Original Research Article

PERFORMANCE OF A SOLAR WATER FLAT PLATE COLLECTOR MADE FROM LOCALLY AVAILBLE MATERIALS.

Abstract:

A solar water heater is one of the ways through which sunlight energy can be harnessed for domestic use. The performance of a typical solar water heater made from locally available materials was determined and in the process a solar water heater is designed, construct and tested on the university of Maiduguri campus. The sunlight energy is absorbed by the collector made up of an aluminum absorber plate enclosed within a transparent cover to prevent the emitted radiation from escaping (greenhouse effects). The absorber is made with fluid carrying tubes to absorb heat and increases the temperature of the water in the tank through theromsyphon principle. Maximum fluid output temperature and the collector temperature of 59℃ and 70℃ respectively were obtained on a sunny day. This solar water heater find useful application as a source of hot water for cooking, washing and laundry, and acts as a renewable energy resources in regions where there is abundant sunlight.

Keywords: Solar water heater, renewable energy, solar energy, flat plate collector, thermosyphon principle.

1.0 INTRODUCTION

Solar water heating is the conversion of renewable sunlight energy into heat energy for home and industrial usage. Renewable energy resources, of which sunlight is an excellent example, are those that refill at a quicker rate over a shorter period of time than they are used. The energy of the sun is generated from the nuclear fusion of the of its hydrogen into helium, with its resulting mass depletion rate of approximately of 4.7×10^{6} tons per seconds and a tremendous release of heat and light (Ogie *et. al.*, 2016).

Solar energy being transmitted from the sun to through space to earth by electromagnetic radiation must be converted to heat before it can be used for practical heating or cooling (Shaikh, *et. al.*, 2017). This energy is relatively dilutes, therefore the size of a system used to convert it on a practical scale must be relatively large. Solar collectors usually consists of a surface that efficiently absorbs radiations, and convert the incident flux to heat which raises the temperature of the absorbing material. A part of this energy is then removed from the absorbing surface by a means of heat transfer fluid that may either be liquid or gaseous. One of the simple forms of a solar energy collector built is the flat plate collector. The later usually accomplish a fluid-to-fluid exchange with more conventional heat transfer rates but with emitted radiation as an unimportant factor (Dobriyal *et. al., 2019*). Flat-plate collectors unlike focusing systems are designed for applications requiring energy delivery at moderate temperature up to perhaps 80% above ambient temperature (Prakash *et.al.,* (2016). They have the advantage of using beam and diffused solar radiations, not requiring orientation toward the sun, no any significant optical terms and requiring little maintenance.

The household solar water heater under consideration is a passive system with three components: a storage tank, an absorber plate, and a fluid route. Some countries, such as Nigeria, have an abundance of solar energy that can be used for a variety of reasons (despites the drawback of night losses). The aim of this research work is to test the performance a solar water heater from locally available materials and in the process design, constructs and test the performance of a solar water heater in Maiduguri.

2.0 THEORETICAL BACKGROUND

2.1 Passive solar water heating system

A passive solar water heating system is a device that converts solar energy to heat energy using natural convection process. Passive solar water heater heating system but they are usually not as efficient as other types. Passive systems are more efficient and may last long, passive system are of two types, they are the integral collector passive systems, which works best in areas where temperature rarely fall below freezing and thermosyphon system which utilizes water density difference between hot and cold water (Prado *et.al.,* 2016). Thermosyphon system works best in warmer climate.

2.2 Flat plate collector

A simple flat plate collector is a rectangular or square metal box with dark colored absorber at the bottom and a transparent glass cover and insulated from all sides to prevent heat loss. Sunlight passes through the glass and is absorbed by the dark colored metallic collector and thereby increasing the temperature of the collector. Heat energy from the collector is transferred to the fluid through the absorber pipes (Dobriyal *et. al.,* 2019). The variation in density between the hot water in the absorber pipes and the cold water in the storage tank(slightly elevated in height than the collector casing) cause a movement(circulation) of the hot water (less dense) into the storage tank and flow of the cold water into the absorber tubes (Kujawska *et.al.,*, 2018).

2.3 Storage Tank

A well-insulated water tank can store hot water for space heating or domestic usage for days, and water has a high specific heat capacity, making it a handy heat storage medium (Yang and Zeng 2017). Water can store more heat per unit weight when compared with other substances. Water is cheap or even free in most countries and non-toxic. In order to heat the water using solar power, run the water through the hot collector. Solar water heater has the following disadvantages of No hot water when the sun isn't shinning and the collector might get cold enough to freeze which can be very dangerous. The storage tank can store enough water and made hot water available even in cold or cloudy atmosphere.

