A Study to Evaluate Heat Loss Phenomenon in A Flat Plate Solar Collector System

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Abstract- The constant supply of energy for various activities has become a major challenge in recent years. One of the cheapest and most sustainable avenues to generate and ensure constant energy supply is using a flat plate solar collector system. This study focuses on evaluating the heat loss phenomenon of flat plate solar collector systems. The designed flat plate collector was exposed to radiation to determine the parameter of heat loss within the system. Several tests were carried out on the collector system for about 30 days with temperature measurements. The main objective of this research was to investigate the system's parameters, including the heat loss at the top, bottom, and edges. System design and operation of the locally produced flat plate solar collector system are described, and the absorber plate area of the collector system has been calculated. Experimental results and simulations provided average total heat loss coefficient values ranging from 3.146 W/m2K to 4.697 W/m2k from day 1 to day 30. The determination of the heat loss coefficient led to the computation of the heat loss and hence the useful heat, vis-à-vis, the collector efficiency, and performance. The useful heat value is 20 kw/m2; the collector has a highest efficiency of 61 % at the lowest heat loss coefficient, and a lowest efficiency of 26 % at the highest heat loss coefficient.

Indexed Terms- Energy, Flat Plate Solar Collector, Useful Heat, Irradiation, Insolation.

I. INTRODUCTION

The sun's energy is discharged directly to the earth. It is an abundant, sustainable, and pollution-free resource [1]. Nigeria is located in a tropical area of the world with massive sunlight intensity endowed with significant renewable energy resources for which adequate conversion technologies are available to produce heat for various engineering applications[2]. The total landmass of Nigeria is blessed with abundant solar energy throughout the year, with the global radiation ranging between 12 MJ/m^2 and 24 MJ/m^2 a day across the country from the southern Atlantic end to the northern Sahelian end [3]. The solar energy available for conversion is more significant than all current world requirements by several orders of magnitude [4]. Solar collectors can be considered as the best and most efficient system for collecting and storing solar energy. The abundant solar radiation in the tropical and subtropical regions is suitable for many purposes such as domestic water heating, solar cooking, water pumping, electricity for lighting, drying of agricultural products, and solar power, to mention a few. It is environmentally friendly, renewable, and universally abundant [5].

A flat plate solar collector is the simplest and most widely used means to convert radiation from the sun into useful heat. Solar radiation passes through the transparent cover plates and strikes the collector absorber surface, where the heat is absorbed. Determining the heat loss co-efficient U_t can lead to the computation of the total heat loss and hence the useful heat flow vis-à-vis the collector efficiency and thus the collector performance. The flat plate collector was tilted at 22.5^{0}C to collect irradiation that capable of raising water temperature from 20 to 60 Celsius.

II. THEORY OF FLAT PLATE SOLAR COLLECTOR

A flat plate solar collector system is usually a metallic absorber plate with good thermal conductivity with closely spaced water channels. The box is painted black on top to absorb the sun's energy or is provided with a particular blackened surface that absorbs solar radiation. Fig. 1 shows a typical sketch of a flat plate solar collector.

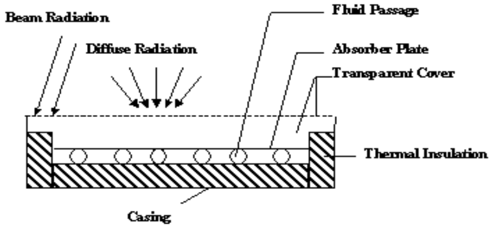


Figure 1 Flat plate collector system

In a domestic solar hot water system, the flat plate solar collector is the central part of the system. Hence, the optimal performance of the solar collector is critical. An energy equation is essential for determining the performance of the flat plate collector, and hence its efficiency, but, the second law of thermodynamics analysis is more applicable regarding the optimum operating zone, quantifying the inefficiencies and achievable performance.

