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PERFORMANCE EVALUATION OF A LOCALLY FABRICATED CYLIDRICAL SOLAR WATER HEATER

Benjamin O. Udoye[1]; Joseph J. Obodoeze[2]
[1]Department of Chemical Engineering Technology, Federal Polytechnic, Oko, Anambra State, Nigeria;
[2]Department of Chemical Engineering Technology, Federal Polytechnic, Oko, Anambra State, Nigeria;
[1] benudoye@yahoo.com, +2348065991888; [2] jide.tees@yahoo.com, +2348036774822

Abstract
The design, construction, and measured performance of a cylindrical solar water heater capable of generating hot water for domestic use were presented. It is made from locally sourced polycarbonate material which served as the glazing material and a spiral black painted copper tube that serves as an absorber of solar collector. The entire system was tested under meteorological condition of Owerri, Nigeria at three different mass flow rates of 0.001kg/s, 0.002kg/s and 0.003kg/s. The effect of orientation on the cylindrical solar water heater was equally determined by running the test in different orientations of North-South and East-West directions. The result obtained indicates that maximum instantaneous efficiency of 51.10% and a maximum temperature of 68.5^{o}C corresponding to 34.5^{o}C increase in water temperature is possible. In addition, it was found that cylindrical solar water heater orientation does not affect its performance. It was suggested that further optimization of the equipment will still improve its efficiency.
Keywords: Irradiation, Greenhouse effect, Deforestation, Flow rate, Thermal conductivity

Introduction

Heating water dominates the energy needs of households worldwide. In United States of America households, heating water is second only to heating and air conditioning in energy consumption (Arizona Solar Centre, 2007), and for households in developing countries, heating water is often the most energy-intensive process and therefore the most expensive or time-intensive. In communities throughout the developing world, poor households struggle to meet their hot water needs. Some households rely on biomass for their hot water needs. In many countries, demand for fuelwood is one of the principal contributors to deforestation (Rasheed,1995). Others rely on electricity or liquid fuels such as propane to heat their water. These fuel options are unsustainable as they are expensive and contribute to the buildup of greenhouse gases in the atmosphere. Many communities face limited or intermittent access to fuel and/or electricity, limiting their ability to access hot water for hygiene and domestic uses.

One potential solution to this problem is the use of solar energy to heat water. Solar water heating technology is used in many parts of the world including the United States of America, China, India, and the Middle East. These systems have been adopted for a wide range of use patterns and climate conditions. However, most existing systems are only affordable to wealthy clients. These systems often include sophisticated pump systems and advanced materials. While these systems are profitable to their developers, they are often far beyond the financial reach of households in poor communities of developing countries such as Nigeria.

In recent times, engineers and scientists can harness solar energy with common materials and basic technologies. One of the simplest versions is the cylindrical solar water heater. Access to a low-cost water heater would provide numerous benefits to households in developing communities. Many households could reduce their fuel cost by eliminating or reducing their need for wood, gas, and electricity to heat water. Substituting traditional fuel sources with solar energy would reduce carbon emissions. Domestic solar water heating systems can produce net greenhouse gas savings in 2.5 – 5.0years(Crawford, et al, 2003). Furthermore, reducing biomass consumption would relieve stress on depleted forests. There are also health benefits

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associated with solar heaters due to reduced exposure to toxins and pollutants released from burning fuels. By enabling access to the solar heater, households could improve their health and hygiene.

Objectives of the work

The objectives of the work were,

•to design and evaluate the performances of cylindrical solar water heater

•to develop a sustainable solar water heater with local content to eliminate risks associated with the covid-19 pandemic.

Materials and method

The following material were procured and used for this work,

Table 1:**Materials Used for the Design and Fabrication of Solar Water Heater**

Insulated water storage tank	1 piece
Table (1.8m height)	1 piece
Table (0.8m height)	1 piece
Polycarbonate material (glazing material)	Designed
Copper coil (absorber material)	Designed
Circular transparent plastic with hole at the centre	2 pieces
Insulated cup (water collector)	1 piece
Mercury in glass thermometer	1 piece
Solarimeter	1 piece
Thermocouple	5 pieces
Insulated hose	2 good lengths
Valves (regulating taps)	2 pieces
Design specification	
The design specification for construction of cylindrical solar water heater is shown below,	
Glazing material (transparent plastic)	
Thickness	2mm
Length	0.9m
Diameter (d)	0.4m
Base (perimeter of circular end = πd)	1.3m
Absorber tube (copper)	
Outer diameter of absorber tube (D_{abs})	12.7mm

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Length of absorber tube, L (calculated)	18.0m
Overall heat transfer coefficient	1.93W/m^{2}K
Tilt angle	0^o
Expected water temperature rise (assumed)	27^{o}C
Paint used in absorber tube	black.

Design method

In the design, a cylindrical transparent plastic was sealed at its end with the same cylindrical material which was used as the glazing material that transmits maximum possible solar irradiation to the absorber tube and thereby acts as energy trapper. The cylindrical material what was used to seal its end helps to prevent dust and moisture contents from settling on the absorber tube surface.

A 12.70mm outer diameter and 11.40mm inner diameter, black painted copper tube was chosen as the absorber tube material. It is necessary to calculate the length of the copper material used as the absorber tube for adequate construction of the heater. The actual work of solar energy conversion to thermal energy is done by the absorber tube. Copper material was selected because of its high thermal conductivity and high resistance to corrosion (nonreactive with water).

The solar intensity of Owerri in Imo state was used in the design. And because the heater is expected to generate hot water at all weather conditions, the lowest average monthly insolation was used in the design. This lowest average monthly insolation level which occurs in July is 13.02MJ/m^2 (Anyanwu, et al., 2003).