2.4 Greenhouse Effects

The Green House Effect describes a situation in which the sun's short wavelengths of visible light pass through a transparent medium, but the longer wavelengths of infrared emitted by heated objects are unable to pass through that medium. The trapping of the longer wavelengths radiation leads to more heating and a higher resultant temperature. In greenhouse, energy from the sun passes through the glass as rays of light, it is absorbed by the metallic collector and it is removed by the circulating fluid. In our design, a glass act like a greenhouse; allowing sunlight most of low wavelength from the flat plate collector from escaping, the resultant energy within the collector is therefore more than that outside (Darkwah *et.al.*, 2018).

2.5 Blackbody Radiation

A blackbody is a perfect absorber of light. It absorbs sunlight at all temperature, wavelength and angle of incidence. Therefore a blackbody is used for comparison with real bodies that emits and absorbs solar radiation. The color of any objects is the color of the spectrum of light it reflects, blue objects are blue because they reflects blue light while absorbing the other spectra of white light (sunlight), red objects are red because reflect only the red spectrum of solar radiation, therefore the best absorber is black. This is why a flat plate solar collector need to be black, so that it absorbs much energy (Patrick *et.al.*, 2019).

3.0 MATERIALS AND METHOD

3.1 MATERIALS

The materials used for the construction of the solar water heater are listed in Ttable 1.

Tables 1: List of Materials Used In Solar Water Heater.

S/NO:	Name of Materials
1	1mm Aluminum sheet
2	3mm transparent glass
3	Copper pipe
4	22 mm water storage tank
5	Fibre insulator
6	plywood
7	Angle iron
8	Metal sheet
9	valve

3.2 Method

An already built solar water heater was considered and a similar solar water heater was constructed with focus on simplicity, installation and maintenance cost as well as durability with our new measurement and specifications (Ogie *et. al.*, 2016). The solar water was specifically made from a locally available materials. A flat plate collector is used as the absorbers made with a coils of fluid carrying tubes and covered with a transparent glass cover. The water get heat and flows through the absorber pipes into the storage tank. The efficiency of the solar heater rely on the capacity and insulation of the storage tank and the thermal capacity of the absorber plate. All components were designed for and constructed in line with the design values obtained (Ogie *et. al.,* 2016).

3.2.1 Working principle

Principle of operation of a flat-plate solar water heater, the solar radiation passes through the glass in front of the absorber plate and strikes the flat black surface of the absorber plate where the solar energy is absorbed as heat (i.e by increasing the internal energy).

The collector becomes very hot and the water in the absorber fluid carrying tube attached to the collector becomes very hot by conduction. The water in the fluid carrying tubes becomes very hot and less dense than the cold water in the storage tank (Dervinis, 2018).

On the thermosyphon principle hot water in the pipes rises by natural convection and cold water in the tank descend by gravity pull into the fluid carrying tubes.