The solar collector box is usually stationary. Therefore, it must be situated so that the optimum solar radiation is collected and stored during the day. However, this implies a specific angle for a given latitude that yields the maximum solar energy over the year. In practice, the low latitudes and the collector's angle are almost equivalent to the latitude angle but increase by 10° at 40°N and 40°S latitudes [6]. All these arrangements are for flat-surfaced collectors. The temperatures achievable by flat plate collectors vary between 40 °C and 80 °C depending on the topographic and meteorological conditions. In a flat plate collector, the optimum sunlight energy can be captured from the irradiation by ensuring that the surface absorbs as much of the incident radiation as possible to reduce the losses from this surface.

L. Magó *et al.*, (2023) [7] presented a dynamic model of a single cover flat-plate collector which was further adapted by Duffie and Beckman [8]. Duffie and Beckman represented the cover and the absorber energy balances by an ordinary differential equation, while a partial differential equation described the fluid temperature. Although the derived model was non-linear, a linear approximation was obtained using Taylor series expansion around the average operating conditions. However, the model is not valid for an extensive range of disturbance involving wind speed and flow variations.

Low-temperature flat plate collectors can raise the water temperature to boiling point in the summer, provided that they are double-glazed and the water circulation is not fast enough to carry away the heat too quickly. Choundhury et al. [9] proposed modifying the simple absorber flat plate to be corrugated [9]. Garg et al.[10] introduced an absorber plate with fins attached.

2.1 HEAT LOSS IN FLAT PLATE COLLECTOR SYSTEM

In a flat plate collector, the energy incident cannot increase on the surface of the collector. The only possible way to improve this is to ensure that the surface of the collector absorbs as much as possible of the incident radiation. The solar collector can absorb and store a high amount of energy by means of painting the solar box with black paint on the surface of the collector system; about 95 % of the solar radiation can be absorbed by the box, while some of the incident radiation is lost by reflection.

This study focuses on the heat losses at a flat plate collector's top, bottom, and edge. The lower surface and the sides usually have an insulating layer of material, e.g., glass wool or sawdust. In this study, sawdust with a thermal conductivity of 0.059 W/mK was used. The mode of heat loss is through conduction, convection, and radiation mechanisms.

B.S Mukesh [11] calculated the overall heat loss coefficients of a trapezoidal cavity absorber [11]. The thermal performance of eight sets of trapezoidal absorbers for linear concentrating collectors was analyzed and studied under constant flow rate and steady-state temperatures. Their analysis found that the heat loss coefficient increased with an increase in the absorber temperature, and that a double glass cover reduced the overall heat loss coefficient by 10 % to 15 % compared to a single glass cover.

It is well known that black surfaces absorb solar radiation more than any other color. Therefore, when a surface is blackened, it will absorb most of the incident solar radiation. The continuous flow of solar radiation onto such a surface will increase its temperature. The heat inflow will continue until the heat gain from the solar radiation is in equilibrium with the heat loss from the collector. There are two types of heat losses, namely, naturally unavoidable losses and losses due to human use. The heat absorbed can be directed to where required through pipes soldered to the heated metal plate. The heat balance of a collector has three components related as follows according to ASHRAE (1981).

Useful heat by coolant =Absorbed Heat – Lost Heat 2.1

Therefore, useful heat =absorbed Heat – Heat loss 2.2

$$Q_U = Q_A - U_L \qquad 2.3$$

It is possible to define the collector as:

$$\text{Collector efficiency} = \frac{(\text{absorbed heat} - \text{lost heat})}{\text{incident solar radiation}} \qquad 2.4$$

In practice, the collectors must be designed in such a manner that the efficiency is as high as possible. There are two ways of achieving high efficiency: reduce heat losses, or increase the collector area and incident solar radiation, and, hence, the heat absorbed per unit area. For low-temperature collectors, heat loss reduction methodology is suitable. It is possible to reduce heat loss by using transparent cover plates, specially treated absorber surfaces, and evacuating the space between the cover plate and the absorber surface. In contrast, for high-temperature solar collectors, the efficiency can be increased by increasing the incident radiation through solar concentrators. Of course, for this purpose, only direct radiation is considered. Any solar energy design should consider three heat transfer modes: efficiency, conduction, convection, and radiation. For any solar radiation collector to work efficiently, reducing the heat losses or minimizing them is necessary. As the material is heated by solar radiation, it seeks to reach equilibrium with its surroundings by conduction, convection, and radiation processes.

