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Design and Construction of a Solar Water Heater for Environmental Sustainability

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors designed the study, performed the statistical analysis and wrote the protocol. Author JIE wrote the first draft of the manuscript. Both authors managed the analyses of the study. Author PIE managed the literature searches. Both authors read and approved the final manuscript.

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ABSTRACT

This research work involves the design and construction of a solar water heating system with 2.3 m^2 solar collector area proposed to extract enough solar energy to raise the temperature of 0.075 m^3 of water by 34°C based on the available solar window to Port Harcourt. This solar heating device is made of the solar collector and storage tank connected with inlet and outlet pipes. This solar system is insulated at the bottom and sides against thermal energy loses, with the front covered with glass which allows solar energy absorption and reduces thermal energy loses by convection. The solar system was tested within the days of optimum solar window for about 3 hours. The ambient temperature, inlet temperature and outlet temperature were observed to vary from 37 to 44°C, 41 to 42°C and 71 to 76°C respectively. This test result gave a maximum temperature rise of between 30°C and 36°C as proposed. Our designed solar system has the capability of providing boiled water for domestic and other uses and at the same time, is very environmental friendly.

Keywords: Solar collector; heated water; environment; sustainable.

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1. INTRODUCTION

It is common place nowadays to say that energy is the ability to do work. The generation of the capacity to do work could be through human power, the burning of fossil fuels or any other means through which work can be executed more easily without so much stress on human power and capacity. In Nigeria as well as most developing nations, electricity generation for domestic and industrial uses is mainly through burning of fossil fuels which in the long run is non-economical and less environmental friendly. Diesel (a type of fossil fuel) engine exhaust produces a mixture of primary pollutants such as; particulate matter (PM), Carbon monoxide (CO), Nitrogen oxides (NOx), Hydrocarbons (HC), Volatile organic compounds (VOCs), etc. and when humans are exposed to these pollutants, their respiratory systems are affected and this worsens asthma, allergies, bronchitis, and lung functions and could even cause lung cancer [1]. Diesel engine generates electricity more economically than any other device in their size range. But diesel is one of the largest contributors to environmental pollution problems worldwide. Diesel emissions contribute to the development of cancer; cardiovascular and respiratory health effects; pollution of air, water, and soil; reductions in visibility; and global climate change [2]. Pollutants such as methane emission, nitrogen oxide, sulfur, mercury, and particulates resulting from burning of natural gas have been linked with problems such as asthma, bronchitis, lung cancer, and heart disease [3]. Some environmental friendly means of energy generation include; solar energy, wind power, hydroelectric power, ocean or tidal energy, geothermal energy and biomass energy. These energy sources are environmental friendly since they release little or no particles that can cause air pollution or negatively impact on human health [4].

Energy resources are classified either as renewable or non-renewable resources. Renewable energy is energy which is gotten from natural processes that are continuously replenished. This form of energy cannot be exhausted since it is constantly renewed [4]. Renewable energy is very environmental friendly and its examples have earlier been presented. Non-renewable energy resources are energy resources that are available in limited amount in nature and develop over a long period of time. As a result of their limited nature, they are likely to be exhausted one day and energy generation from these resources impacts negatively on the environment [5]. Some forms of this type of energy include; coal, crude oil, natural gas, nuclear power, etc. The four common major sources from which energy resources are generated include fossil fuel, solar energy, nuclear energy and geothermal energy. Among these four, the 'dirtiest' is the fossil fuel (coal, petroleum oil and gas) whereas, the 'largest' source is the sun. Climate change resulting from global warming is as a result of combustion processes from fossil fuel and is one of the greatest challenges facing the world. A good source of remedy would be to employ cleaner energy sources which are derivable from solar energy [6]. Plants and animals derive their energy directly and indirectly from the sun and subsequently their remains buried under certain pressure and temperature regimes for millions of years will generate fossil fuel [7]. The global utilization of the abundant solar energy as major energy resource in the last couple of decades will improve energy availability thereby improving the standard of living across various places and conserving the environment for future generation [5].

In an effort to lessen the energy burden on the environment due to burning of fossil fuel, this research work is aimed at the design and construction of solar water heater (based on available solar radiation prevalent in Port Harcourt and using materials readily available) with the aim of producing a hybrid solar system that will be very efficient and cost effective. This design is intended for use in households and hospitals as an alternative source of heating water as it will reduce the rate at which fossil fuel is burnt for water heating in our households and promote the utilization of clean energy resources for environmental sustainability.

2. METHODOLOGY

2.1 Material Selection

The materials selection is mainly aimed at efficient absorption of the solar energy and prevention of energy losses back to the surrounding of the heating device. The following materials were used in the construction of the solar water heater; copper tubes, aluminum sheets, matt black coating paint, steel angle-iron, glass sheet, wooden containment and fiberglass materials. The Matt black coating paint absorbs 97%-99% of the incident solar energy from the sun. Aluminum absorber sheets and Copper tubes with excellent thermal conductivities;

273 W/(m.K) and 401 W/(m.K) respectively transfer the solar energy into the storage substance as heat energy. In order to prevent heat losses to the surrounding environment as the temperature of the heating device exceeds ambient temperature; the device is encapsulated in wood and fiber glasses that are very poor thermal conductors with thermal conductivities of 1.4 W/(m.K) and 0.04 W/(m.K) respectively. The ability of glasses to transmit 90% of the incident solar energy and its poor thermal conductivity of 0.96 W/(m.K) makes it a suitable window for the heating device to receive the incident solar radiation . The physical properties that inform the selection of these materials are listed in Table 1.