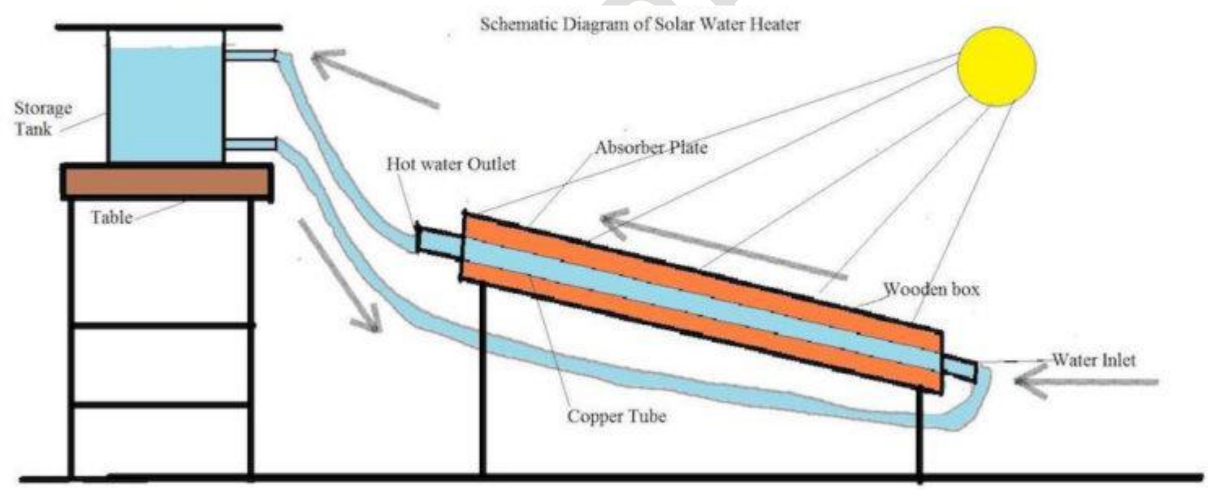

Figure 1. The working principle of solar water heater (SUNPOWER, accessed 17/01/2022)

3.2.2 Design Analysis/Method of Analysis

Efficiency is the ration of the input energy to the output energy, for the solar water heater; (Ogie *et. al.,* 2016).

$$Efficiency\ (\eta) = \frac{useful\ energy\ collected\ by\ the\ collector\ (Qu)}{solar\ incident\ illumination\ upon\ the\ collector\ (l) \times collector\ area\ (Ac)} \quad (3.1)$$

$$Qu \ = IA_c - Q_{loss} \tag{3.2}$$

$$Qu \ = IA_c\tau\alpha - Q_{loss} \tag{3.3}$$

Where Q_{loss} = heat loss by the collector

$$\tau = transmitivity\ of\ the\ glass\ \&\ \alpha = absorbtivity\ of\ the\ collector$$

Q_{loss} is related to the overall heat loss coefficient (UL) by

$$Q_{loss} = U_L A_{c(}T_{p-}T_a) \tag{3.4}$$

$therefore$

$$Qu \ = IA_c\tau\alpha - U_L A_{c(}T_{p-}T_a) \tag{3.5}$$

$$Qu \ = A_c[I\tau\alpha - U_L(T_{p-}T_a)] \tag{3.6}$$

The average global solar insolation constant (I), is 1367W/m^2

3.2.3 Design of Collector Area

Collector area is the ratio of the quantity of heat (Q_w) required to raise the temperature of water from T_{in} to T_{out} to the energy absorbed by the collector over a specified period of time.

Collector area (A_c) = $\frac{Qw}{\mu l}$= $\frac{MwCw\Delta T}{\mu l}$= useful energy absorbed by the water. (3.7)

$$Qw \ = MwCw(Tout - Tin) = \ \rho VCw(Tout - Tin) \tag{3.8}$$

$$volume\ of\ water\ on\ the\ collector\ plane\ is\ given\ by:$$

$$V = \frac{\mu \times Re}{\rho \times D} \tag{3.9}$$

Where Re = Reynolds number for lamina flow,

$\rho = density\ of\ water,$

$\mu = viscosity\ at\ temperature\ of\ 70℃,$

$$v = volume\ of\ water\ obtained\ after\ 30sec. D = Diameter\ of\ pipe.$$

$$desired\ volume\ of\ water\ to\ be\ obtained\ from$$
$$the\ system\ \ is\ 3.1\ litres, therefore\ useful\ absorbed\ \ by\ the\ water\ \ for$$

Therefore useful energy absorbed by the water for 1 hr (3600 sec.)

$$= \frac{Qw}{t} = \frac{\rho VCw(Tout - Tin)}{3600}$$

$$Qw = 163.75W$$

But $I = 1367W/m2$

Average efficiency for flat-plate collector (η) = 40% and viscousity of water at 70℃, $\mu =$ 0.4

$area\ of\ colllector\ (Ac) = \frac{Qw}{\mu l} = \frac{162.75.}{1367\times0.4}$ =0.297m^2

This is the minimum requirement; hence we choose 1m^2 as the area of collector Ac.

Mass flow rate of water within the collector is given by $Mf = \frac{Mass}{Time}$

Where $t = 30sec. = time\ to\ drain$ 3.1 $litres\ of\ water\ within\ the\ collector.$

$Mass = Density\ (\rho) \times volume\ (v),$

$where\ \rho = 10^3$kg/m^3 and v= 3.1 litres = 3.1 × $10^{-3}$$m^3$

$mass = 10^3$kg/m^3 × 3.1 × 10^{-3} m^3 = 3.1 kg

$$massflow\ rate\ (Mf) = \frac{3.1}{30} = 0.1kg/sec.$$

3.2.4 Heat Loss Coefficient

The heat lost coefficient is given as follows.