Heat Coefficient (U_L)

The absorber coil and the plastic cylinder (polycarbonate material) arrangement are assumed to be concentric, as such the overall heat loss transfer coefficient of the heater is the sum of the edges and curved surfaces heat loss coefficients, i.e.

$U_L = U_e + U_C$ .....equ.(1)

But the edge losses of the heater is assumed to be zero(0), because of circular shape of the edges(Hussain, 2006). Equation (1) therefore becomes,

$U_L = U_C$ .....equ.(2).

The losses is by radiation,($h_{1,r}$) and convection,($h_{1,c}$), between absorber and plastic cylinder. Again, there are heat losses by radiation,($h_{2,r}$) and convection,($h_{2,c}$), due to wind effect to the ambient. The diagram of the thermal circuit is shown in fig. 1 below.

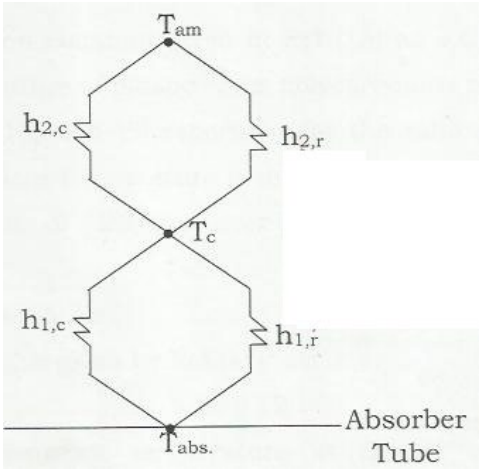


Fig. 1: The thermal circuit diagram.

Therefore, from the thermal circuit diagram,

$U_C = (1/(h_{1,c}+h_{1,r})+1/(h_{2,c}+h_{2,r}))^{-1}$ .....equ.(3).

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Since, from equ.(2), $U_L = U_C$, equ.(3) now becomes,

$U_L = (1/(h_{1,c}+h_{1,r})+1/(h_{2,c}+h_{2,r})^{-1}$ …….equ.(4).

The radiation heat transfer coefficient from plastic cylinder to ambient is given as,

$h_{2,r} = \sigma(T_C^2+T_{sky}^2)(T_C+T_{sky})/(1/\varepsilon_c+(A_c/A_{sky})(1/\epsilon_{sky}-1))$ ……equ.(5),

where, σ = Boltzmann constant given as $5.67x10^{-8}$W/mK, T_C = temperature of plastic cylinder, given as ratio of T_C to T_{am} , and ε_C = emissivity of plastic cylinder given as 0.82(Holman,2002). The ratio of T_C to T_{am} is from 1.0 – 1.5(Saraja, et al,1997), and using an average of 1.25, $T_C/T_{am} = 1.25$ ……equ.(6),

therefore $T_C = 1.25 \times T_{am} = 1.25 \times 31^oC = 38.75^oC$.

Sky temperature is given as,

$T_{sky} = (T_{am} – 6)$ ……equ.(7) (Incropera, et al,2001).

Since the area of sky is by far, larger than the area of plastic cylinder, equ.(5) will reduce to,

$h_{2,r} = \sigma(T_C^2+T_{sky}^2)(T_C+T_{sky})/(1/\varepsilon_c)$ ……..equ.(8),

and substituting values in equ.(8), we have, $h_{2,r} = 5.67x10^{-8}(38.75^2+25^2)(38.75+25)/(1/0.82) = 0.0063W/m^2K$.

Coefficient of heat convection due to wind is given as,

$h_{2,C} = 2.8+3.0V$ ……..equ.(9),

for $0 \leq V \leq 7$ m/s(Watmuff, et al,1977), where V, is the velocity of wind and in Owerri, a wind velocity of 1m/s is common, therefore wind velocity of 1m/s is chosen, and $h_{2,C} = 2.8+3(1) = 5.8W/m^2K$.

The radiation heat transfer coefficient between copper coil and plastic cylinder,

$h_{1,r}= \sigma(T_{abs}^2+T_C^2)(T_{abs}+T_C)/(1/\varepsilon_{abs}+(A_{abs}/A_C)(1/\varepsilon_C-1))$……equ.(10) (Duffie,et al,1991).

Since area ratio = diameter ratio,

$h_{1,r} = \sigma(T_{abs}^2+T_C^2)(T_{abs}+T_C)/(1/\varepsilon_{abs}+(D_{abs}/D_C)(1/\varepsilon_C-1))$ ……..equ.(11),

where ε_{abs} = emissivity of copper coil absorber = 0.98(Saraja, et al,1997). Also, absorber temperature at steady state is 1.2-1.5 times, higher than exit water temperature (Saraja, et al, 1997).

Haven considered a temperature increase of 27°C and ambient temperature of 31°C, and a factor of 1.5, Tabs=1.5x58oC = 87°C.

Therefore, $h_{1,r} = 5.67x10^{-8}(87^2+38.75^2)(87+38.75)/((1/0.98)+(0.18/0.4)(1/0.82-1)) = 0.0580W/m^2K$.

The convection heat transfer coefficient between the copper coil and plastic cylinder, $h_{1,C}$ is calculated from Nusselt correlation, i.e.,

$h_{1,C} = KNu/X$ …….equa.(12),

where,

Nu = Nusselt number = $0.55(GrPr)^{0.25}$ ……equ.(13).

The Grash of number, Gr is the ratio of buoyant force to the viscous force acting on air between copper coil and plastic cylinder, i.e.

$Gr = g\beta(T_{abs}-T_C)X^2/\nu^2$ ……..equ.(14),

where g = acceleration due to gravity = $9.81m/s^2$, β = coefficient of volume expansion = $1/T_{mean}(K) = 1/335.86$, X = characteristic length between copper coil absorber and plastic cylinder = $(D_{abs}+D_C)/2 = (0.18+0.4)/2 = 0.26$m, ν = kinematic viscousity of air at mean temperature of copper coil and plastic cylinder, obtained from a table(Twari,2006), as $19.32x10^{-6}m^2/s$.