The surface finish of the absorber plate performs better when painted lamp black with an appropriate primer. A thin coat is required since a thick undercoat of paint increases the resistance to heat transfer. It is also necessary that the primer be the self-etching type to avoid peeling with time due to repeated thermal expansion and contraction.

The significant heat losses of the collector are from the front cover (glass cover) because the sides and the back of the collector are adequately insulated. In contrast, the front face must focus on solar radiation and ambient temperature. Minimizing heat losses from the front cover of the collector and maximizing heat extraction from the absorber can be accomplished by forcing air to flow over the front glass cover (preheat the air) before passing through the absorber.

III. METHODOLOGY

3.1 SYSTEM DESIGN AND OPERATION

The Solar Heating Design – collector and storage tank

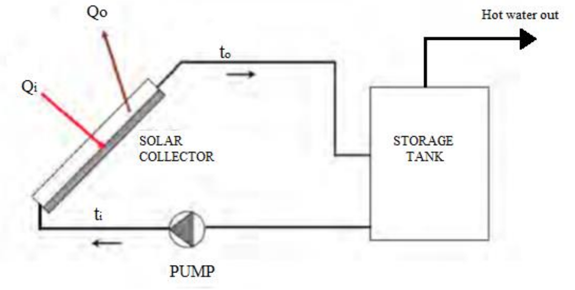


Figure 2 Heating system design-collector and storage tank.

Fig. 2 shows a schematic diagram of a typical active solar system employing a flat plate solar collector and a storage tank. The collector absorbs heat, with I being the amount of solar radiation received by the collector. The collector's temperature increases to higher than the surrounding temperature, and heat is lost to the atmosphere by convection and radiation; Qi represents this heat loss rate. t_1 represent water temperature into solar collector while t_2 represent water temperature flowing into the storage tank. The flat plate solar collector is positioned at 22.5° tilted away from the horizontal computed as Ø + 15° for low latitude regions [12], where Ø is the latitude of the location (Ado-Ekiti, 7.5°N). The returned water from the tank flows into the collector system with the aid of a circulating pump. The collector absorbs the sun's energy and transfers it to the circulating water being heated, which comes out at a higher temperature. This fluid now flows into the storage tank, where hot water for the house is drawn.

3.2 DESIGN OF THE FLAT PLATE SOLAR COLLECTOR SYSTEM

Determination of Absorber Plate Area

The design aims to raise water temperature from 20 °C to about 60 °C within the shortest hour of sunshine for heating purposes. The total heat absorbed by the collector was determined as Q:

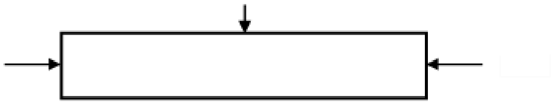
$Q = \tau I_T \alpha$, $Q = \tau\alpha I_T A_C$ (3.1)

Where I_T = Clear sky direct radiation intensity at Ado-Ekiti (1026 W/m^2)

τ = Transmittance (0.76)

α = Absorptance (0.93)

A schematic representation of the energy balance on the absorber plate.



$Q = mc\Delta t$ (3.2)

$Q = mc\ (t_2 - t_1)$

Assuming the collector is operating in a constant state

$Q_u = Q_a - Q_L$ (3.3)

Where Q_a = Heat absorbed in W/m^2

Q_u = Useful heat in W/m^2

Q_L = Heat loss in W/m^2

The heat absorbed is equal to the product of radiation flux, I, the collector area, A_C, and the cover plate's absorber transmissivity-absorptivity product, τa

$Q_a = \tau\alpha IA$ (3.4)

The heat lost from the system is from the collector absorber plate of temperature T_c to the surroundings at T_a