Total thermal resistance (RT) = R1 + R2 + R3

Where R = $\frac{T2-T1}{Q}$

Where Q= IAc$\tau\alpha$

R = $\frac{T2-T1}{IAc\tau\alpha}$ (3.10)

Since all heat losses are approximately through conduction on both edges and bottom only.

The nusselt number calculated using the formular givig by):

Nu= 1+ 1.44$\{\frac{1-708(sin1.88\beta)16}{Racos\beta}\}[\frac{1-1708}{Racos\beta}] + (\frac{Racos\beta}{5830})^{\frac{1}{3}} - 1]$ (3.11)

Where $\beta = the\ thermal\ expansion\ coefficient$.

Overall heat loss coefficient obtained is 6W/m^2℃

Recall equation (4)

$$Qu = A_c[I\tau\alpha - U_L(T_{p-}T_a)] = 1[1367 \times 0.88 \times 0.95 - 6(60 - 25)]$$

$Qu =$ 1018.92W/m^2

3.2.5 Design of the Water Storage Tank

The water storage tank is single thin-walled cylinder of 40 litres capacity with a height (length of 480mm) and since 1 litre = 1000m^3

40litres = 40 × 1000 = 40,000m3

Therefore;

Volume (V_T) = Area (A_T)* Height (H_T).

But $A_T = \frac{\pi D^2 H_T}{4}$, Therefore

$V_T = \frac{\pi D^2 T}{4} H_T$

$$DT = \sqrt[2]{\frac{4V_T}{H_{T\pi}}} = \sqrt[2]{\frac{4\times40\times10^6\ mm}{480\ \times3.142}} = 325\text{mm} \quad (3.12)$$

Therefore, diameter of the cold water tank (D_T)IS 325mm. the pressure at the cold water tank at full capacity is given by

$P_T = \rho w_1 g H_T$

Where P_T = pressure at the cold water exit of the storage tank

g= acceleration due to gravity m/s^2

$\rho = density\ of\ cold\ water\ (kg/m^3)$

P_T = 1000 * 9.81 * 0.56 = 5493.6Pa or 5.5KPa.

It means that as H_T increases. This increase in the pressure in the tank results in an increase in the flow rate of water through the flat-plate collector, hence, efficiency is improved because transfer of the entrapped heat in the collector to the water inside will be faster, thereby minimizing convection and other losses from collector.

The coefficient of cubic expansions of water at 40-60^{0}C is give as $4.58K^{-1} \times 10^{-4}$

Pressure of hot water in the storage tank at full capacity is given by

$$P^1 = \rho W_2 g {H_T}^1$$

$$\rho W_2 \ is \ the \ density \ of \ hot \ water$$

$$\rho W_2 = \ \rho W_2[1 + \gamma \Delta T]^{-1}$$

$$1000[1 + 4.58 \times 10^{-4}\, K^{-1} \times 45℃]^{-1}$$

Where γ is the coefficient of cubic expansion of water at

$70℃ = 4.58 \times 10^{-4}\, K^{-1}$

$$\rho W_2 = 978.81 Kg/m^3$$

P_T = 978.81 * 9.81 * 0.56 = 5493.6Pa or 5.5KPa.

4.0 RESULTS AND DISCUSSION

4.1 Testing

Figure 2: The Constructed Solar Water Heater

After sufficient filtering, the tank was filled with water. The carriage pipe transports the water to the circulating pipes, which are made up of riser and header pipes (i.e the inlet pipe). The water is heated by the heat supplied by the absorber plate to the tubes integrated beneath the absorber plate; hence, the cold and hot water are separated by density differences (1.e the cold water goes down, while the hot water comes up), a flow is initiated (thermosyphon or natural convection). The water flows to the water storage tank, and the circulation continues until the temperature is evenly distributed. The ambient temperature, temperatures of the collector as well as the temperature of the water in the storage tank is measured using a thermometer at every one (1) hour interval.