2.2 Available Solar Irradiance

The availability of the solar energy for useful applications in Nigeria depends on the prevalent atmospheric conditions which are influenced by time of the year, location and other human activities (deforestation, industrialization, etc.). Four Nigerian cities; two in the southern rain forest belt (Port Harcourt and Lagos), and two in the northern arid desert (Sokoto and Maiduguri) were selected to assess their Insolation. Typically, the monthly average Insolation (obtained over 22 year period) incident on a horizontal surface in those cities was recently downloaded from NASA Langley Atmospheric Science Data Center website [8]. The highest Insolation of 7.15 $KWh/m^2/day$ is received in Sokoto during the month of April and the lowest Insolation 3.24 $KWh/m^2/day$ is received in Port Harcourt during the month of July. The Insolation data are presented in Table 2.

2.3 Solar Water Heater Description and Operation

The solar water heater is made of the solar collector and substance storage tank connected with inlet and outlet pipes. A steel stand is used to ensure proper inclination of the solar collector to receive incident sun rays. The flat plate solar collector consists of the absorbing plate glued to network of piping into which the heat extracting substance (water) flows. The network of piping is made of two copper headers ($0.75^{//}$) connected together by equally spaced copper flow tubes ($0.5^{//}$) to form what is referred to as the copper grid. This arrangement is insulated at the bottom and sides against thermal energy loses, with the front covered with glass which allows solar energy to be absorbed and reduces thermal energy loses by convection. This design used only wood as the insulation material for the bottom and edges. A Schematic diagram of our constructed thermal-type Flat Plate Solar Collector is shown in Fig. 1. Picture showing the constructed thermal-type flat plate solar collector is show in Fig. 2.

In the operation of this device, water from the bottom of a storage tank positioned above the solar collector flows through the inlet connection to the bottom header and the flow is evenly distributed to the flow tubes. Solar energy absorbed by the absorber plate glued to this flow tubes heats up the water which reduces the density and results in expansion of the water. The expanded water experiences less resistance to flow at the top header than the bottom header due to differences in densities between heated and cold water, and consequently flows to the top header, through the outlet line to the top of the storage tank. This flow of heated water is due to the thermo-siphon principle [9]. The storage tank is stratified into water layers whose temperature decreases from top to bottom. The picture of the solar collector together with the storage tank is shown in Fig. 3.

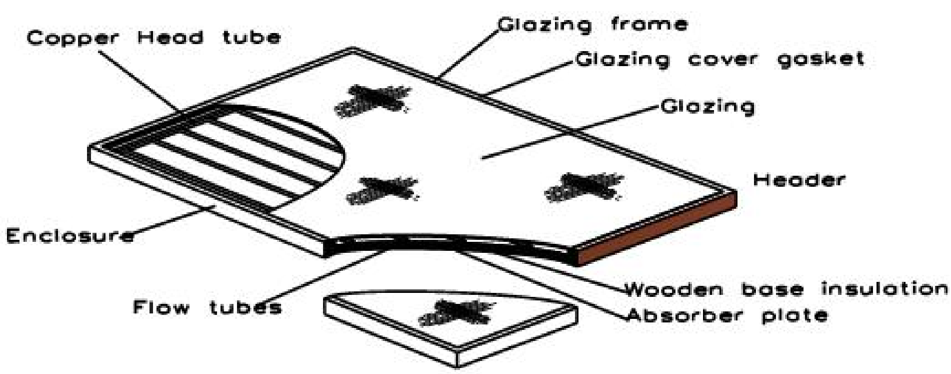

Fig. 1. Schematic diagram of solar water heater

Table 1. Physical properties of solar heater construction materials

Properties	Copper	Aluminum	Coating	Steel	Glass	Wood	Fiberglass
Thermal conductivity W/(m.K)	401	273	-	43	0.96	0.1-1.4	0.04
Specific heat capacity $KJKg^{-1}K^{-1}$	0.39	0.87	-	0.49	0.84	-	-
Density g/cm^3	8.96	2.70	-	7.85		0.3-0.7	-
Coefficient of linear expansion 10^{-6} K^{-1} @ 20°C	17	23	-	11	8.5	-	-
Coefficient of volumetric expansion 10^{-6} K^{-1} @ 20°C	51	69	-	33	26	-	-
Solar absorptivity	-	0.4-0.7	0.97-0,99	-	-	-	-
Solar transmissivity	-	0.2-0.3	-	-	0.90	-	-
Thermal emissivity	-	-	0.97-0,99	-	-	-	0.75

Table 2. Solar irradiance data for Port Harcourt, Sokoto, Lagos and Maiduguri [8]

Monthly averaged Insolation Incident on a Horizontal Surface ($KWh/m^2/day$)														
Cities	**Geographical location**	**MSL elevation**	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May.**	**Jun.**	**Jul.**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**
Port Harcourt	4.7500°N 7.0000°E	27 m	5.20	5.24	4.80	4.59	4.23	3.54	3.24	3.42	3.43	3.68	4.21	4.95
Sokoto	13.0667°N 5.2333°E	296 m	5.47	6.41	6.87	7.15	7.03	6.91	6.26	5.73	6.01	6.03	5.79	5.25
Lagos	6.4530°N 3.3958°E	11 m	5.28	5.49	5.46	5.21	4.76	4.04	3.95	3.98	4.09	4.55	4.95	5.17
Maiduguri	11.8333°N 13.1500°E	354 m	5.61	6.30	6.70	6.62	6.36	5.97	5.43	5.14	5.57	5.89	5.84	5.35

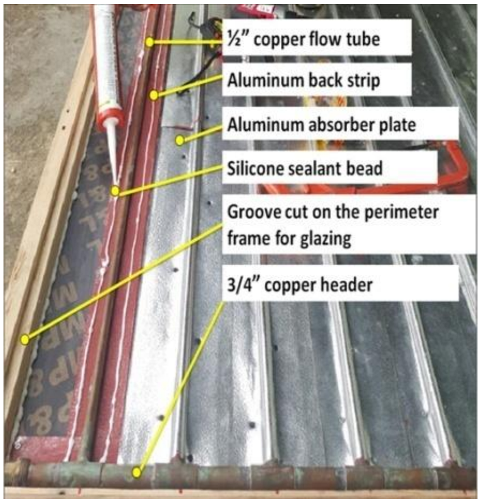

Fig. 2. Picture showing the constructed thermal-type flat plate solar collector

Fig. 3. Picture of the solar collector together with the storage tank

2.3.1 Thermal-type flat plate solar collector design

Central to this heating device is the thermal-type flat plate solar collector, connected to the storage tank by means of copper supply and return lines. The design flow chart showing the sequence of design process is presented in Fig. 4.

