\alpha)_b (W-d_{co})L + I_b r_b (\tau\alpha)_b d_{co} L}{I_b r_b W L} \quad (8.10)$$

$$= I_b r_b \rho \gamma (\tau\alpha)_b \frac{(W-d_{co})}{W} + (\tau\alpha)_b \frac{d_{co}}{W}$$

$$= \times 0.95 \times 0.88 \times 0.96 \times \frac{(1.30-0.044)}{1.30} + 0.88 \times 0.96 \times 0.94 \frac{0.044}{1.30}$$

= 0.758.

(7.7)Discussion of Results:

In order to have a numerical application of the results, we consider the parameters of the concentrating collector as follows:

Area of the absorber of the collector

A_c) = 0.166m^2

Overall heat loss coefficient from the absorber

U_L) = 12.82W $K^{-1} m^{-2}$

Reflectivity of the reflective surface

ρ) = 0.94

Absorptivity of the absorber

α) = 0.96

Emissivity of the absorber

(ε) = 0.96

Stefan-Boltzmann constant

(σ) = 5.67$\times 10^{-8}$ W$m^{-2} K^{-4}$

Efficiency factor of the absorber

(F') = 0.98

The concentration ratio of the collector (C) in the range 20-100 and mass flow rate of the fluid (m) in the range 0.01-1.0 gs^{-1}. The hourly solar radiation (I_s) in Wm^{-2} and corresponding ambient temperature(T_a) used in this study are taken from measuring instrument.

8 Aluminum Tube without Glass Cover (13April 2012):

(8.1) Variation of Solar Intensity and Temperature with Time: Table (1) gives the following results:

Table: 1

Time(hours)	Solar intensity (W/m^2)	Temperature (°C)
8:00	500	24
9:00	557	30
10:00	595	42
11:00	642	52
12:00	692	61
13:00	752	69
14:00	732	64
15:00	614	58
16:00	511	53

Fig. 8 shows the variations of solar intensity and outlet temperature of water with time.

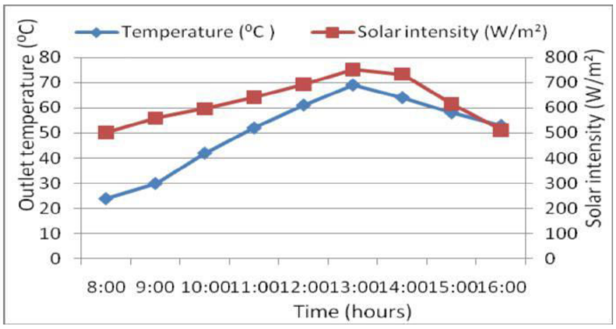

Fig. 8 Variation of solar intensity and temperature with time in case of Al tube without glass cover.

This graph shows that outlet temperature of water increases as the solar intensity increases till 13:00 hr. The maximum temperature difference between inlet and outlet water temperature is 12°C between 9:00 to 10:00 hr. This means that the maximum useful heat gain rate occurs in this region. The minimum temperature difference is 6°C between 8:00 to 9:00 hours. The maximum temperature is obtained at 13:00 hr and its value is 69°C. The maximum solar intensity is also obtained at 13:00 hr and its value is 752 W/m^2. The steady state is obtained at 13:00 hour; it means that after this time the outlet temperature decreases continuously till 16:00 hr.

Taking, mass of water (m_w) =15kg, specific heat of water (c_{pw}) = 4.2KJ/kg-K

Time duration (t) =5 hours (8am-1pm), A_a = aperture area = 1.387m^2.

Efficiency η = $\frac{m_w c_{pw}(T_{out}-T_{in})}{I \times A_a \times t}$

$= \frac{15 \times 4.2 \times 10^3 (69-24)}{623 \times 1.387 \times 5 \times 60 \times 60}$

= 0.1823 = 18.23%

(8.2) Efficiency Vs Time Graph: Here efficiency is calculated for one hour. We assume that the

(Time hours)	Efficiency(η)
9:00	0.1432
10:00	0.2628
11:00	0.2042
12:00	0.1702
13:00	0.1398

efficiency is zero at 8:00 hr. Efficiency at 9:00 hr is given by,

$$\text{Efficiency } \eta = \frac{15\times4.2\times10^{3}(30-24)}{528.5\times1.387\times3\times1\times60\times60}$$

$$= 0.1432 = 14.32\%$$

Similarly we have calculated the efficiency at 10:00, 11:00, 12:00, and 13:00hr.