4.2 Result

The collector temperature and final fluid temperature for the solar water heater shows a maximum collector temperature of 70℃ at 2:00PM and maximum fluid temperature of 59℃ at 3;00PM, the collector has a temperature of 41℃, 51, 60℃, 63℃, 65℃, 63℃, 70℃, 69℃, 68℃, 60℃ and 50℃ while the water in the storage tank has a temperature of 30℃, 34℃, 38℃, 44℃, 52℃, 53℃, 56℃, 58℃, 59℃, 55℃ and 53℃ at 08: 00AM, 09:00AM, 10:00AM, 11:00AM, 12:00PM, 13:00PM, 14:00PM, 15:00PM, 16:00PM, 17:00PM and 18:00PM respectively. The ambient temperatures for same period of time still remain far below the two temperatures, as follows; 32℃, 33℃, 38℃, 39℃, 38℃, 39℃, 39℃, 44℃, 40℃, 38℃, 30℃ respectively.

as shown in Table 2.

Table 2: Give test results of the system on a normal sunny day.

TIME (hr)	AMBIENT TEMPERATURE (℃)	COLLECTOR TEMPERATURE (℃)	FINAL (FLUID) TEMPERATURE (℃)
08:00	32	41	30
09:00	33	51	34
10:00	38	60	38
11:00	39	63	44
12:00	38	65	52
13:00	39	63	53
14:00	39	70	56
15:00	44	69	58
16:00	40	68	59
17:00	38	60	55
18:00	30	50	53

4.3 Discussion

The collector and final fluid temperature of the fluid have massively increased as shown by figures 3, figures 4 and figures 5

Efficiency = $\frac{output}{input} \times 100$ (4.1)

Thus,

The collector efficiency= $\frac{sum\ of\ collector\ temp.}{insum\ of\ ambient\ temp.} \times 100 = \frac{660}{370} \times 100 = 160.97\%$ (4.2)

Also the overall solar heat efficiency = $\frac{sum\ of\ fluid\ temp.}{sum\ of\ collector\ temp.} \times 100$ (4.3)

$$= \frac{479}{660} \times 100 = 72.57\%$$

The system has a collector efficiency of 160.97% and overall solar efficiency of 72.57%.