The collector design area, A_C is related to the energy demand of the required application (Q_h) and the available incident energy at a given location (Q_i) as given in [10];

$$A_c = \frac{Q_h}{Q_i} \quad (1)$$

The energy demand, Q_h for heating the substance (water) is derived from the useful energy gain of a solar collector (Q_U) which is given by the incident solar energy minus the energy losses as in [11];

$$Q_u = A_c[S\Gamma\alpha - U_L(T_0 - T_1)] \quad (2)$$

where Γ is transmissivity of the glass cover; α is the absorptivity of the aluminum absorber plates; A_C is the collector area; S is the absorbed solar radiation; U_L is overall loss coefficient of the solar collector and $T_o - T_i$ is the difference between the output and input temperature of the solar collector also called T_{RISE}.

The performance of a solar collector can be described by an energy balance that shows incident solar radiation Q_i, distributed into useful energy gain Q_U, thermal losses Q_L, and optical losses which could also be transmissivity-absorptivity product, Γα expressed as in [11]:

$$Q_u = Q_i - Q_L \quad (3)$$

Let the equation for incident solar radiation be as in [7];

$$Q_i = S \times A_c \times \Gamma \times \alpha \quad (4)$$

The average daily solar radiation in Port Harcourt for the 5 months rainy season (June- October) computed from Table 2 is 3.462 $KWhm^{-2}day^{-1}$ and that for the 7 months dry season (November- May) from the same source is 4.745 $KWhm^{-2}day^{-1}$ [8]. This work will be based on the average of the two values 4.104 $KWhm^{-2}day^{-1}$. Taking solar transmissivity of the glass covers as 0.896 and average solar absorptivity of the aluminum absorber plate as 0.55; Equation 4 would imply that the solar energy received per unit area of A_C collector plate can be obtained from:

$$\frac{Q_i}{A_c} = S \times \Gamma \times \alpha \quad (5)$$

$$= 4.104 \times 0.896 \times 0.55 = 2.02\ KWhm^{-2}day^{-1}$$

75 liters (0.075 m^3) of water was chosen for design of the solar heating system to give about 75 liter output daily at 60°C. The energy demand to raise the temperature of the water from input temperature T_i, taken as 26°C to the output temperature T_o, designed for 60°C was determined by the normal heat equation;

$$Q_{h=}\ _V \times C_p \times \Delta T \quad (6a)$$

Where V = 0.075 m^3 (volume of water consumption per day), C_P is specific heat capacity of water (1.16 KWh/m^3K) [12], ΔT is Temperature difference between heated and cold water (T_o-T_i).

Therefore,

$$Q_h = 0.075 \times 1.16 \times 34 = 2.958 \text{ KWh} \quad (6b)$$

The minimal required collector area A_C to extract this energy from the solar radiation is given as;

$$A_c = \frac{Q_h}{Q_i} = \frac{2.958\ Kwh}{2.02\ KWh/m^2} = 1.464\ m^2 \quad (7)$$

The calculated collector area A_C is therefore designed with a 60% mark-up to be approximately 2.3 m^2. This design actual output will depend on the thermal losses due to the flat-plate collector orientation and other assumptions.