$Q_L = U_L A_c(\Delta t)$

$= U_L A_c (T_c - T_a)$

$\frac{Q_L}{A} = U_L(\Delta t)$

The heat collected therefore

$Q_u = Q_a – Q_L$

The overall heat balance

$Q = \tau\alpha IA - U_L A_c (T_c - T_a)$

$\frac{Q_U}{A} = \tau\alpha I - U (T_c - T_a)$

The heat generated in the system

$Q = mc\Delta t$

$$Q = mc\ (t2 - t1)$$

For this design study the value of

t_1 = 20 °C

t_2 = 60 °C

Temperatures (t_1 and t_2) were measured with the aid of a thermometer

V = m^3/s

$m = \rho V$

Density ρ of water = 1000 kg/m^3

The specific heat capacity of water = 4.2 kJ/kg °C

Volume v of water flowing into the system per time taken is 0.005 m^3/s

$m = \rho V = 1000 \times 0.005 = 5$ kg/s

= 5 kg/s

$Q_c = mcp\Delta t$

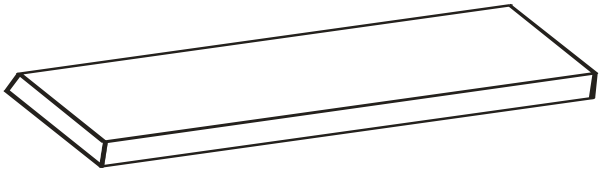
$= mcp\ (t_2 - t_1)$

= 5 x 4.2 (60 - 20)

= 5 x 4.2 (40) kJ/kgK

$Q_c = 840\ kW/m^2$

Now to determine the area of the flat plate collector system



$\frac{Q_c}{A} = mc\Delta t$

$A = \frac{Q_c}{mc\Delta t}$

$\frac{Q_c}{A} = 840\ kW/m^2$

$Q_c = \tau\alpha IA_c - U_L A_c (T_c - T_a)$

$\frac{Q_c}{A_c} = \tau\alpha I - U(T_c - T_a)$

$\frac{Q_c}{A_c} = \tau\alpha I - U_L(T_c – T_a)$

$A_c = \frac{Q_c}{T\alpha I - U_L(T_c - T_a)}$

Assuming the heat loss U_L = 8.2 W/m^2K

$\frac{Q_c}{A_c} = \tau\alpha I – 8.2(T_2 – T_1)$

$840/A_c$= 0.76 x 0.93 x 1026 – 8.2 (40)

$840/A_c$= 0.76 x 0.93 x 1026 – 328

$A_c = 0.3532\ m^2$; L = 1.0 m; B = 0.3532 m.

3.3 COEFFICIENT OF HEAT LOSS COMPUTATION

It is helpful to develop the concept of an overall loss coefficient for a solar collector by simplifying the parameters. Consider the thermal network for a two-cover plate shown in Fig. 4 below. At some location on the plate where the temperature is reduced by optical losses, as shown in the diagram, this absorbed irradiation S is converted to useful energy gain, with thermal losses through the top and bottom. The energy loss through the top is the result of convection and radiation between parallel plates. The energy transfer between the plate at T_p and the first glass cover at T_{c1} is the same as the other two adjacent surfaces and equals the energy lost to the surroundings from the top glass cover.

The energy loss through the top per unit area ($q_{loss,\ top}$) is then equal to the heat transfer from the absorber plate to the first cover,

$$q_{loss,top} = h_{p-c1}(T_p - T_{c1}) + \frac{\sigma(T_p^4 - T_{c1}^4)}{\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_c} - 1} \qquad 3.5$$

where $h_{p\text{-}c1}$ is the heat transfer coefficient between two inclined parallel plates.
T_p = Mean absolute plate temperature (K).
T_c = Cover glass temperature in (K)
σ = Stefan Boltzmann's constant
ε_p = Infra-red emissivity of the plate
ε_g = Infra-red emissivity of the glass cover
If the radiation term is linearized, the radiation heat transfer coefficient can be used, and the heat loss becomes

$$q_{loss,top} = (h_{p-c1} + h_{r,p-c1})(T_p - T_{c1})$$

$$h_{r,p-c1} = \frac{\sigma(T_p + T_{c1})(T_p^2 + T_{c1}^2)}{\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_c} - 1} \qquad 3.6$$

