# DESIGN AND PERFORMANCE EVALUATION OF A SERPENTINE THERMOSYPHON FLAT PLATE SOLAR WATER HEATER IN OWERRI, NIGERIA

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**Abstract** – *Serpentine thermosyphon flat plate solar water heater has been designed, constructed from locally available material and its performance evaluation carried out under the metrological conditions of Owerri, Nigeria. Construction of the serpentine thermosyphon flat plate consist of copper tube and elbows used in formation of serpentine shape piping system attached to a black painted aluminum sheet that act as absorber plate. Clear white edge glass material and wood chips are used as glassing and insulator materials, respectively. The solar water heater was tested in October and November, 2021 at Federal Polytechnic Nekede Owerri. Result presented in this paper shows that the solar water heater is capable of generation of 28.5 $^{o}$ C change in water temperature between outlet and inlet of the serpentine solar water heater. Instantaneous thermal efficiency estimated for the solar water heater range between 13.94 and 51.1 % at various mass flow rate and insolation level.*

**Keywords**: **mass flow rate, serpentine, solar energy, test rig, water heater**

## 1. INTRODUCTION

It is now universally accepted that fossil fuels are finite and it is only a matter of time before their reserves become exhausted [1]. Most countries of the world still depend on convectional energy to meet their energy demands [2]. The problem with over dependence on this form of energy is that it is rapidly depleting. Furthermore, the greenhouse gas it produces has become a threat to life on earth [3]. Increased dependence on convectional energy has no doubt been of benefit at large to most countries by providing employment, development of infrastructures, opportunities for strategic alliance among counties and primary source of income. Industrial and economic development which have been made possible through the use of convectional energy resources have brought about significant environmental degradation and climate change with severe impact on human and ecosystem. The world oil crisis in the 1970s and climate shifts noticed by World Meteorological Organization (WMO) in the 1980s have stimulated a global action on the environment. To this effect, so many research works are being carried out to replace or augment the use of convectional energy resources with renewable energy resources, such as solar energy, wind energy, biomass, etc.

Solar energy has been described as the most promising energy of the future [4]. It is the energy transmitted from the sun in form of electromagnetic radiation which requires no medium for its transmission. The earth receives about two hundred billion megawatts (200 x $10^9$ MW) of the total solar radiation output [5]. This form of energy is finite, abundant, cheap and environmentally friendly.

A common utilization of solar energy is in solar thermal application. In solar thermal application, solar energy is directly converted into heat energy which is used for heating and cooling purposes. However, for effective conversion of solar energy into heat energy, solar thermal collectors are required. Solar thermal collector is an assemblage of different related parts aimed at collection of solar radiation and conveys the thermal energy to a receiving medium. Solar water heater is one of the oldest types of solar thermal collector. Review of different configuration, performance and economic considerations of solar water heaters have been carried out by refs [6], [7], [8], [9] and [10]

## 2.0 Methodology

### 2.1 Design Analysis

At steady state condition, instantaneous useful energy gain of flat plate solar thermal collector is given as [11]

$$Q_u = F_R A_c [I_T(\tau\alpha) - U_L(T_{in} - T_a)] \quad (1)$$

Where $Q_u$ is useful energy gain, $F_R$ is collector heat removal factor, $A_c$ is collector area, $I_T$ is incident solar radiation on the collector, $\tau\alpha$ is transmittance-absorptance product, $U_L$ is overall heat transfer coefficient, $T_{in}$ and $T_a$ are inlet fluid temperature and ambient air temperature, respectively.

Transmittance-absorptance product for most practical collector is given as [11]

$$(\tau\alpha) = 1.01\tau\alpha \qquad (2)$$

Approximately, transmittance $(\tau)$ of glass material is given as [11]

$$\tau = \tau_a \tau_r \qquad (3)$$

Where $\tau_a$ represents Bouguer's law absorption of transmittance of glass, given as [11]

$$\tau_a = exp\left(-\frac{K_g L_g}{\cos\theta_r}\right) \qquad (4)$$

Where $K_g$ and $L_g$ are extinction coefficient and thickness of glass, respectively. The value of $K_g$ varies from 4m-1 for water white glass, which appear white when viewed on the edge to 32 m-1 for high iron oxide glass that appear greenish when view from the edge. In this study a water white glass is used, hence, $K_g$ = 4 m-1.