From equ.(14), $Gr = 9.81(1/335.86)(87-38.75)0.26^3/(19.32x10^{-6})^2 = 6.64x10^6$, Pr = Prandtl number, obtained from table(Tiwari,2006), as 0.700, and from equ.(13), $Nu = 0\text{-}55(6.64x10^6x0.700)^{0.25} = 25.54$, K = thermal conductivity of air at mean temperature(335.86K) of absorber coil and plastic cylinder, obtained from table(Tiwari,2006) as 0.0289W/m°C.

Therefore, from equ.(12), $h_{1,C} = 0.0289X25.54/0.26 = 2,84W/m^2K$. And, from equ.(4), $U_L = (1/(0.058+2.84)+1/(0.0063+5.80))^{-1} = 1.93W/m^2K$.

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energy absorbed by copper tube (q_{abs})

At steady state, the net rate of thermal energy absorption by the copper absorber tube from the incident solar radiation = the net rate of heat transferred to the water, i.e.,

$Q_U = Q_{abs}$ .....equ.(15).

The net heat absorbed per unit area of copper tube absorber,

$q_{abs} = I_{(t)}R_{(b)}(\tau\alpha)-q_L$ .....equ.(16),

Where $I_{(t)}$, is the total solar radiation intensity, $R_{(b)}$, is the tilt correction factor, τ, is the transmissivity of copper material, α, is the absorptivity of copper material and q_L, is the rate of energy loss.

And the rate of energy loss,

$q_L = U_L(T_{abs}-T_{am})$ .....equ.(17).

Then, substituting equ. (17) into equ. (16) and at steady state, we have,

$q_{abs} = I_{(t)}R_{(b)}(\tau\alpha)-U_L(T_{abs}-T_{am}) = q_U$ .....equ.(18).

July is the worst month of solar radiation harvest in Owerri and its average intensity for a horizontal surface is 13.02MJ/m^2day (Anyanwu, et al,2003). And, from months of July-August, sunshine duration per day ranges from 0-8 hours per day (Anyanwu, et al,2003). But in this design analysis, 4 hours sunshine duration per day was chosen to give solar intensity of 904.17W/m^2. Transmissivity, τ, of plastic cylinder cover material and absorptivity, α of black painted copper tube are 0.82 and 0.98 respectively. The tilt correction factor, $R_{(b)}$ is the ratio of radiation on the tilted surface to that on a horizontal surface. And, since the cylindrical solar water heater is positioned horizontally, $R_{(b)}$ = 1.0 . Therefore, from equ.(18), q_{abs} = 904.17x0.98x0.82-1.93(87-31) = 618.51W/m^2.

And still from equ.(18), $q_{abs} = q_U$, at steady state. Therefore, useful energy transferred to the water = 618.51W/m^2.

Estimation of copper tube length (L)

The rate of useful energy absorbed by the copper tube is equal to the rate at which the fluid internal energy flowing through the tube increases for an internal flow with constant heat flux condition,

That is $Q_u=q_uA_{abs}$, ...equ.(19),

where A_{abs} is the copper tube absorber surface area.

The rate of increase in internal energy of the fluid is given by,

$Q_u=\dot{m}C_p(T_e-T_i)$.....equ.(20),

where $\dot{m}$ is the mass flow rate of the fluid(water), C_p is the specific heat capacity of water at constant pressure, T_e and T_i are exit and inlet temperatures of the water stream respectively.

The absorber surface area,

$A_{abs}=\pi D_{abs}L$ .....equ(21),

where D_{abs} is the diameter of the copper tube and L is the length of the copper tube. On assumption that half of the copper tube surface is exposed to the radiation, therefore equ.(21) becomes,

$A_{abs}=(\pi D_{abs}L/2)$.....equ.(22).

Thus substituting equs.(20) and (22) into equ.(19), we have,

$q_u\pi D_{abs}L/2=\dot{m}C_p(T_e-T_i)$.....equ.(23),

therefore,

$L=2\dot{m}C_p(T_e-T_i)/q_u\pi D_{abs}$.....equ.(24).

The ambient temperature was considered as the water inlet temperature i.e. T_i=31°C and increase in water temperature of 27°C due to heating with the solar heater was chosen, therefore water exit temperature T_e=31°C+27°C=58°C.

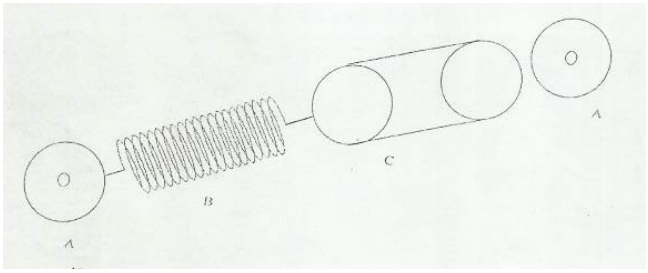
Mean temperature, $T_{mean}=(T_e+T_i)/2=(58+31)/2=44.5$°C, therefore specific heat capacity at constant pressure, $C_p$read from a property table at mean temperature of 44.5°C=4174KJ/kg°C.

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Also, an assumed mass flow rate, $\dot{m}$, for a gravity driven flow of 0.002kg/s was used in the design. Therefore, L=(2X0.002kg/SX4174J/kgCX27°C)/(618.51W/m²X3.142X0.0127m)=18.26m .