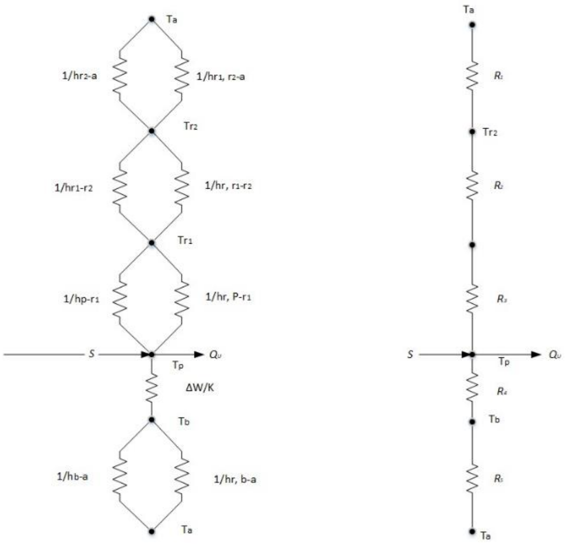


Figure 3 Thermal network for a two-cover flat plate collector in terms of conductor, convention, and radiation resistance and terms of resistance between plates.

Resistance, R_3, can then be expressed as

$$R_3 = \frac{1}{h_{p-c1} + h_{r,p-c1}} \qquad 3.7$$

R_2 and R_3 is the resistance at the second and third plate, respectfully.

A similar expression can be written for R_2. In this case, two cover plates were used. Generally, we can have as many cover plates as desired, but in practice, it seems to be three, usually in most collectors one or two glass covers are used.

The radiation resistance from the top cover accounts for an exchange with the sky at T_3. According to Duffie and Beckman (1991), the radiation heat transfer can be written as

$$h_{r,c2-a} = \varepsilon_c \frac{\sigma(T_{c2} + T_3)(T_{c2}^2 + T_3^2)(T_{c2} - T_3)}{T_{c2} - T_a} \qquad 3.8$$

Resistance to the surroundings is then given by

$$R_1 = \frac{1}{h_w + h_{r,c2-a}} \qquad 3.9$$

In this two-cover system, the top loss coefficient from the collector plate to ambient is U_t

$$U_t = \frac{1}{R_1 + R_2 + R_3} \qquad 3.10$$

The procedure for solving for the top loss coefficient is necessarily an iterative process. A guess is made for the unknown cover plate temperatures, from which convective and radiative heat transfer coefficients between parallel plates are calculated. The heat transfer coefficient, wind heat transfer coefficient (hw), and top loss coefficient (U_t) are determined with these estimates. The top heat loss is the top loss coefficient multiplied by the overall temperature difference. Since the energy exchange between plates must equal the overall heat loss, a new set of plate temperatures can be calculated. Starting from the absorber plate, a new temperature is calculated for the first cover. This new first cover temperature is used to find the next cover temperature and so on. No further iteration is needed if the temperature (T_c) on the cover plate is close to the initial guess. Otherwise, the newly calculated cover temperature (T_c) is used, and the process is repeated until the cover plate's cover temperatures no longer change between each iteration. From Duffie and Beckman (1991) [6],

$$U_t = \left\{ \frac{N}{\frac{C}{T_{p,m}}\left[\frac{T_{p,m} - T_a}{(N+f)}\right]^c} + \frac{1}{h_w} \right\}^{-1} + \frac{\sigma(T_{p,m} + T_a)(T_{p,m}^2 + T_a^2)}{(\varepsilon_p + 0.00594Nh_w)^{-1} + \frac{2N + f - 1 + 0.133\varepsilon_p}{\varepsilon_q} - N}$$

3.11

Where N = Number of glass covers;

$f = (1 + 0.089h_w – 0.1166h_w\varepsilon_p)(1 + 0.07866N)$

$C = 520 (1 – 0.000051\beta^2)$ for $0° < \beta < 70°$. For $70° < \beta < 90°$, use $\beta = 70°$,

$e = 0.43 (1 – 100/T_{p,m})$

β = Collector tilt (degrees)

ε_g = Emittance of glass (0.88)

ε_p = Emittance of plate

T_a = Ambient temperature (K)

$T_{p,m}$ = Mean plate temperature (K)

h_w = Wind heat transfer coefficient (W/m^2 C)

The energy loss through the bottom of the collector is shown by two series resistance, R_4 and R_5 (Fig. 3.4). R_4 represents the resistance to heat flow through the insulation, and R_5 represents the convection and radiation resistance to the environment. The magnitudes of R_4 are more significant than R_5, and it is possible to neglect the value of R_5 and all resistance to heat flow due to the insulation. Thus, the back loss coefficient, U_b, is approximately

$U_b = 1/R_4 = 1/L_4/K_4$

$U_b = k/L$

Where k and L are the insulation thermal conductivity and thickness, respectively.