For a given number of glasses $(N_g)$, transmittance $(\tau_r)$ of reflection of radiation by glazing material is given as [11].

$$\tau_{r,N_g} = \frac{1}{2}\left(\frac{1-e_2}{1+(2N_g-1)e_2} + \frac{1-e_1}{1+(2N_g-1)e_1}\right) \qquad (5)$$

Where $e$ is reflection of beam, diffuse and ground-reflected components of solar radiation estimated from Fresnel equation, given as [11].

$$e_1 = \frac{\sin^2(\theta_r-\theta_1)}{\sin^2(\theta_r+\theta_1)} \qquad (6)$$

and

$$e_2 = \frac{\tan^2(\theta_r-\theta_1)}{\tan^2(\theta_r+\theta_1)} \qquad (7)$$

The refracted angle $(\theta_r)$ of incident beam, diffuse and ground reflected radiation are obtained from sneil's law as [11]

$$\theta_r = \sin^{-1}\left[\frac{\sin\theta_i}{n_f}\right] \qquad (8)$$

Where $n_f$ is reflective index of glass which is equal to 1.526.

Thus, angle of incident beam radiation is estimated from [11]

$$\cos\theta_{i,b} = \cos\emptyset\cos\delta\cos\omega + \sin\emptyset\sin\delta \qquad (9)$$

Where $\emptyset$ is latitude of study location, $\omega$ is hour angle and $\delta$ is angle of declination.

While, incident angles for diffuse and ground-reflected radiation are given as [12]

$$\theta_{i,d} = 50.7 - 0.1388\beta + 0.001497\beta^2 \qquad (10)$$

and

$$\theta_{i,g} = 90 - 0.5788\beta + 0.002693\beta^2 \qquad (11)$$

Where $\beta$ is collector tilt angle

Solar radiation absorptance of glazing material is given as [11]

$$\alpha \cong 1 - \tau_a \qquad (12)$$

Overall heat transfer coefficient $(U_L)$ is effective combination of all losses out of the collector and it is given as [11]

$$U_L = U_{top} + U_{bottom} + U_{edge} \quad (13)$$

Where $U_{top}$ is top heat loss coefficient, $U_b$ is bottom heat loss coefficient, $U_{edge}$ is edge loss coefficient and assumed to be negligible in this work.

Top heat loss coefficient of flat plate solar collector is given as [11]

$$U_{top} = \left[\frac{N_g}{\frac{C}{T_{pm}}\left[\frac{T_{pm}-T_a}{(N_g+f)}\right]^e} + \frac{1}{h_w}\right]^{-1} + \frac{\sigma(T_{pm}+T_a)(T_{pm}^2+T_{pm}^2)}{\frac{1}{\varepsilon_p+0.00591Nh_w} + \frac{2N_g+f-1+0.133\varepsilon_p}{\varepsilon_g} - N_g} \qquad (14)$$

Where

$$f = (1 + 0.089h_w - 0.1166h_w\varepsilon_p)(1 + 0.07866N \qquad (15)$$

$$C = 520(1 - 0.000051\beta^2) for\ 0^0 < 70^0; for\ 70^0 < \beta < 90^0, use\ \beta = 70^0 \qquad (16)$$

$$e = 0.430(1 - 100/T_{pm}) \qquad (17)$$

$$h_w = 2.8 + 3.0V \qquad (18)$$

Where $N_g$ is number of glass cover, $\beta$ is collector tilt angle (degree), $\varepsilon_g$ is emittance of glass = 0.88 [13], $\varepsilon_g$ is emittance of absorber plate = 0.90 [13], $T_{pm}$ is mean plate temperature (K), $h_w$ is wind transfer coefficient (W/m$^2$ $^0$C)

Bottom heat loss coefficient of a flat plate collector is given as

$$U_{bottom} = \frac{K_{ins}}{\delta_{ins,bottom}} \qquad (19)$$

Where $K_{ins}$ is thermal conductivity of insulator material, $\delta_{ins,bottom}$ is thickness of the insulation material at bottom of the solar collector

Collector heat removal factor $(F_R)$ for serpentine flat plate collector is given as [14]

$$F_R = F_1 F_3 F_5 \left[\frac{2F_4}{F_6 exp[-\sqrt{1-F_2^2}/F_3]+F_5} - 1\right] \qquad (20)$$