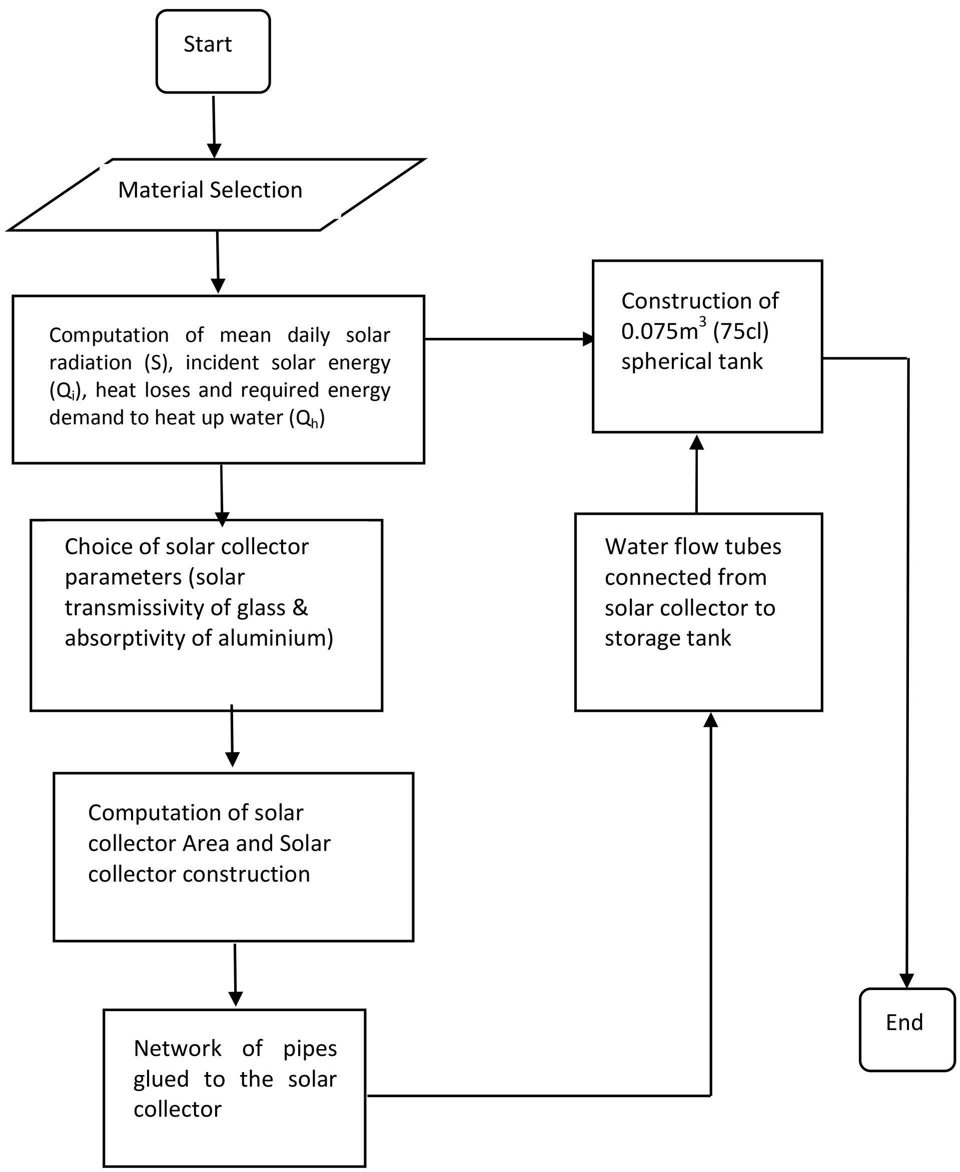

Fig. 4. Design flow chart showing the sequence of design process of the solar collector

The thermal energy losses from the collector to the surroundings by conduction, convection and infrared radiation, are through the bottom, edges and top covers of the solar collector. This is determined by calculating a quantity called the overall loss coefficient, U_L which is the sum of all the top U_T, bottom U_B and edge U_E loss coefficients as in [11];

$$U_L = U_T + U_B + U_E \quad (8)$$

Let the thermal energy loss from the collector be the product of the overall loss coefficient, U_L and temperature difference between the mean absorber plate temperature, T_o and the ambient temperature, T_i; then the overall thermal energy losses from the collector of surface area Ac can be determined as in [7]:

$$Q_L = A_C\, U_L\, (T_{PM} - T_A) \quad (9)$$

In our design, considering a spacing of 4.5 cm between the glass cover and the aluminum absorber plate, we estimated U_T to be approximately 5.4 W/m^{2}C from Fig. 5; considering that thermal emissivity, ε_P = 0.97; T_{PM} > 50°C and one glass cover was used (N=1) [11].

The bottom loss coefficient was computed using;

$$U_B = \frac{K}{L} = \frac{0.4\, W/m^2K}{0.045\, m} \quad (10)$$

$$= 8.9\ \text{W/m}^3\text{K}.$$

Where k is bottom insulation thermal conductivity; and L is insulation thickness.

Tabor recommended edge insulation of about the same thickness as bottom insulation and estimated edge loss coefficient U_E (assuming one-dimensional sideways heat flows around the perimeter of the collector system) to be [13];

$$U_E = \frac{E_C \times E \times C_T}{E_T \times A_c} \quad (11)$$

where E_C is Edge Insulation conductivity (0.4 W/m.K for wood), E_T is Edge Insulation thickness (0.0475 m), E is Edge perimeter (1.34 m + 1.95 m) x 2 = 6.58 m and C_T is Collector thickness, 0.09 m.

The edge loss coefficient for collector box design from wood is therefore from (11);

$$U_E = \frac{0.4 \times 6.58 \times 0.09}{0.0475 \times 2.30} = \frac{8.42 \times 6.58 \times 0.09}{2.30} = 2.159\ \text{W/m}^3\text{K}$$

The useful energy gain in the designed solar collector is obtained by substituting Equations (9) and (4) in (3)

$$Q_u = SA_c\, \Gamma\alpha - A_c U_L\, (T_0 - T_i) \quad (12)$$

$$Q_u = A_c\, [S\Gamma\alpha - U_L\, (T_0 - T_i)] \quad (13)$$

Recall that $U_L = U_T + U_B + U_E$ = 5.4+8.9+2.159 = 16.459 W/m^{3}K

Therefore useful energy gain;

$$Q_u = 2.30[2031 - (16.459 \times 34)] = 3.38\ \text{KWh}. \quad (14)$$

The actual temperature increase ΔT for the solar water heating system, can be obtained from equation (5) as;

$$\Delta T = \frac{Q_u}{VC_p} = \frac{3.38}{0.05 \times 1.16} = 38.85\ \text{K} \quad (15)$$

2.3.2 Flow tube spacing for efficient flow distribution

The liquid to be heated is supplied to the solar collector through uniformly spaced tubes running from a supply header to a collection header, with the goal to provide uniform flow per unit area of the collector and equal flow to each tube. The design is also aimed at minimizing the lateral temperature gradient in the collector plate which is necessary to carry the absorbed heat to the flow tubes.

For the solar collector sections in Figs. 6 and 7, the temperature difference ($T_1 - T_2$) at a location midway between two tubes and the tube centerline is given as in [14]:

$$T_1 - T_2 = \frac{qL^2}{2KH} \quad (16a)$$

Where thermal conductivity of the plate for tube 1, k_1= 273 W/m.K; plate thickness, H_1 = 0.0005 m, thermal conductivity of the plate for tube 2, K_2 = 401 W/m.K and tube thickness, H_2 = 0.0102 m and L = 6.9 cm (0.069 m).