Table (2) gives the following results:

Fig. 9 shows the variation of efficiency with time.

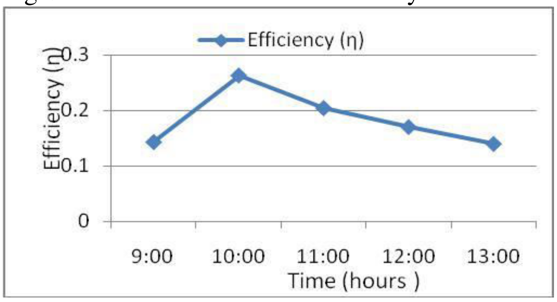

Fig 9 Variation of efficiency with time in the case of Al tube without glass covers.

This graph shows that the efficiency increases as time increases till 10:00 hr and after that it decreases till 13:00 hr. The maximum efficiency is obtained at 10:00 hr and its value is 0.2628. The minimum is obtained at 13:00 hr and its value is 0.1398

9 Copper Tube without Glass Cover (15 April 2012):

(9.1) Variation of Solar Intensity And Temperature With Time: Table (3) gives the following results.

Table: 2

Time(hours)	Solar intensity (W/m^2)	Temperature (°C)
8:00	510	24
9:00	562	32
10:00	598	44
11:00	664	54
12:00	712	66
13:00	768	75
14:00	705	69
15:00	632	64
16:00	572	57

Table: 3

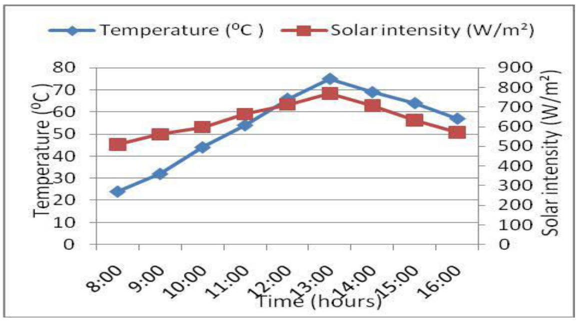

Fig. 10 shows the variation of temperature and solar intensity with time.

$$\text{Efficiency } \eta = \frac{15\times4.2\times10^{3}(75-24)}{635.6\times1.387\times3\times60\times60} = 0.2025$$

$= 20.25\%$

(10.2) Efficiency Vs Time Graph: Table (4) gives the following results.

Table: 4

Time	**Efficiency**(η)
9:00	0.1883
10:00	0.2610
11:00	0.1999
12:00	0.2201
13:00	0.1534

Fig. 11Variation of efficiency with time in case of Cu tube without glass cover.

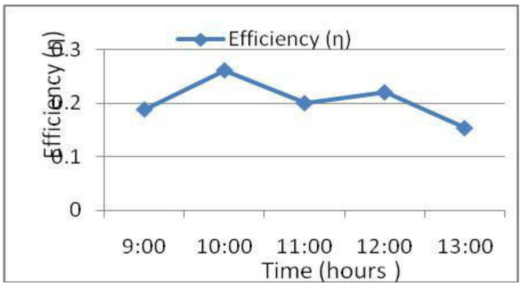

Fig. 11 Variation of efficiency with time in case of Cu tube without glass cover.

This graph shows that the efficiency increases as time increases till 10:00 hr and after that it decreases till 11:00 hr. The efficiency is again increases till 12:00 hr and after that it decreases till 13:00 hr. The maximum efficiency is obtained at 10:00 hr and its value is 0.2610. The minimum efficiency is obtained at 13:00 hr and its value is 0.1534.

10 CONCLUSIONS

In this paper, a study was made to enhance Kenyan research in solar thermal for heat water generation by use of appropriate materials. The efficiencies for the PTSC were as follows: when without glass cover: aluminum tube receiver: 18.23%, copper tube receiver 20.25%. The efficiencies observed for parabolic trough concentrator demonstrates that this technology with appropriate absorber tube systems can produce hot water that is hot enough for solar thermal conversion power systems. This can be achieved by use automatic tracking system and smoother reflecting surfaces. In this case higher temperatures and higher efficiencies would be realized. On the other hand use of aluminum tube receiver, led to low absorptive resulting to low operating efficiency of the concentrating collector.

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