Construction details and system assembly

The entire length of the copper tube was reduced by spiral shape formation (copper coil of 0.18m diameter). Five thermocouples were brazen properly in five equally spaced holes in the tube (coil) to measure temperature of water running through the tube at five different points. The tube was painted black to increase radiation absorptivity of the tube. The flat transparent plastic was shaped into a cylinder of 0.4m diameter by heating over a flame. The prepared copper coil was installed in the transparent plastic cylinder and the ends of the cylinder were sealed with two circular transparent plastics with one hole each drilled for passage of the tube ends of the coil as shown in fig.2 below;



KEY
A – Circular plastic cover
B –Spiral copper tube
C – Transparent cylindrical plastic

Fig.2:Aligning diagram of circular plastic cover, spiral copper tube and transparent cylindrical plastic

The cylindrical solar water heater was placed on a table that is 0.8m high, wedged against rolling off. One end of the tube was connected to an insulated hose connected to an insulated water storage tank raised 1.8m high for pressure head (gravity) flow of water into the heater. Two valves are attached to the part of hose nearer to the tank. The valve immediately after the tank is used to open and close the tank while the other valve is used to regulate the flow rate of water. Also the exit end of the heater was connected to an insulated hose leading to an insulated water collector (cup). This system configuration is shown in fig.3 below:

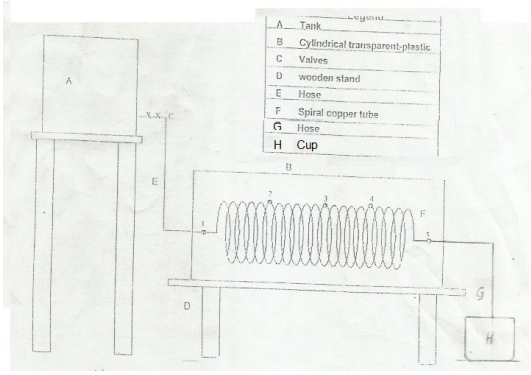


Fig.3: A line diagram of cylindrical solar water heater at operation

Equipment performance test

The heater was tested by allowing cold water at three different mass flow rates (0.001kg/s, 0.002kg/s and 0.003kg/s) to flow through the heater at two different orientations (east-west and north-south) from 8am to 5pm daily, for twenty days. The readings taken were the **solar intensity** with solarimeter, **ambient temperature**, and **temperature** of water in the storage tank, in collector (cup)with mercury thermometer and in the copper tube with the inserted thermocouples, at 30 minutes interval. Graphs of temperature vs. time (only that of figure 22 shown here for analysis), temperature rise vs. time, efficiency vs. time and solar intensity vs. time, for each flow rate and orientation were generated. The cylindrical solar water heater operated on the design mass flow rate of 0.002kg/s for eight consecutive days from 21/10/16. At first four days, the heater was positioned in the east-west direction while it was positioned in the north-south direction for the last four

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days. On a mass flow rate of 0.003kg.s, the cylindrical solar water heater was operated for six days starting from 29/10/16 –3 /11/16 with the orientation of the heater in the direction of north-south in the first three days and east-west for the last three days. Equally, in another six days that is 04/11/16 -09/11/16, a mass flow rate of 0.001kg/s was used in operation of the cylindrical solar water heater. The cylindrical water heater was positioned in the first three days and last three days in the east-west and north-south directions respectively. The solar intensity temperature, time for water heating and time were also variables considered as shown in figures 4 to 22 below.

Collector efficiency (η)

Efficiency is the amount of useful energy taken up or absorbed by a material. The collector efficiency is a parameter for comparing various types of collectors. Efficiency can be done hourly or overall. It depends on the analyst. The efficiency of this work was done hourly.

Efficiency was evaluated with the formula, $\eta = Q_U/A_{abs}I_{(t)}$……equ.(25), (Tiwari,2006), where Q_U is net rate of heat transferred to the water, $I_{(t)}$ is the total solar radiation intensity and A_{abs} is surface area of copper absorber tube. The values used for the plot of efficiency graph were obtained using equ.(25).

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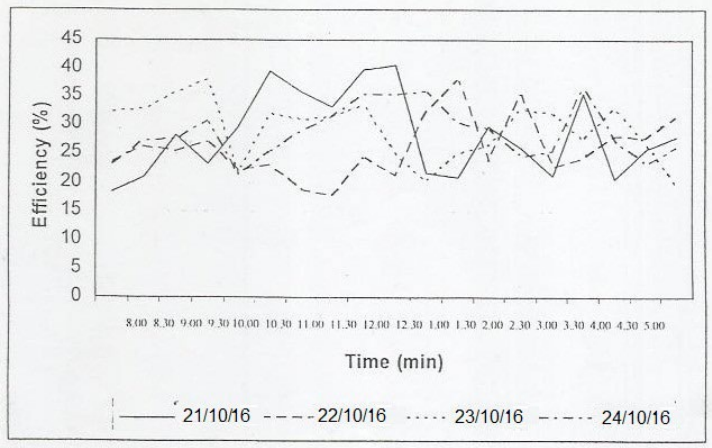