Where

$$F_1 = \frac{k}{U_L W} \frac{kR\,(1+\gamma)^2 - 1 - \gamma - kR}{[kR\,(1+\gamma)-1]^2 - (kR)^2} \qquad (21)$$

$$F_2 = \frac{1}{kR(1+\gamma)^2 - 1 - \gamma - kR} \qquad (22)$$

$$F_3 = \frac{\dot{m} C_p}{F_1 U_L A_c} \qquad (23)$$

$$F_4 = \left(\frac{1-F_2^2}{F_2^2}\right)^{1/2} \qquad (24)$$

$$F_5 = \frac{1}{F_2} + F_4 - 1 \qquad (25)$$

$$F_6 = 1 - \frac{1}{F_2} + F_4 \qquad (26)$$

And

$$k = \frac{(K\delta\, U_L)^{1/2}}{Sinh\,[(W-D)\,(U_L/K\delta)^{1/2}]} \qquad (27)$$

$$\gamma = -2Cosh\left[(W-D)(U_L/k\delta)^{1/2}\right] - \frac{DU_L}{k} \qquad (28)$$

$$R = \frac{1}{C_b} + \frac{1}{\pi D_i h_{fi}} \qquad (29)$$

Where $\dot{m}$ is mass flow rate of working fluid, $C_p$ is specific heat capacity of fluid, $K$ is absorber plate thermal conductivity, $R$ is resistance between plate and tube, $W$ is distance between tube, $c_b$ is bond conductance, $D$ is outside tube diameter, $D_i$ is inside tube diameter, $\delta$ is absorber plate thickness and $h_{fi}$ is fluid to tube heat transfer coefficient.

For a cylinder with length very large compared to diameter at steady state. Fluid to tube heat transfer coefficient is estimated from [13].

$$h_{fi} = \frac{In(r_o/r_i)}{2\pi KL} \qquad (30)$$

Where $r_i$ and $r_o$ are inner and outer radius of copper tube, respectively and $L$ is length of serpentine tube

Hence, thermal efficiency of solar water is given as [11]

$$\eta = \frac{Q_u}{A_c I_T} \qquad (31)$$

Owerri is a city in south-east of Nigeria with two major climatic conditions namely rainy and dry seasons. The average monthly insolation level in Owerri ranges between 13.02 and 16.16 MJm$^{-2}$day$^{-1}$ [15] with the least occurring during the wet season. Since the solar dryer is expected to operate under all weather conditions, it is best to choose as design month that with lowest average monthly insolation level. From Ref [15], it is the month of July with a value of 13.02 MJm$^{-2}$day$^{-1}$. Thus, in this study, July is used as the design month.

### 2.2 Construction Procedure

The serpentine thermosyphon flat plate solar water heater is constructed from locally available materials within Owerri. A clear transparent glass of 0.003m thickness and 108m$^2$ area is used as cover material. Aluminum sheet of 0.5mm and 102.60 m$^2$ in thickness and area, respectively, is used as absorber plate. Uppers surface of the absorber plate that faces the sun is painted black as to increase its ability for absorption of solar heat energy trapped by glassing material.

Two types of copper tubes are used;

i. Non insulated copper tube of inner diameter of 0.143m and outer diameter 0.15m is used to form a serpentine shape. To form serpentine shaped piping, the copper tube is cut into two different lengths of 0.53m and 0.19m. These two lengths of copper tube are joined together using copper elbows. To prevent leakage, pipe-elbow-pipe joints are properly sealed using Teflon tape and sealant. At intervals, the serpentine shaped copper tube piping is attached to the unpainted surface of the absorber plate using thin copper wires as shown in Fig 1a. This is to aid the serpentine copper tube to have good contact with the aluminum sheet. Thereby, resulting in a situation where the copper tube and aluminum sheet acts as heat exchanger to the working fluid when exposed to incident solar radiation.

ii. Euro tube BS 2871–1057, diameter 0.15 x 0.5mm insulated copper tube is used to supply a lagged hot water storage tank placed at the same level with the hot water point end of the solar water heater. The reason for the use of insulated copper tube is to prevent heat loss from hot water to surrounding as it flows from the solar collector to hot water storage tank.