Assume edge insulation thickness is kept equal to bottom insulation thickness. In that case, the edge losses may be estimated by assuming one-dimensional sideways heat flow around the perimeter of the collector system. Tabor (1958) recommends edge insulation of about the same thickness as bottom insulation. For most collectors, the evaluation of edge losses is very complicated. However, in a well-designed system, the edge loss should be slight so that it is not necessary to predict it with great accuracy. The edge losses may be evaluated when the perimeter of the collector is known.

$$U_e = \frac{(UA)_{edge}}{A_c}$$

The loss coefficient is made up of three components, the top (U_t), bottom (U_b), and edge (U_e) loss coefficient. The collector overall loss coefficient, U_L, is then the sum of the top, bottom, and edge loss coefficients

$$U_L = U_t + U_b + U_e$$

The unit of total loss (U_L) is W/m^2k.

3.4 EXPERIMENTAL SET-UP AND METHODOLOGY

An experimental research collector was developed for this work. It consists of a 5 mm thick glass cover plate, coated black absorber copper being 1 m x 0.353 m x 0.3 m high, and wooden housing filled with sawdust (K = 0.059 W/mK) at the back and the sides of the collector system. The experimental rig is placed on a horizontal plane where sunlight energy is collected without obstruction. The solar collector system is exposed to irradiation. A multimeter device is attached to the absorber plate, bottom of the glass cover, bottom side, and edge of the collector to measure the temperature. Also, another multimeter was exposed to the surrounding environment to measure the ambient temperature. The readings were taken at six different points on the collector system. Readings were taken off the multimeter for 30 days between 8:00 am and 6:00 pm at 30 minutes intervals (Table 1). The flat plate solar collector was positioned at 22.5° away from the horizontal; the latitude of the location (Ado-Ekiti) is 7.5°. Fig 5 shows a photographic view of the experimental set-up.

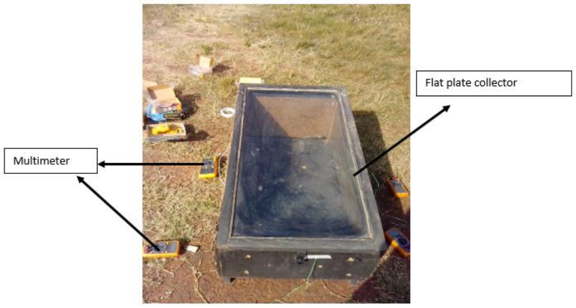


Figure 4 The experimental set up of a flat plate solar collector system.

IV. RESULTS AND DISCUSSION

A flat plate collector system was exposed to irradiation; the readings were taken using a multimeter to obtain the temperature values within the collector box at various points. Ado-Ekiti (7.50°) was the location where the task took place. The values of mean plate temperature (T_{pm}) and ambient temperature (T_a) were obtained via the multimeter.

Table 1 Daily average collector reading for 30 days

Day	Average Plate Temperature (K)	Average Ambient Temperature (K)	Average Total Loss (W/m^2 K)	Average Collector Efficiency (η)
1	311.238	309.143	3.392	0.602
2	304.000	301.857	3.209	0.602
3	315.000	310.524	3.498	0.610
4	300.857	297.381	3.489	0.583
5	311.333	309.762	3.489	0.590
6	294.619	292.524	3.237	0.589
7	298.190	294.952	3.410	0.584
8	308.952	307.381	3.369	0.600
9	310.000	308.048	3.514	0.589
10	313.667	311.333	3.645	0.603
11	303.667	301.143	3.448	0.587
12	309.524	306.810	3.575	0.586
13	311.333	308.238	3.592	0.584
14	310.286	309.429	3.347	0.592
15	307.667	305.810	3.414	0.589
16	313.286	310.619	3.683	0.605
17	303.714	300.238	3.496	0.583
18	309.762	305.048	3.740	0.578
19	300.667	300.143	3.243	0.597
20	310.762	309.667	3.340	0.599
21	299.524	297.000	3.146	0.603
22	299.667	298.762	3.166	0.598
23	300.429	299.190	3.393	0.591
24	346.429	342.048	4.055	0.578
25	300.286	295.333	3.282	0.611
26	327.048	304.619	4.200	0.503