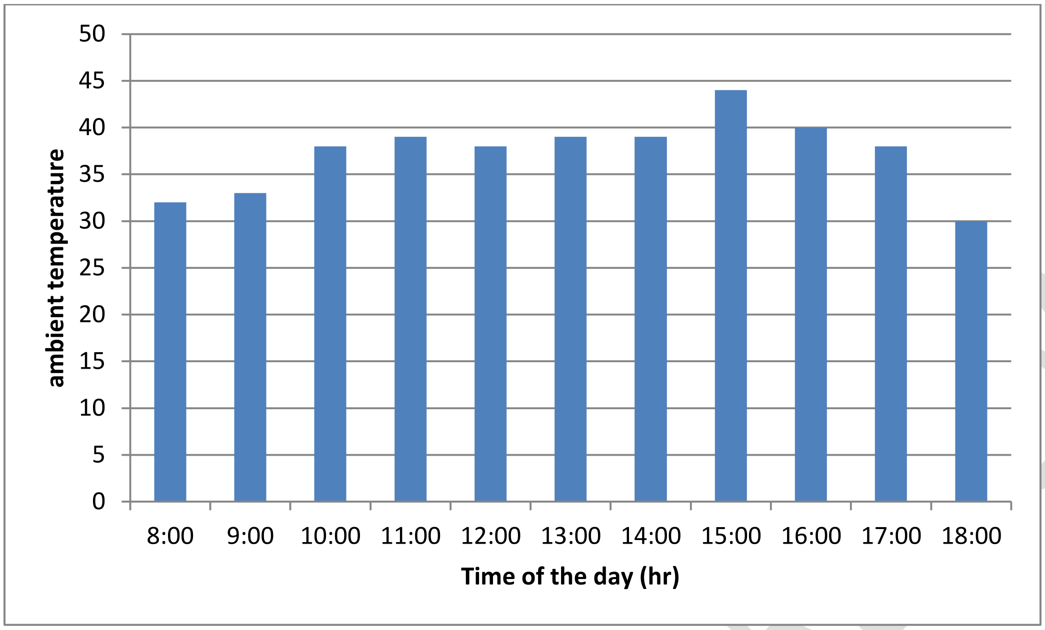

Figure 3. variation of ambient temperature with time

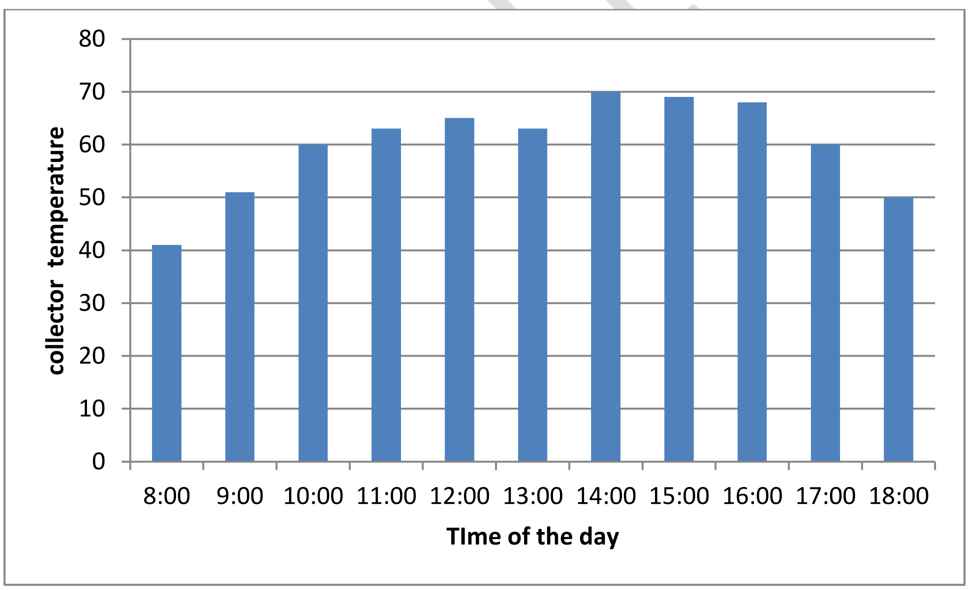

Figure 4. variation of collector temperature with time

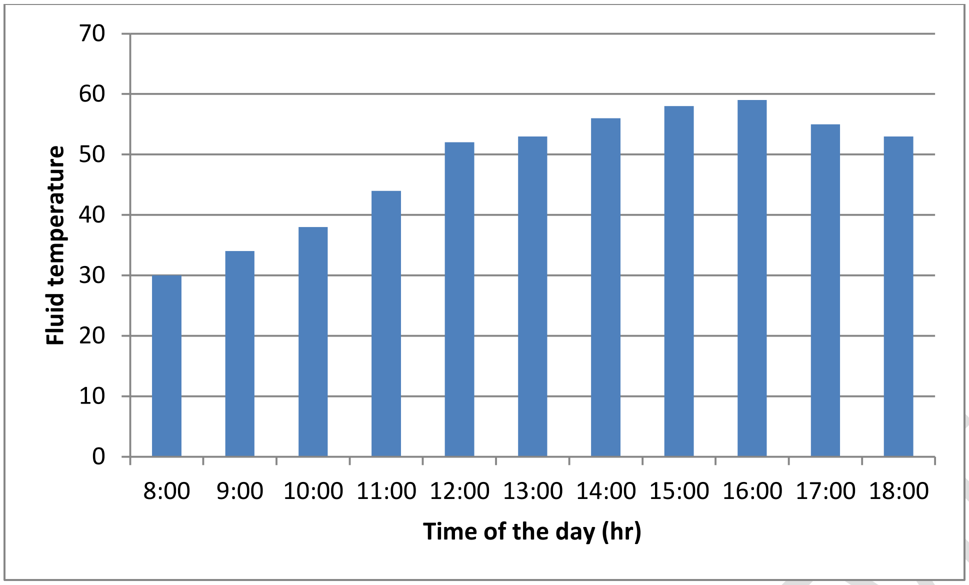

Figure 5: Variation of final (fluid) temperature with time

From the results, ambient temperature varied between 38 and 40 on average. Maximum fluid (water) output temperature and the collector temperature was obtained between noon and 4:00pm. The fluid temperature increased from a low 8:00 AM to a peak between noon and 4:00PM. The fluid temperature increased from a low value 8:00 AM got to a peak between noon and 4:00 PM and then fell back to a low value. The collector temperature averagely above the ambient temperature by a value of about 160.73%, this is a significant increase in temperature with shows that the greenhouse effect is at work.

The cold water temperature increase averagely by about 72.57%, this mean that any cold water heated by this solar water heater, will have it temperature increased by more than half of its original temperature. A cold water will be heated and have its temperature increases by more than half of its original temperature. This shows that thermosyphon principle is at work.

5.0 CONCLUSION

Through the thermosyphon principle, the water is heated and flows into a storage tank. On a sunny day, the system was tested, with maximum fluid output temperature and collector temperature of 59°C and 70°C, respectively. This solar water heating system has a wide range of applications and can be used as a sustainable energy source in areas where sunlight is plentiful and consistent.