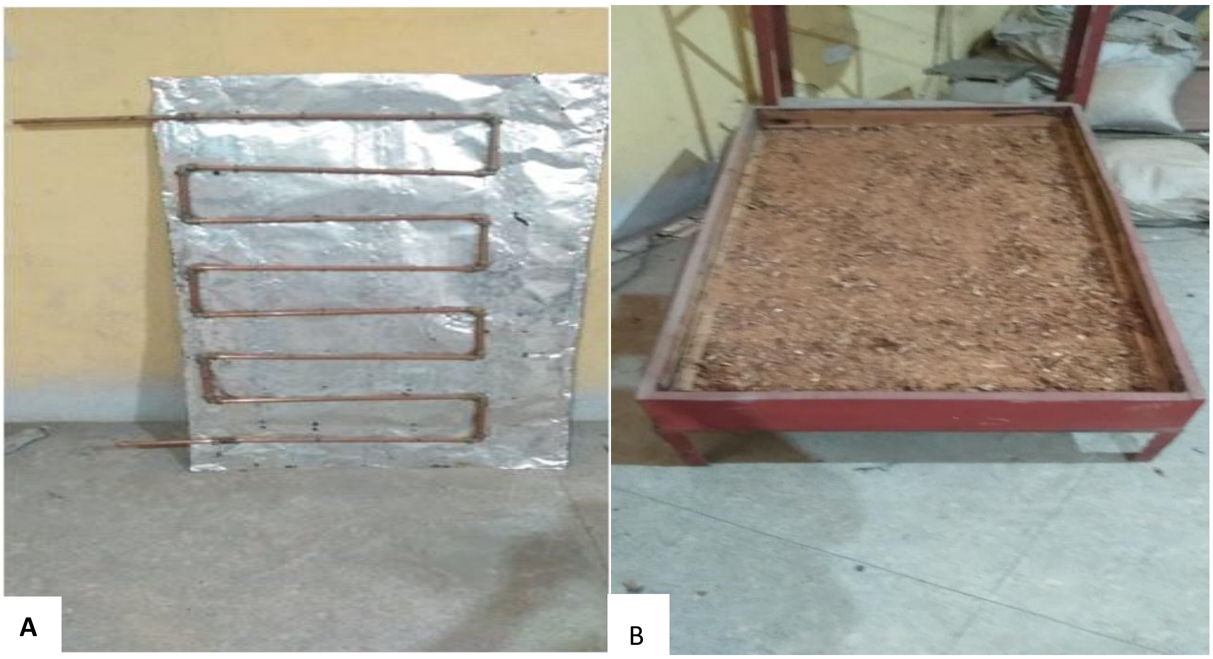


**Figure 1** (a) serpentine copper tube (b) wood chips used as insulator material

To prevent edge and bottom heat losses, wood chips are used as insulation material as shown in Fig.1b. A wooden frame is used to house the transparent glass, serpentine shaped copper tube that is bounded to absorber plate and wood chip. The transparent glassing material is placed 0.04 m from absorber plate. Edges of transparent cover to wooden frame are sealed with glue as to prevent heat loss. Two 30 liters tanks are constructed from stainless steel sheet and used as cold and hot water storage tanks. Hot water tank storage tank is lagged as to prevent heat loss from hot water stored inside it. The cold water tank is placed above the wooden frame. This is necessary as to allow flow of water through the serpentine copper tube and hence to hot water storage tank. Angle iron of 0.01m thickness is used to construct the frame on which the wood frame and the hot and cold water tanks are place. The part of angle iron frame on which the wooden frame is placed is tilted to latitude of study location (latitude = $15^{o}$). This is necessary as to enhance incident solar radiation on the collector. Side and back view of the serpentine thermosyphon solar water heater are shown in Fig. 2

**Fig. 2** side and back view of the serpentine solar water heater.

## 3.0 Experimental Rig Set Up

The serpentine thermosyphon flat plate solar water heater was tested in September and October 2021 under the metrological condition of Federal Polytechnic Nekede, Owerri, Imo State, Nigeria. It was operated on mass flow rate of 0.002 kg/s in September and mass flow rate of 0.001 kg/s and 0.003 kg/s in November. These mass flow rates are capable of generating a minimum daily hot demand of 20 liters per day [16]. During experimental rig set up, the following parameters were measured: ambient temperature, temperature of storage water tank, inlet water temperature and outlet water temperature and insolation. Data were collected at intervals of thirty minutes from 8.00 am to 5.00 pm each day. A type K thermocouple insulated with Teflon and metal gauze wire with maximum insulation temperature of 260 $^{o}$C and probe accuracy of ± 2.2 $^{o}$C or ± 0.75 % of reading from 0 $^{o}$C to 800 $^{o}$C was connected to a digital thermometer that has a measurement range of -50 $^{o}$C to 1300 $^{o}$C and a high resolution of 0.1 $^{o}$C and accuracy of 18 $^{o}$C to 28 $^{o}$C. Insolation for the period during rig set up was measured using daystar solar meter which uses a polycrystalline silicon PV cell as sensor. The solar meter provides an accurate reading of 3 % from 0.0 to 1200 watts and has a resolution of 1 W/m$^2$.