This solar collector design has 50% efficiency and therefore, net heat flux, q = 1010 W/m^2 (50% of Q_I (2020 Whm^{-2}day^{-1}). Therefore;

$$T_1 - T_2 = \frac{1010 \times (0.069)^2}{2[(273 \times 0.0005) + (401 \times 0.0102)]} = \frac{4.0861}{8.4534} = 0.57\ ^\circ\text{C} \quad (16b)$$

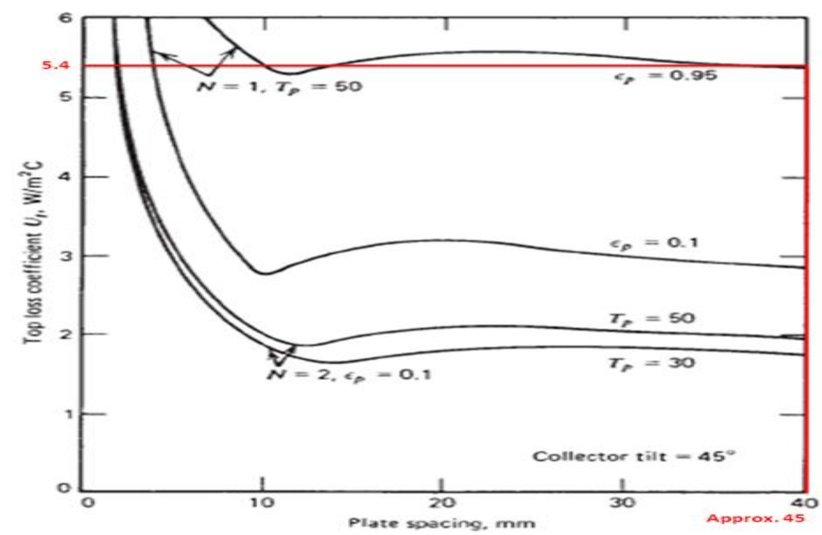

Fig. 5. Typical variation of top loss coefficient with plate spacing [11]

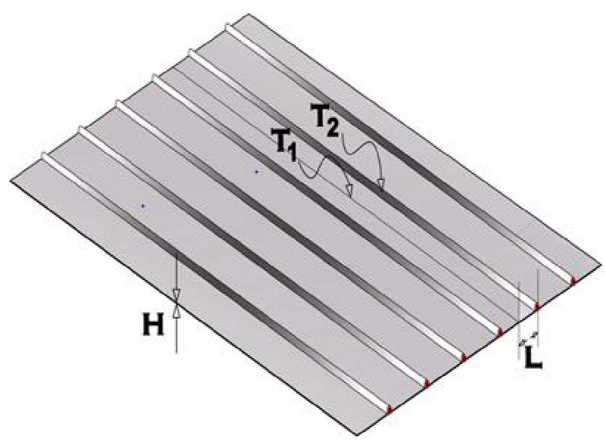

Fig. 6. Section of a solar collector absorber plate with flow tubes

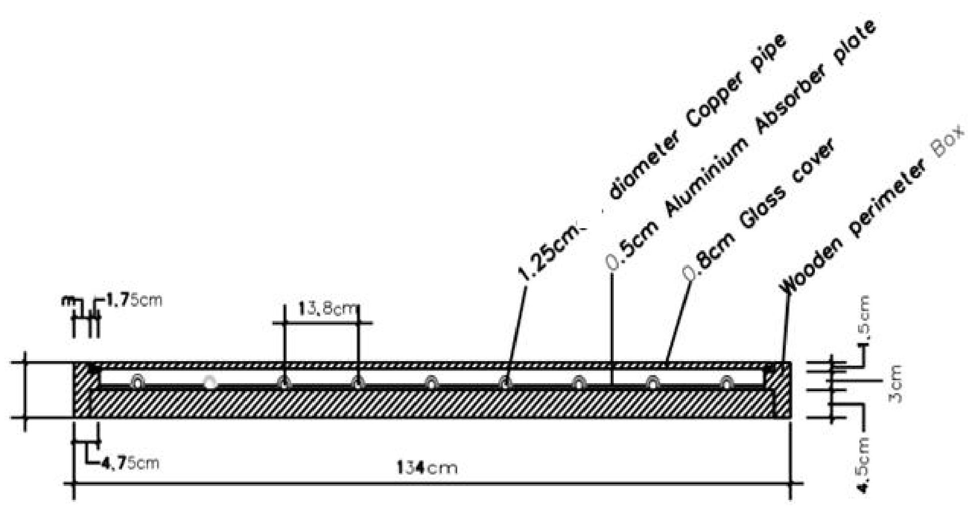

Fig. 7. Cross-section of our constructed solar collector with detailed dimensions

2.4 Thermal Expansion of the Solar Heating System

We looked at the copper grid and the tank design to ensure that the maximum pressure that the system will be subjected to due to fluid hydrostatics and thermal expansion will not exceed the test pressure, 150 psi (1030 KPa) of the system while holding water at temperature of between 66-70°C during peak insolation. Let the total pressure experienced by the system when filled with cold water at ambient temperature (26°C) be as in [15];

$$P_T = P_A - P_H \quad (17)$$

where P_A is atmospheric pressure (101 KPa) and P_H is the fluid hydrostatics pressure;

$$P_H = \rho_c g y \quad (18a)$$

Where ρ_c = density of cold water (1000 Kgm^{-3}), g = gravitational acceleration (9.81 ms^{-2}); and y = the height of storage tank from the supply header (0.65 m).