Fig. 4Efficiency against time at 0.002Kg/s east-west orientation

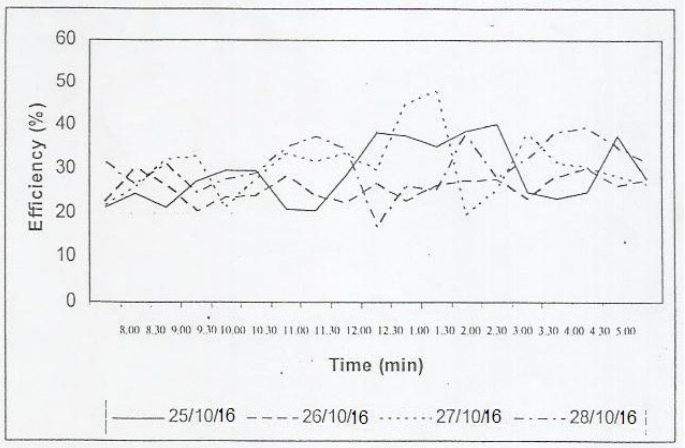


Fig. 5Efficiency against time at 0.002Kg/s north-south orientation

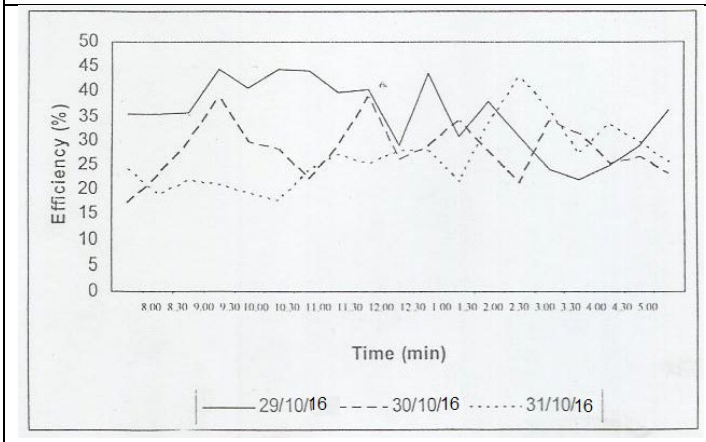


Fig. 6 Efficiency against time at 0.003Kg/s north-south orientation

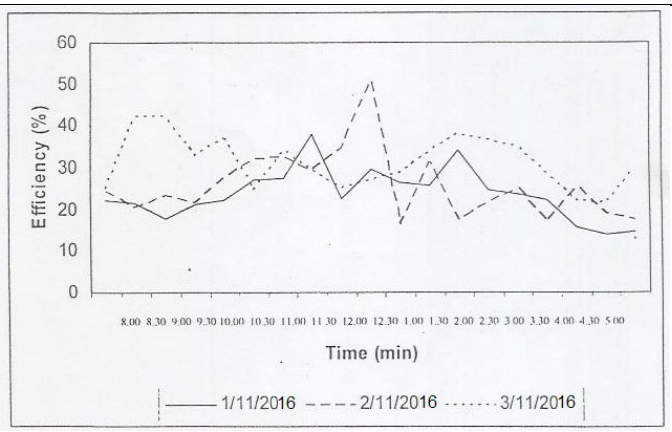


Fig.7Efficiency against time at 0.003Kg/s east-west orientation

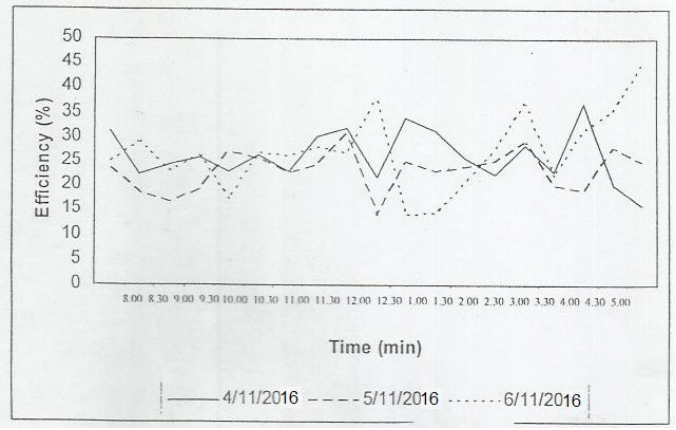


Fig. 8 Efficiency against time at 0.001Kg/s east-west orientation

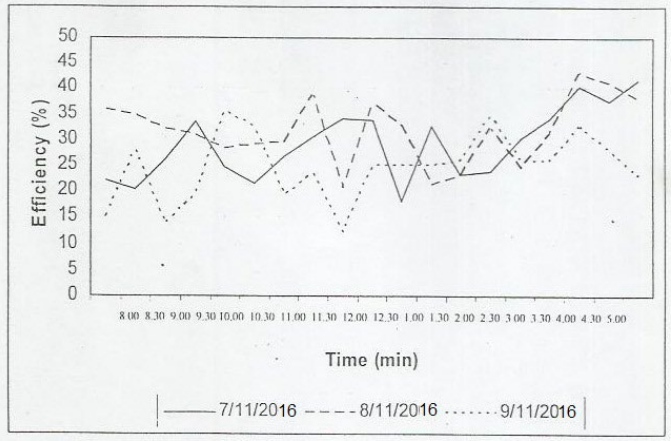


Fig. 9 Efficiency against time at 0.001Kg/s north-south orientation

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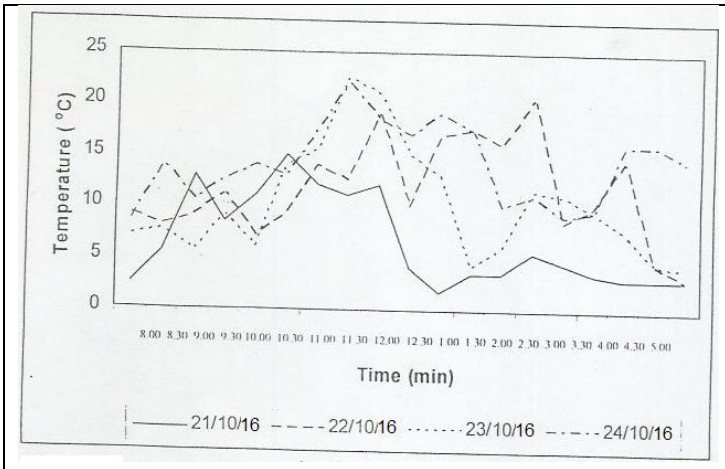