## 4.0 Result and Discussion

The serpentine flat plate solar water heater was operated on 10/10/2021 and 22/10/2021 at a mass flow rate of 0.002 kg/s. While, on 2/11/2022 and 5/11/2021 it was operated on mass flow rate of 0.003 and 0.001 kg/s, respectively. Fig. 3 present insolation level for some days during which the test was carried out. It is observed from Fig 3, that on days 10/10/2021 and 22/10/2021 insolation level differs. Days 10/10/2021 and 22/10/2021 may be said to be sunny and overcast, respectively. Ambient temperature for 10/10/2021 and 22/10/2021 are also seen to exhibit similar line pattern as shown in Fig. 4 like those of Fig 3.

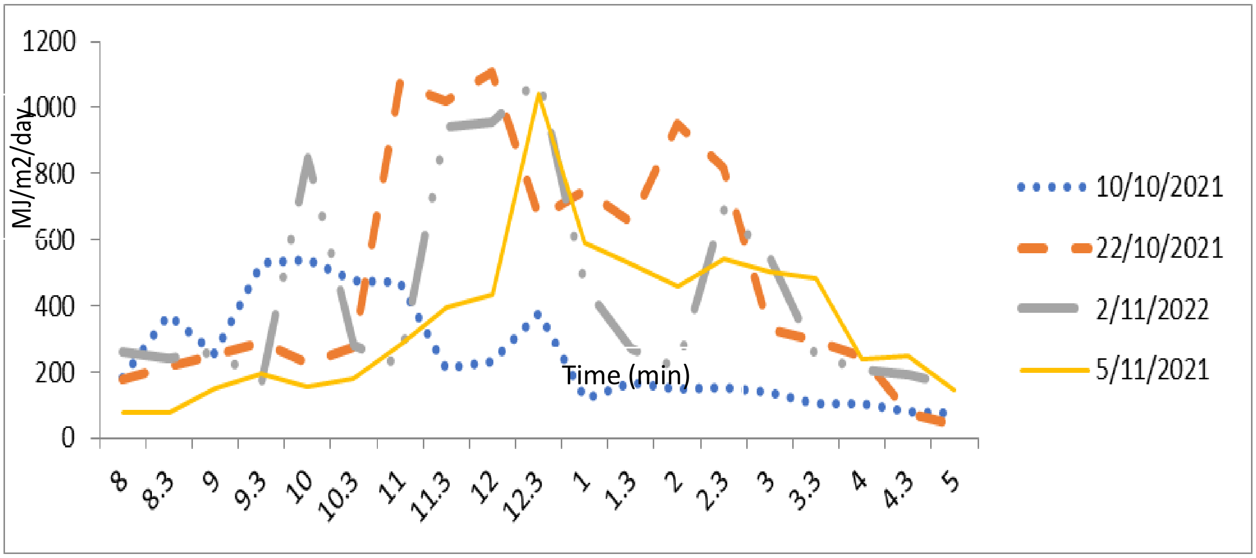


**Fig. 3** insolation levels for some days

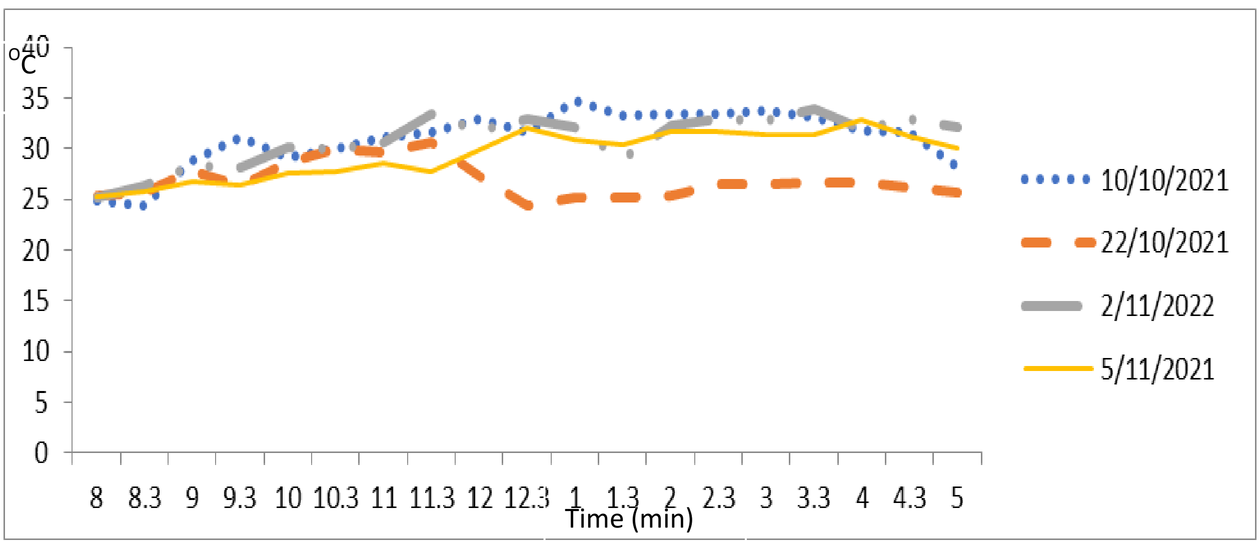


**Figure 4** ambient temperatures for some days

This reveal that as time of the day varies, magnitude of insolation level and ambient temperature fluctuates. Furthermore, it is observed that between the hours of 10:30 am – 2:30 pm insolation level recorded for each day is