Therefore,

$$P_H = 1000 \times 9.81 \times 0.65 = 6376.5 \text{ Pa} = 6.3765 \text{ KPa} \quad (18b)$$

From (17), P_T = 6.3765 KPa+101 KPa = 107.3765 KPa

At 70°C; the density of hot water is calculated from the equation below:

$$\rho_h = \rho_c[1 + \gamma\Delta T]^{-1} \quad (19)$$

Where, ρ_h = the density of hot water at 70°C; ρ_c = the density of cold water at 26°C; γ = the coefficient of cubic expansion of water at 70°C (5.85×10^{-4} K^{-1}); and ΔT = (70 – 26 = 44°C). Therefore,

$$\rho_h = 1000[1 + (5.85\text{x}10 - 4 \text{ x } 44)]^{-1} = 974.91 \text{ Kgm}^{-3}$$

The expanded volume of water from the initial volume (V_1 = 0.075 m^3) can be obtained using:

$$\Delta V = V_1 \times \gamma \times \Delta T \quad (20)$$

Therefore,

$$\Delta V = 0.075 \times 5.85\text{x}10^{-4} \times 44 = 0.0019305 \text{ m}^3$$

The final volume of hot water at 70°C is therefore,

$$V_2 = V_1 + \Delta V = 0.0769305 \text{ m}^3.$$

Total pressure experienced in the solar water heating system when filled with hot water at 70°C can be deduced by equating the change in volume of fluid-in-pipe to the change in volume of the grid; and equating the change in volume of fluid-in-tank to the change in volume of the tank using the expression below:

$$\gamma\Delta T - \beta\Delta P = \gamma_V\Delta T + \Delta P\frac{D}{tE} \quad (21)$$

Where, γΔT = thermal expansion of liquid; $\gamma_V\Delta T$ = thermal expansion of the grid or tank; βΔP = compressibility of liquid under increased pressure due to constrained volume; and $\Delta P\frac{D}{tE}$ = increase in volume of vessel under increased pressure of fluid. So, the pressure increase can be calculated from Equation 21 as follows:

$$\Delta P = \frac{(\gamma - \gamma V)\Delta T}{B + \frac{D}{tE}} \quad (22)$$

2.4.1 Pressure increase in copper grid due to thermal expansion

For the copper grid,

γ_V = the coefficient of cubic expansion of copper grid = 51 x 10^{-6} K^{-1}; D/t = diameter-to-thickness ratio for the ¾" pipe is 19.4 and ½" pipe is 15.6; β = the compressibility factor of water at 70°C = 0.0004518[1/MPa] and E = elastic modulus of the copper = 120,000 MPa.

Therefore from (22),

$$\frac{(5.85 \times 10^{-4} - 51 \times 10^{-4}) \times 44}{4.518 \times 10^{-4} + (15.6/120000)}$$

= 40.39 MPa (for 44 degree rise in copper grid)

2.4.2 Pressure increase in steel storage tank due to thermal expansion

For the steel tank,

γ_V = the coefficient of cubic expansion of steel tank = 33 x 10^{-6} K^{-1}; D/t = diameter-to-thickness ration for the tank is 240 mm/0.6 mm =400; B = the compressibility factor water at 70°C = 0.0004518[1/MPa] and E = elastic modulus of the steel = 210,000 MPa.

Also from (22),

$$\Delta P = \frac{(5.85 \times 10^{-4} - 33 \times 10^{-6}) \times 44}{4.518 \times 10^{-4} + (400/210000)}$$

= 10.31 MPa (for 44 degree rise in steel tank)

2.4.3 Air volume to cushion the pressure increase due to thermal expansion

The required air volume (V_{EXP}) was calculated from the equation as in [10];

$$V_{EXP} = \frac{\Delta V.(PE+1)}{P_E - P_A} \quad (23)$$

Where, ΔV = expansion of volume (m^3); P_E = maximum pressure (Pa) and P_A = Pressure at ambient temperature, 26°C (Pa)

$$\text{So, } V_{EXP} = \frac{0.0019305\ (10.31 \times 10^6 + 1)}{10.31 \times 10^6 - 107.38 \times 10^3}$$

= 0.0019 m^3 (≅ 2 Liters)

The 2 liters air volume is maintained in the storage tank. Also an over-pressure relief valve rated 0.8 MPa (120psi) is installed on the storage tank as a secondary safety feature.

3. RESULTS AND DISCUSSION

3.1 Preliminary Field Test

The preliminary field test of the assembled solar water heater filled with cold water was done at a site where the unit received insolation throughout the day without shedding from trees or buildings. For optimum performance, the orientation of the flat-plate solar collector should be latitude +15^0 facing south for northern hemisphere [16]. As Port Harcourt is on latitude 4.75^{0}N, the stand constructed from 4 mm by 40 mm steel- angle Iron was made to orient the solar collector at 19.5^0 facing South as well as support the water storage tank.

During the preliminary tests, the tank and the connecting lines to the solar collector were not insulated as the unit was equally inspected for leaks to ascertain its integrity.

Mercury-in-glass thermometers (with temperature range 0-100°C) were clamped to the solar collector supply and return lines. Their readings were recorded as “Tin” and “Tout” respectively. The readings were recorded at 30 minutes intervals from 8:00hrs to 16:00hrs (local time) for two days: February 08, 2016 (hazy day) and February 11, 2016 (sunny day). The preliminary results are presented in Tables 3 and 4. The variations between the collector inlet and outlet temperatures are also presented in Figs. 8 and 9.

Figs. 8 and 9 show a very steep decline in the collector output temperatures at sunset. These figures also show that the optimum solar window within Port Harcourt on the days observed were between 10:30 hrs and 15:30 hrs (local time).