Fig. 10 Water temperature rise against time at 0.002Kg/s east-west orientation

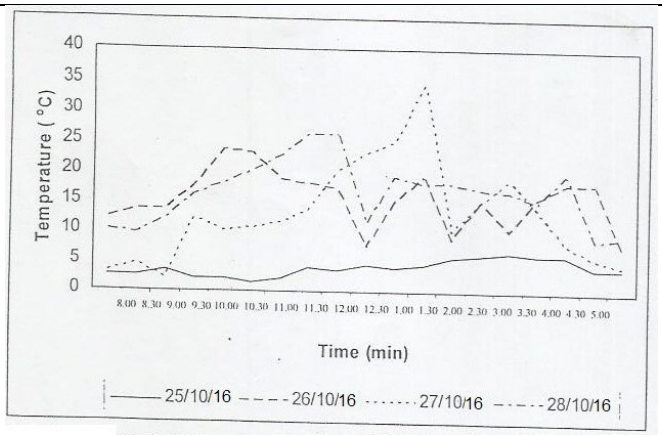


Fig. 11 Water temperature rise against time at 0.002Kg/s north-south orientation

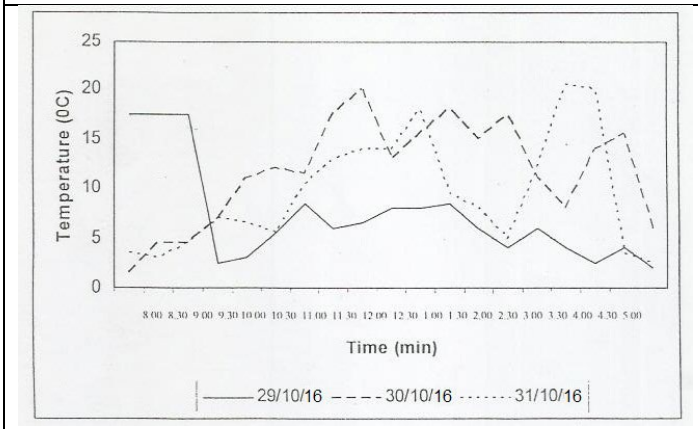


Fig. 12 Water temperature rise against time at 0.003Kg/s north-south orientation

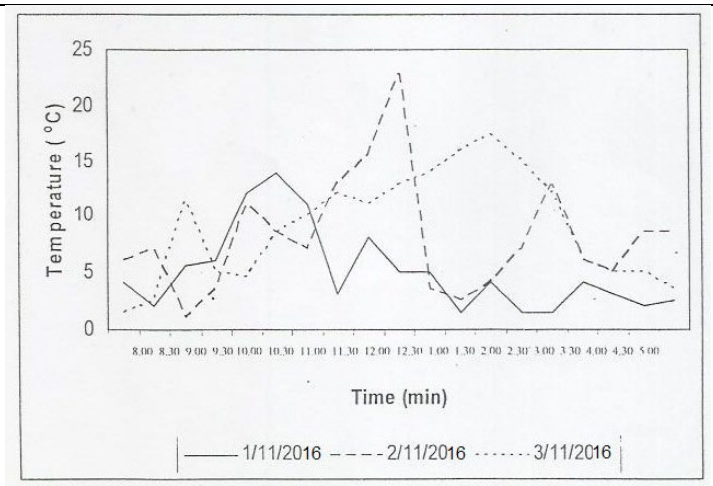


Fig. 13 Water temperature rise against time at 0.003Kg/s east-west orientation

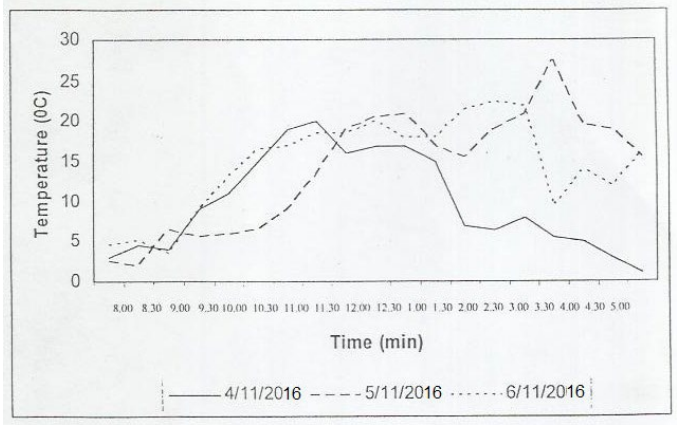


Fig. 14 Water temperature rise against time at 0.001Kg/s east-west orientation

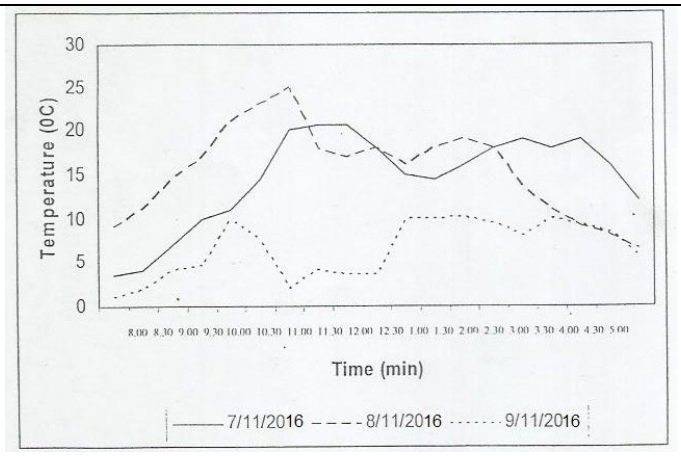


Fig. 15 Water temperature rise against time at 0.001Kg/s north-south orientation

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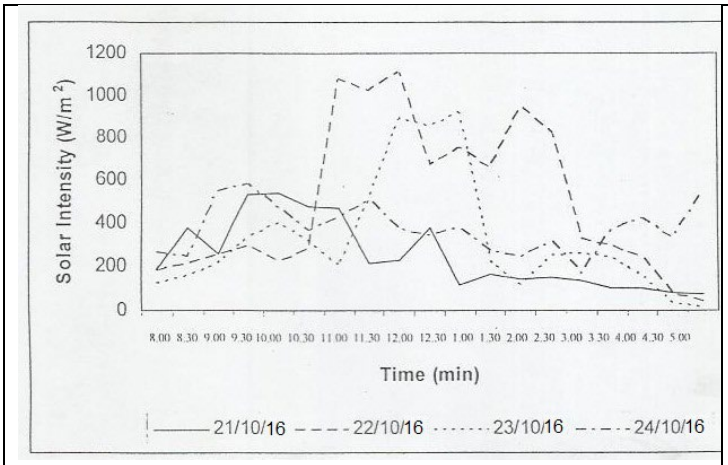