higher compare to those of 8:00 – 9:30 am and 3:00 – 5:00 pm. This reveals possibility of harvest of more solar radiation between the hours of 10:30 am – 2:30 pm than any other period of the day. Thus, solar water heaters are expected to perform more effectively during this period.

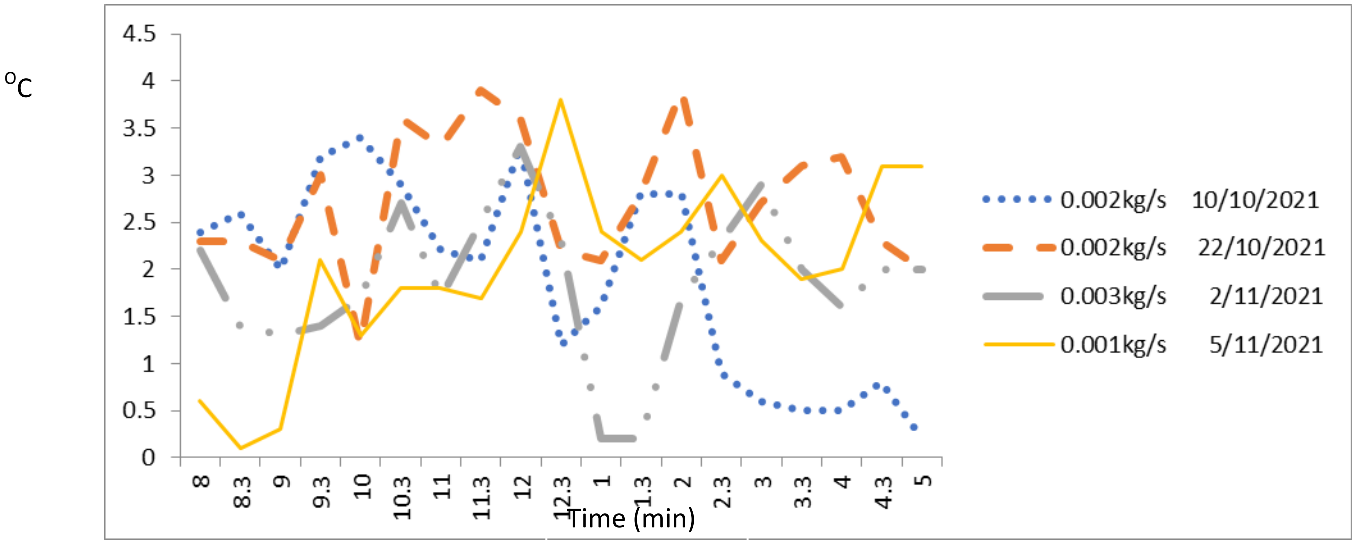


**Fig 5** temperature variations between inlet water and cold water storage tank

Temperature variation between inlet water and cold water storage tank is presented in Fig 5. It is observed that water in cold water storage tank increased in temperature as it flow through the copper tube that supply water into the serpentine thermosyphon solar water heater. Measured temperature variation ranged between 0.1 - 3.9 °C. This could have been possible considering the fact that cold water storage tank and supply copper tube is not lagged. This also reveals that by not insulating cold water storage tanks and cold water supply piping system of solar water heaters there is possibility of gaining relatively increase in fluid temperature.