Table 3. Preliminary temperature readings collected on 8th February, 2016 (hazy day)

Time (hrs)	Tin (°C)	Tout (°C)	T_{RISE} = Tout-Tin (°C)
8:00	27	27	0
8:30	29	28	- 1
9:00	31	29	- 2
9:30	34	33	- 1
10:00	37	39	2
10:30	38	40	2
11:00	38	40	2
11:30	38	42	4
12:00	39	43	4
12:30	40	44	4
13:00	42	48	6
13:30	42	48	6
14:00	43	49	6
14:30	43	49	6
15:00	44	50	6
15:30	37	58	21
16:00	37	55	18

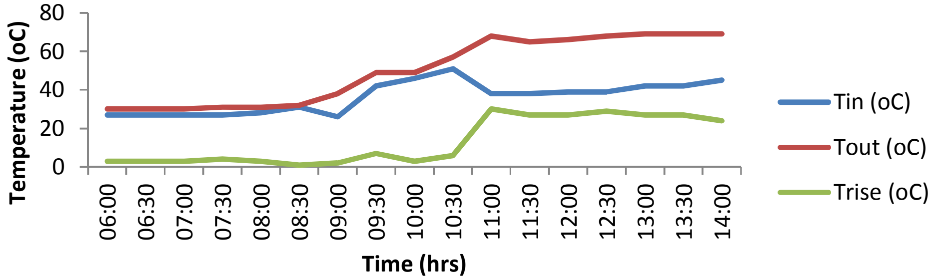

Fig. 8. Variations of solar collector inlet and outlet temperatures for readings obtained on a hazy day (8th February, 2016)

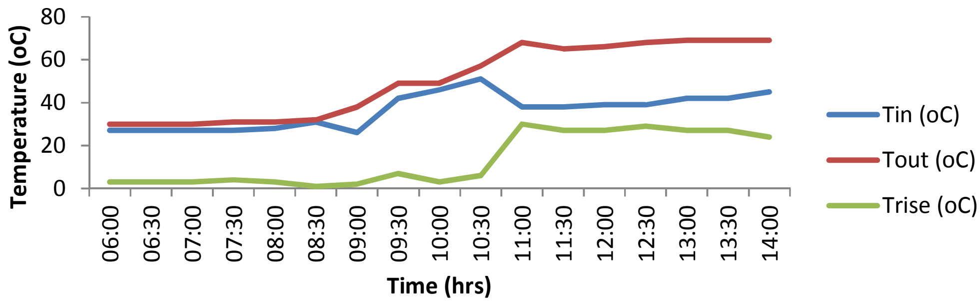

Fig. 9. Variations of solar collector inlet and outlet temperatures for readings obtained on a sunny day (11th February, 2016)

Table 4. Preliminary temperature readings collected on 11th February, 2016 (sunny day)

Time (hrs)	Tin (°C)	Tout (°C)	T_{RISE} = Tout-Tin (°C)
8:00	25	24	-1
8:30	26	25	-1
9:00	31	29	-2
9:30	39	37	-2
10:00	44	42	-2
10:30	45	52	7
11:00	46	56	10
11:30	40	67	27
12:00	41	69	28
12:30	42	74	29
13:00	43	76	33
13:30	44	74	30
14:00	44	76	32
14:30	45	75	30
15:00	46	75	29
15:30	47	67	20
16:00	44	65	21

3.2 Final Field Test Results and Discussions

The tank supply and return connections to the solar collector were covered with 10 mm fiber glass insulation material prior to the final field test. The readings were taken from 6:00 hrs to 18:00 hrs (local time) using mercury-in-glass thermometers. There were four sets of readings obtained at 30 minutes intervals. These were the collector inlet “Tin”; the collector outlet “Tout”; tank output and the ambient temperature. The results obtained for February 23, 2016 and February 24, 2016 are presented in Tables 5 and 6.

Table 5. Final temperature readings collected on 23rd February, 2016.

Time (hrs)	Ambient temp. (°C)	Tank temp. (°C)	Tin (°C)	Tout (°C)	T_{RISE} =Tout-Tin (°C)
6:00	30	37	27	30	3
6:30	30	38	27	30	3
7:00	29	38	27	30	3
7:30	29	40	27	31	4
8:00	30	37	28	31	3
8:30	31	37	31	32	1
9:00	33	37	36	38	2
9:30	34	37	42	49	7
10:00	35	38	46	49	3
10:30	36	38	51	57	6
11:00	38	48	38	68	30
11:30	36	51	38	65	27
12:00	40	54	39	66	27
12:30	39	57	39	68	29
13:00	41	58	42	69	27
13:30	40	61	42	69	27
14:00	46	60	45	69	24
14:30	47	64	47	74	27
15:00	48	63	48	72	24
15:30	48	64	47	67	20
16:00	42	62	47	68	21
16:30	41	60	48	61	13
17:00	38	59	47	57	10
17:30	35	53	45	52	7
18:00	33	56	42	47	5

Table 6. Final temperature readings collected on 24th February, 2016

Time (hrs)	Ambient Temp. (°C)	Tank Temp. (°C)	Tin (°C)	Tout (°C)	T_{RISE} =Tout-Tin (°C)
6:00	29	40	27	31	4
6:30	29	40	27	31	4
7:00	29	39	27	31	4
7:30	29	39	27	31	4
8:00	32	39	28	31	3
8:30	31	39	30	32	2
9:00	32	38	33	33	0
9:30	32	38	35	36	1
10:00	35	38	40	43	3
10:30	35	39	45	52	7
11:00	35	39	48	56	8
11:30	37	43	41	71	30
12:00	41	51	41	74	33
12:30	40	57	40	76	36
13:00	41	61	41	76	35
13:30	44	61	42	72	30
14:00	45	64	42	74	32
14:30	40	64	42	67	25
15:00	38	61	43	58	15
15:30	43	59	47	63	16
16:00	41	58	50	65	15
16:30	39	57	49	60	11
17:00	37	50	48	57	9
17:30	36	53	45	51	6
18:00	34	52	42	47	5