27	312.333	309.476	3.438	0.605
28	309.667	302.619	3.482	0.619
29	358.524	285.286	4.697	0.260
30	313.000	310.048	3.471	0.605
31	318.286	315.048	3.557	0.606

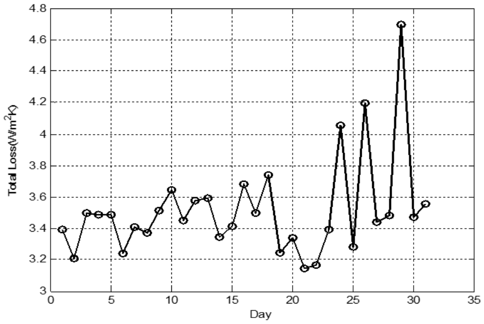


Figure 5 Average total loss per day

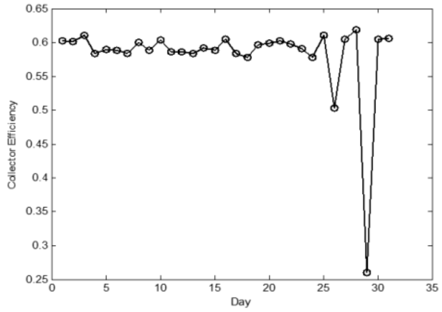


Figure 6 Average collector efficiency per day.

MATLAB programming language was used to write a program to determine top loss (U_t) and total loss (U_L) values.

Using Klein's equation [13].

The values of bottom U_b and edge losses, U_e was constant because they do not depend on temperature.

The value of collector efficiencies was determined using the following equation $\eta = (AcF_R[S-U_L(Tp-Ta)/(Ac\ IF_R)$ per day.

However, the collector efficiency ranged from 26.0 % to 61.9 %. From Table 1, the collector has the highest efficiency of 61.9 % at a low heat loss coefficient (3.146 W/mk) and the lowest efficiency of 26.0 % at the highest heat loss coefficient (4.697 W/mk). It could be deduced that the lower the heat loss coefficient, the higher the efficiency, and the higher the heat loss coefficient, the lower the collector efficiency.

Moreover, from all the graphs, it is clear that the top loss significantly affects the total loss and efficiency. The graph of total loss follows the same pattern as the graph of top loss. That is, where the top loss is at peak, the total loss also is at peak. It can also be deduced from the results that the top loss depends strongly on the plate temperature in relation to the ambient temperature. The efficiency begins to fluctuate and drop significantly beyond day 25, and is mirrored by the increase in heat loss. This is due to the weather condition from day 25.

CONCLUSION

Energy security in the 21st century is more complicated when compared to previous eras in which one type of product has been highly influential. The share of oil in energy consumption is likely to decline because of 'peak oil' and 'price' issues and due to changing consumption patterns, investment priorities, and external constraints [4]. The decline in fossil fuel has created great awareness and interest in solar energy utilization worldwide. Furthermore, environmental problems such as global warming are becoming severe, calling attention to solar energy and other renewable energy sources. The flat-plate collectors have an important area among applications of the solar energy system. The following conclusion can be drawn from this research.

- The heat lost to the environment from the system is from the collector absorber plate of temperature Tc. QL = UL Ac(Δt) = UL Ac (Tc - Ta)
- The highest efficiency of 61.9 % was obtained at a low heat loss coefficient of 3.146 W/mk while the lowest efficiency of 26.0 % recorded at 4.697 W/m which is the highest value of heat loss. It could be deduced that the lower the heat loss coefficient, the higher the efficiency, and vis-visa
- Abundant sunlight intensity available with significant renewable energy resources can be harness for adequate conversion technologies to produce heat for various engineering applications.

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