Variation in temperature between outlet and inlet water is presented in Fig 6. Fluctuation in curve patterns of Fig 6 shows that the serpentine flat plate thermosyphon solar water heater responded to change in insolation level. For the entire mass flow rate an appreciable increase in temperature is observed to occur between 10 am to 2.30 pm compared to other period of the day. During this period in Fig 3, it is observed that insolation level for the entire day is high. Thus, this reveals possibility of the serpentine flat plate thermosyphon solar water heater yielding more hot water during this period. From Fig 6, it is observed that on 10/10/2021 and 22/10/2021 during which the serpentine flat plate solar water heater was operated on the same mass flow rate of 0.002 kg/s on different level of insolation. Temperature variation between the outlet and inlet water is observed to be higher on 22/10/2021, a day with higher insolation value than that of 10/10/2021. On days with relatively similar high insolation values and different mass flow rate, it is observed that mass flow rate of 0.003 kg/s produced the least values of hot water temperature variation between outlet and inlet. This shows that the solar water heater is capable of producing more hot water on days with high or low insolation when operated at low mass flow rate. Water outlet and inlet temperature variation during which the serpentine flat plate thermosyphon solar water heater was tested ranged from 7.8 – 28.5 °C.

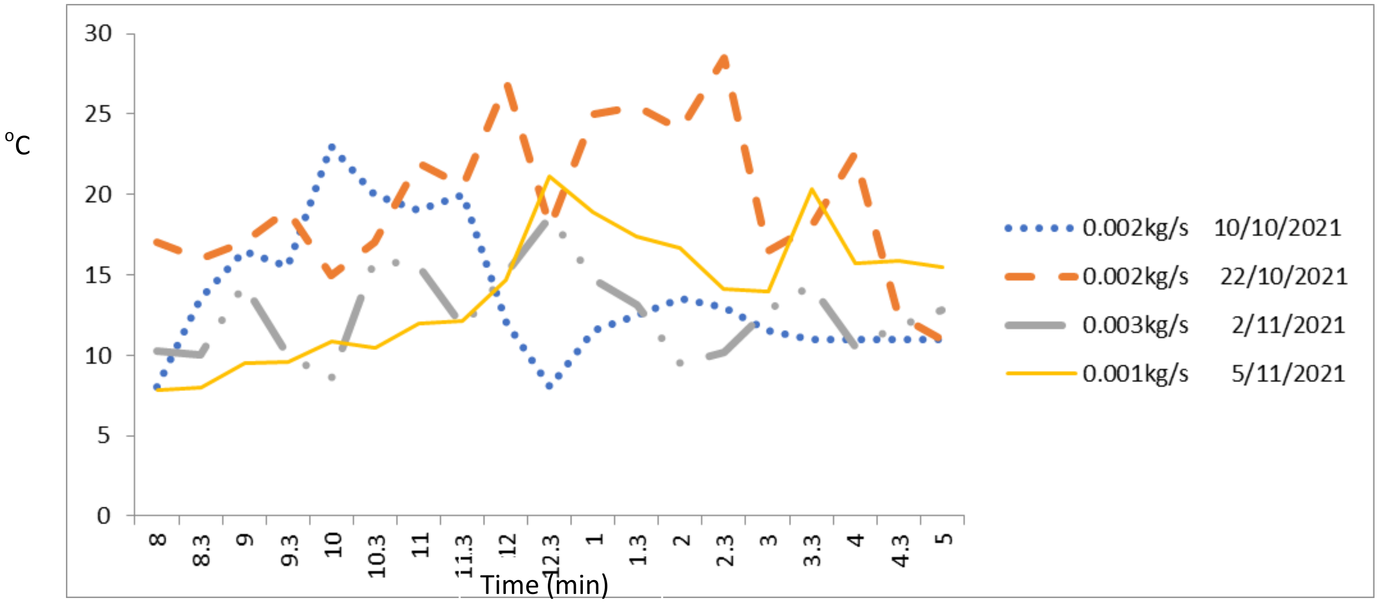