Fig. 16 Solar intensity against time at 0.002Kg/s east-west orientation

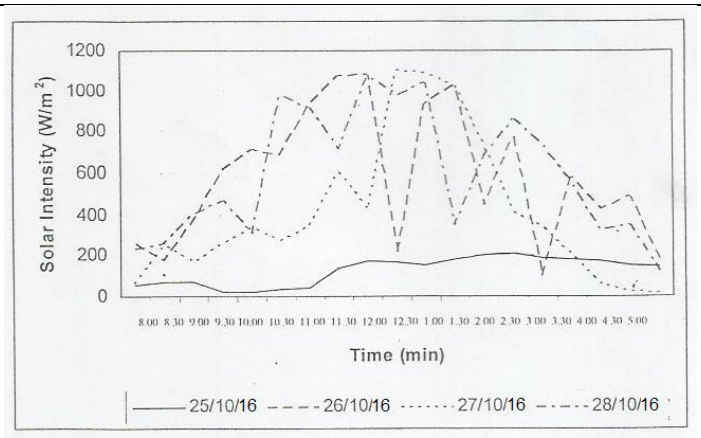


Fig. 17 Solar intensity against time at 0.002Kg/s north-south orientation

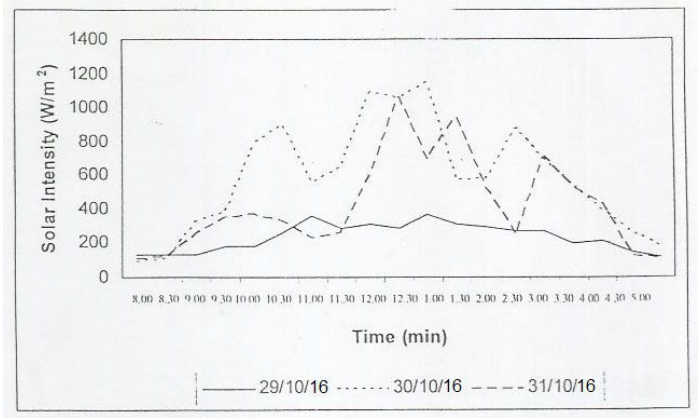


Fig. 18 Solar intensity against time at 0.003Kg/s north-south orientation

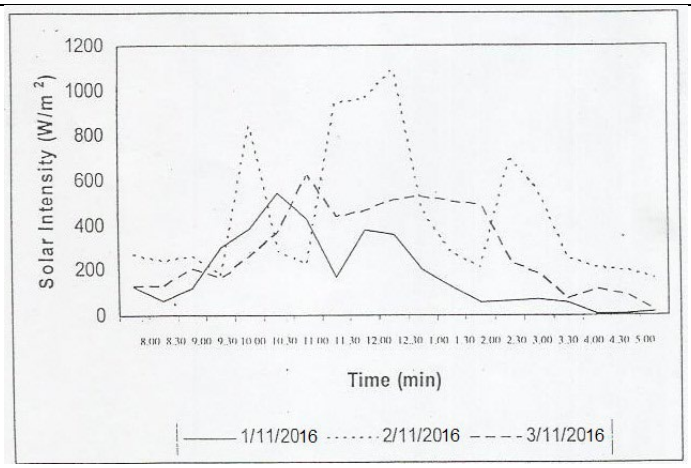


Fig. 19 Solar intensity against time at 0.003Kg/s east-west orientation

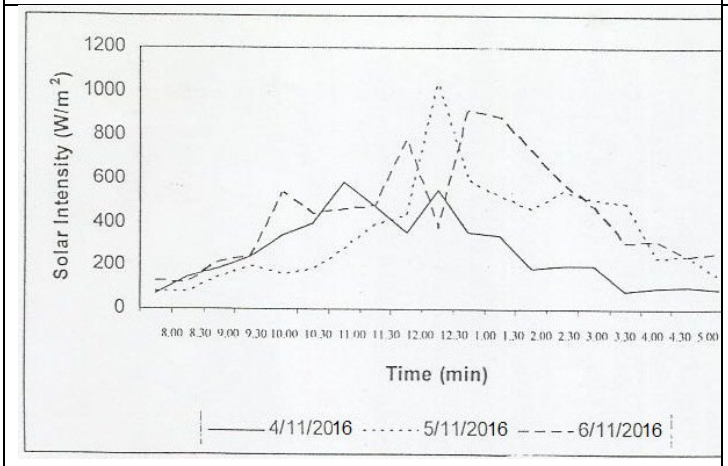


Fig. 20 Solar intensity against time at 0.001Kg/s east-west orientation

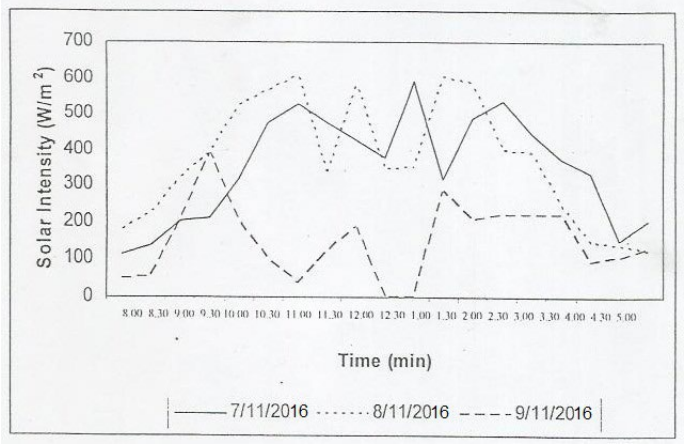


Fig. 21 Solar intensity against time at 0.001Kg/s north-south orientation

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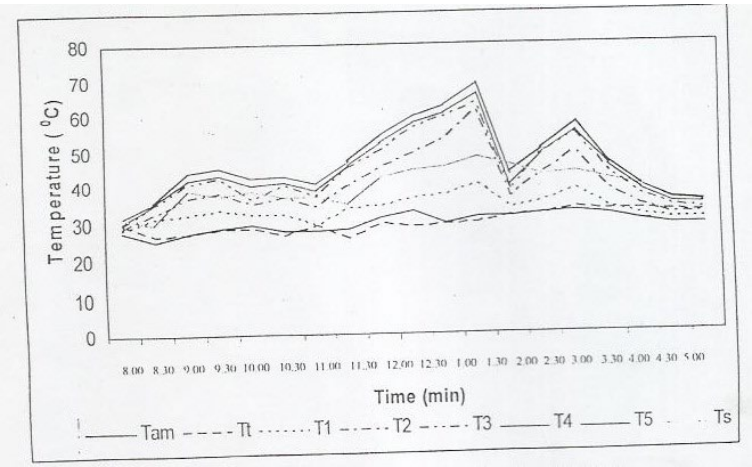


Fig 22: Experimental result on 27/10/16 at 0.002Kg/s north-south orientation

Result obtained and discussion

The result of the performance tests carried out with Minitab and Mat-lab showed that;

i. The graphs of Intensity and Temperature vs. Time contained in figs. 10-21 showed a similar pattern of rise and fall in temperature as the intensity changes. The performance of the cylindrical solar water heater, therefore, does not depend on its orientation. And this implies that the cylinder due to its shape allows maximum possible solar intensity to reach the absorber tube no matter the orientation. The poorest temperature rise performance recorded during the experimental period is shown in fig. 11 on 25/10/16 with the design mass flow rate of 0.002 kg/s. This was as a result of heavy overcast weather condition observed on that day. The solar intensity recorded that day was equally very low, with the lowest value being 26W/m^2 and the highest value being 220W/m^2 as shown in fig. 17. Also, it is observed from fig. 17 that a high solar intensity of 1025W/m^2 was recorded on 27/10/16, which resulted in a higher temperature rise on that same day. The inference drawn from comparing the result of 25/10/16 and 27/10/16 is that solar intensity is directly proportional to water temperature rise.

ii. Efficiency is the amount of useful energy taken up or absorbed by a material. It was observed that an overcast day due to low solar intensity as shown in fig. 18 on 29/10/16 has maximum efficiency of 44.44% shown in fig.6 which is greater than maximum efficiencies of clear days with higher solar intensities and of the same mass flow rates. The reason is that at high solar intensity, there tend to be greater loss of heat than at lower intensity and therefore