The final field tests performed on two sunny days whose results are presented in Tables 5 and 6; and Figs. 10 and 11 confirmed the preliminary findings. The T_{RISE} determined from the constructed solar collector is a very important quantity in determining the overall performance of the solar collector. The computed T_{RISE} falls within the usual values (10-30°C) for commercial flat-plate solar collectors. The results of this work indicate that a reasonable rise in the temperature of the heat extracting substance (in this case water) is achievable using the solar water heater. This process is useful in the inactivation of waterborne pathogens thereby making drinking water safe. Boiling water kills or inactivates viruses, bacteria, protozoa and other pathogens by using heat to damage their structural components and disrupt essential life processes. This can begin at temperatures as low as 55°C for certain pathogens [17]. Also, the heated water (using the present solar water heater) can be used for bathing, cooking, etc, thereby helping to save money that would have been used to secure other sources of energy for provision of bathing water (hot water) for domestic use in our homes. From Table 6, our solar water heater was able to raise the temperature of input water to about 76°C. Our result is within the range of the result of 250-Liter Capacity Solar Water Heating System at Danjawa Renewable Energy Model Village designed to heat water from a temperature of 25°C to at least 70°C for various applications in a typical health centre [18]. The present result shows that our solar heater has a higher maximum output temperature of 76°C when compared with that of another solar water heater constructed based on the thermosyphon principle with maximum fluid output temperature, collector temperature, and insolation of 55°C, 51°C, and 1,480 W/m^2, respectively, which were obtained on a sunny day [19].

Like other renewable energy systems, solar-powered water heaters minimize negative environmental effects and operate at reduced costs because they do not have the hazards introduced by fossil fuels [19]. The use of our designed solar energy system for heating purposes in our homes will aid in reducing the level of pollutants that would have been released to our immediate environment through the use of fossil fuels and other non friendly energy sources.

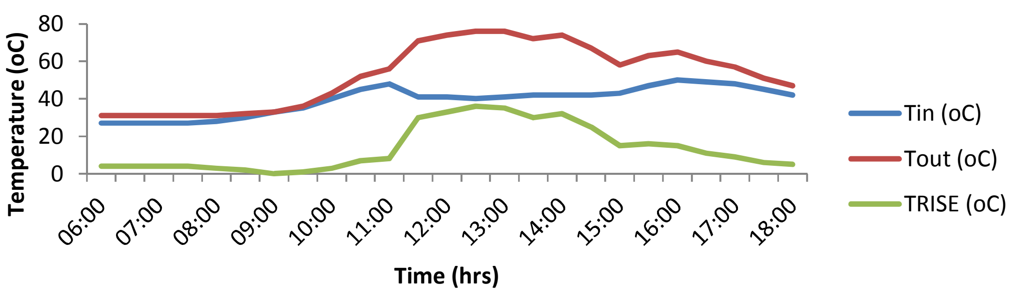

Fig. 10. Variations of solar collector inlet and outlet temperatures for readings obtained on a sunny day– 23rd February, 2016

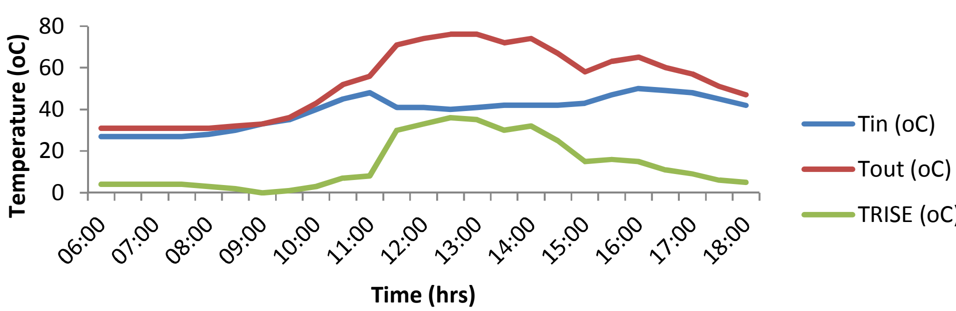

Fig. 11. Variations of solar collector inlet and outlet temperatures for readings obtained on a sunny day– 24th February, 2016

4. CONCLUSION

This research work involved the design and construction of a solar water heating system with 2.3 m^2 solar collector area proposed to extract enough solar energy to raise the temperature of 0.075 m3 of water by 34°C based on the available solar window to Port Harcourt. The unit was tested within the days of optimum solar window (approximately 3 hrs). Ambient temperature, inlet temperature and outlet temperature were observed to vary from 37 to 44°C; 41 to 42°C and 71 to 76°C respectively. This result gave a temperature rise (T_{RISE}) of between 30°C and 36°C as proposed. This solar system has the capability of providing boiled water for domestic and other uses and at the same time, it is very environmental friendly. Our designed solar water heater is intended for use in households and hospitals as alternative source of heating water as it will reduce the rate at which fossil fuel is burnt for water heating. Also the heated water (using the present solar water heater) can be used for bathing, cooking, etc, thereby helping to save money that would have been used to secure other sources of energy for provision of bathing water (hot water) for domestic use in our homes. The use of our solar heater will also reduce the level of pollutants that would have been released to the environment through the use of fossil fuels and other non friendly energy sources. We therefore suggest that solar water technology should be domesticated in order to promote healthy living.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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