**Fig 6** temperature variations between outlet and inlet water

Fig 7 presents instantaneous thermal efficiency of the solar water heater for the tested days. Variation in curves reveals that efficiency of the solar water heater varies throughout the test period. Efficiency estimated for the solar water heater during the test period ranges between 13.98 and 51.1 %. Operating the solar water heater on mass flow rates of 0.002, 0.003 and 0.001 kg/s yield maximum efficiency of 38.03, 51.1 and 30.92 %, respectively, on days with relatively similar insolation (22/10/2021, 2/11/2021 and 5/11/2021).

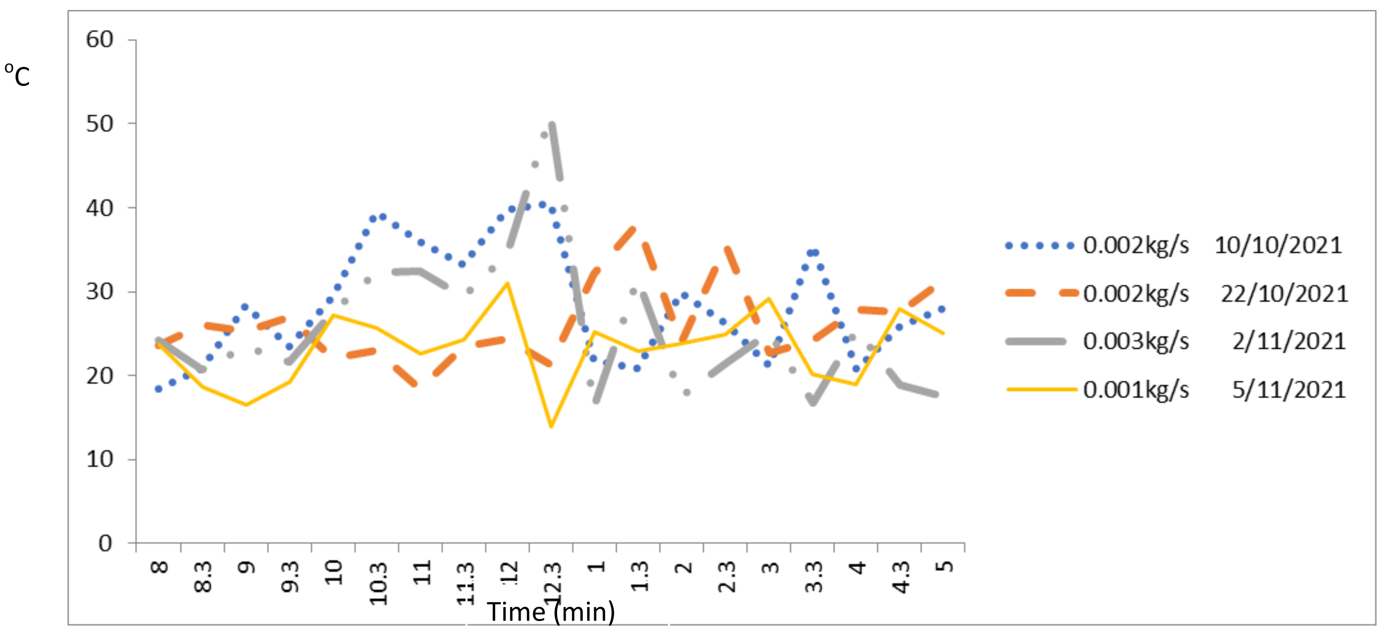


**Fig 7** instantaneous thermal efficiency

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## 5.0 Conclusion

The performance evaluation of a serpentine flat plate thermosyphon solar water heater has been carried out. It is constructed from readily available materials within Owerri, Imo State. It was observed that

i. The solar water heater responded to change in insolation level and it is capable of generating hot water within the range of 7.8 - 28.5 $^oC$ depending on the level of insolation

ii. Operation of the solar water heater on a low mass flow rate (0.001 and 0.002 kg/s) on days with high or low values of insolation is capable of production of higher value of hot water temperature.

iii. Maximum instantaneous thermal efficiency achieved by the solar water under the meteorological condition of Owerri at mass flow rate of 0.002, 0.003 and 0.001 kg/s are 38.03, 51.1 and 30.92 %, respectively.

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