percentage useful energy(efficiency) is lower. This is in consonance with this familiar equation used in calculating efficiency, $\eta=Q_u/A_{abst}I_{(t)}$,where η= efficiency, Q_u= heat absorbed, A_{abst}= area of absorber tube and $I_{(t)}$= solar intensity. Observation is in line with the above equation. Also, efficiency is best at the highest mass flow rate(0.003kg/s)at the same solar intensity. This implies that at any point in time, enough water will be available to extract maximum possible thermal energy from the collector, and this is achieved when mass flow rate is higher than when mass flow rate is low. Therefore, less thermal losses are expected at higher mass flow rates, which result in higher thermal efficiencies. This made the efficiency of the experimental operation of 0.003 kg/s mass flow rate to attain the highest efficiency of about 51.10% recorded in the experiment as shown in fig.7 on 02/11/16 at a solar intensity of about 1087W/m^2 shown in fig.19.

iii. At a mass flow rate of 0.002 kg/s(design mass flow rate), the highest exit water temperature measured was 68.5^{o}C as shown in fig. 22 on 27/10/16 which corresponds to an increase in water temperature of 34.5^{o}C as shown in fig. 11 on the same day. The temperature rise is greater than 27^{o}C used in the design. This is a positive result since the performance increase in temperature of the heater is greater than the design temperature increase chosen.

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Conclusion

The cylindrical solar water heater responds to changes in weather conditions and functions least effectively on an overcast weather. The maximum achievable temperature of a cylindrical solar water heater depends on solar intensity and mass flow rate of water. Thus, at the same solar intensity, the rise in temperature of water is inversely proportional to the mass flow rate of water. Hence, the operation at the lowest mass flow rate yields the hottest water. This is true since the heat capacity of a fluid at the same solar intensity is not the same for different mass flow rates.

The cylindrical solar water heater with local content, haven conformed to the parameters of temperature, intensity, efficiency, time, and it was found that it can replace biomass and electrical energy sources to eliminate health risks associated with post Covid-19 pandemic. However, further optimization of the equipment is suggested to still improve its efficiency.

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