Solar water heater made from locally available materials within maiduguri area can be very effective in producing very hot water for domestic home use. A hot water temperature as high as 59 degree celcius is very much above the normal room temperature of 25C. in the winter season ambient temperature of Maiduguri can fall far below the room temperature of 25C, This make household use of cold water very uncomfortable and unhealthy. The warm water produced by this our solar water heater is very much above the room temperature water. Locals can therefore construct cheap solar water heater from locally available materials to save money from the cost of electricity and fuel(firewood, kerosene gas and petrol). Hot water is stored in the heat insulated storage tank for next day use.

REFERENCES

Alwan, N. & Shcheklein, S. and Ali, O.. (2021). Experimental analysis of thermal performance for flat plate solar water collector in the climate conditions of Yekaterinburg, Russia. Materials Today: Proceedings. 42. 10.1016/j.matpr.2020.12.263.

Darkwah, W. K., Odum, B., Addae, M., Koomson, D., Kwakye D. B., Oti-Mensah, E., Asenso, T. and Buanya, B., (2018). Greenhouse Effect: Greenhouse Gases and Their Impact on Global Warming. Journal of Scientific Research and Reports. 17. 1-9. 10.9734/JSRR/2017/39630.

Dervinis, D. and Balbonas, D.(2018). RESEARCH OF SOLAR WATER HEATERS MODEL.

Dobriyal, R., Negi, P., Sengar, N. & Singh, D.(2019). A Brief Review on Solar Flat Plate Collector by Incorporating the Effect of Nanofluid. *Materials today: proceedings. 21. 1653-1658. 10.1016/j.matpr.2019.11.294.*

Ekpo, J., & Enyinna, P. (2017). Design and Construction of a Solar Water Heater for Environmental Sustainability. *Current Journal of Applied Science and Technology*, *20*(3), 1-15. https://doi.org/10.9734/BJAST/2017/31820 Prado, R., and Sowmy, D.S. (2016). Innovations in passive solar water heating systems. 10.1016/B978-0-08-100301-5.00007-2.

Eschenbach, W. (2015). Things In General | Watts Up With That? *https://wattsupwiththat.com/2015/05/15/things-in-general/*

Kujawska, A., Zajaczkowski, B., Woluntarski, M., and Buschmann, M. (2018). THERMOSYPHON PERFORMANCE IN DEPENDENCE OF CARBON-BASED NANOFLUIDS. 1661-1665. 10.1615/TFEC2018.mnh.021951.

Ogie, Nosa & Oghogho, Ikponmwosa & Jesumirewhe, Julius. (2013). Design and Construction of a Solar Water Heater Based on the Thermosyphon Principle. *Journal of Fundamentals of Renewable Energy and Applications. 3. 1-8. 10.4303/jfrea/235592.*

Patrick, T., Tetang F. A., Marcel. E., Alexis, K., (2019). Numerical study of the greenhouse effect in a flat-plate double glazing solar heat collector. Indian Journal of Science and Technology. 12. 1-9. 10.17485/ijst/2019/v12i38/145315.

Prakash, R., Tv, S., Nandan, G.& Tiwari, A. (2016). An Overview on Parabolic Trough Solar Collector.

Serifi, V. and Sofiu, V. (2011). An Overview of Direct Solar Irradiation.

Shaikh, M. R., Shaikh, S., Waghmare, S., Labade, S. and Tekale, A. (2017). A Review Paper on Electricity Generation from Solar Energy. International Journal for Research in Applied Science and Engineering Technology. 887. 10.22214/ijraset.2017.9272.

Sunpower "Solar Water Heater Working Principles" **https://www.sunpower-solar.com/Solar-Water-Heater-Working-Principles-id3081955.html (accessed on 17/01/2022).**

Tian, Y. Liu, X., Ghanekar, A., Chen, F. and Zheng, Y. (2020). Blackbody-cavity Ideal Solar Absorbers.

Vox, G., Schettini, E., Cervone, A. and Anifantis, A. (2008). Solar thermal collectors for greenhouse heating. Acta Horticulturae. 801. 787-794. 10.17660/ActaHortic.2008.801.92.

Yang, R. and Zeng, H.(2017). Storage Tank Entrance Effect on Solar Hot Water System. 10.11159/ehst17.117.