

Investigation of Temperature and Flow Distribution in a Serially Connected Thermosyphon Solar Water Heating Collector System in Minna, Niger State,Nigeria

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Abstract
Natural circulation solar water heating systems are designed and fabricated with varying collector geometries, materials, storage tank capacities and specifications of individual components. Despite the availability of theoretical and experimental studies including the test procedures, to estimate the performances of these systems, there are few experimental studies showing the temperature profiles of a particular collector geometries and materials with water temperature and flow rates in the units. This paper presents detailed experimental observations of temperature and flow distribution with solar radiations in a thermosyphon solar water heating system with four flat plate collectors, connected in series and using locally available materials, under a wide range of weather conditions of Minna for a whole year, to determine its suitability in meeting the hot water requirement for bathing in residential apartments. Results showed that the system is capable of meeting 70 – 100% hot water requirements and an average of 65.5^{0}C water temperatures is obtained daily with high temperatures reaching 90^{o}C on excessive hot days of March to May annually. Water temperatures in the hot water tank are of the range 45^{o}C to 78^{o}C and a mass flow rate averaging 55kg/hr was achieved for the system. Detailed temperature distributions, solar radiations variations and mass flow rate of the system were determined and presented. The experimental results were compared to the results found in the literatures and they showed good agreement.
Keywords: Flow measurement; Mean absorber plate temperature; Mean fluid temperature; Radiation measurement; Solar thermal collector system; Solar water heating system; Temperature measurement; Thermosyphon.

1. 0 Introduction

With erratic supply and distribution of electricity, increase in cost of energy, there is a need to improve energy efficiency in the built environment. The investigators propose to design, construct, test and evaluate the use of solar system as a possible alternative for heating water for domestic application. The efforts will help to develop efficient use of renewable energy resources, to maintain a healthy land, water and air quality throughout the building life cycle

Thermosyphon or natural circulation solar water heating systems (SWHS) are the simplest and most widely used solar energy collection and utilization devices. They are widely used in Australia and Israel, and are gaining popularity in Japan, the United States, and elsewhere (Malkin P.A; 1985). It consists of a collector, storage tank and connecting pipes. The collector is made up of an absorber plate; risers and headers tube pipes, glazing cover, casing and insulation. Water in the riser pipes get heated and flows towards the storage tank due to density difference. This flow depends on the thermosyphon head due to the buoyancy force, which is due to the change in density of water caused by water temperature rise in the solar collectors thus eliminating the need for a pump and a controller as in the case of the active system.

The key to the operation of a thermosyphon system is, however, the location of the hot water storage tank above the collector/s. By piping the outlets of the collectors to the top part of storage tank and the bottom of the storage tank to the collectors' inlets, a closed loop system is formed (fig.1). Natural-convective solar water heaters using the buoyancy force as the driving force are very reliable, but the weak driving force causes serious temperature stratification in the storage tank and deteriorates the thermal performance. The temperature stratification in forced-convective solar water heaters is not serious because the water in the tank is mixed with water pumps; however, this system cannot be used when the pump or the electromagnetic valve fail.

2.0 Literature Review

Performance evaluation of thermosyphon SWH had been explored via experimental and analytical studies. For example, Gupta and Garg (1968) pioneered the development of the models for thermal performance of a natural circulation thermosyphon SWH system with no load. This was achieved by representing solar radiation and ambient temperature with Fourier series such that the predicted daily performance of a thermosyphon was found to have agreed substantially with the experimental outcome. Moreover, Ong (1974, 1976) carried out a detailed study in which he evaluated the thermal

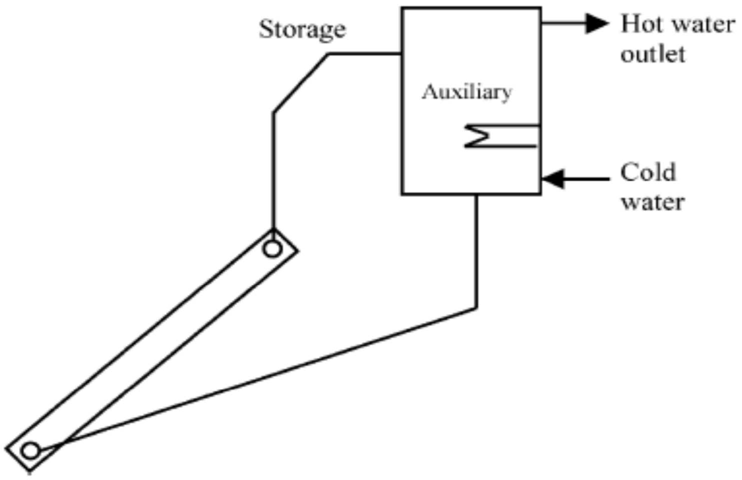

Figure 1.0 Diagram of a thermosyphon solar water heater
(Source: Kalogirou, 2004).

performance of a thermosyphon SWH system by employing five thermocouples on the bottom surface of the water tubes, six thermocouples on the bottom surface of the collector plate, six thermocouples in the storage tank, and a dye tracer mass flow meter. Odusote, (1989) proposed an alternative approach to plot performance curves of flat-plate collector (FPC) especially where standard facilities are not available to carry out the evaluation. His scheme overcame this difficulty by making use of natural effects, and achieved improved results by the use of interpolation and Monte Carlo sampling techniques.

Ojosu and Komolafe, (1989) developed a low cost integral solar water heater for Lagos environment, in which the functions of the solar collector and storage tank were combined into one unit (the ICS type). The design procedure used the solar radiation on the horizontal surface ranging from 13MJ/m^{2}day in August to 20MJ/m^{2}day in April. The solar water heater used in this experiment had a capacity for supplying about 150 litres of water at a temperature varying from 40^{0}C to 60^{0}C on a clear day whenever the water was drawn at regular intervals. A temperature above 70^{0}C was observed between 3-4 pm on a clear day. Efficiency curves obtained from the study revealed that this type of solar water heater has high thermal efficiency apart from its cheapness and smallness of size.

Sambo and Bello (1990) compared the influence of absorbers' materials (flat-plate black painted aluminium sheet, flat-plate black-painted galvanized mild steel sheet, quasi-flat-plate zinc coated mild galvanized aluminium sheet, and quasi-flat-plate zinc coated galvanized mild steel sheet) on the collectors' outlet temperature, and hourly efficiency. Findings from this study indicated that flat-plate black-painted galvanized mild steel sheet produced the highest water outlet temperature while the flat – plate black painted aluminium sheet had the highest hourly efficiency. It can be inferred from this study that materials' choices for the collector's plate could significantly influence its performance. Furthermore, Danshehu *et al.,* (1998) designed, developed, and evaluated the performance of a community based thermosyphon SWH system having a storage tank of 800 litres for the maternity ward of Usman Danfodio University Teaching Hospital in Sokoto. They pointed out that a temperature as high as 79 ^{o}C could be realised after every three hours under average sunshine condition with the hot water being delivered to the maternity ward at 65 ^{o}C. In conclusion, the study discovered that high working temperature had an adverse effect on the collector's efficiency and it was thereby recommended that collectors should be designed in such a way that allows its operational temperature difference to be as low as possible.

Nahar, (2002) investigated the capital cost and economic viability of thermosyphonic solar water heaters manufactured from alternate materials in India. The researcher investigated the performance and testing of solar water heaters having G.S.–Al fin, Cu–Al fin and Cu–Cu fin in flat-plate collectors have been compared. The researcher found that performance of all the three heaters was almost similar. The researcher also discovered that on the average, the payback period varied between 2.92 years to 4.53 years depending upon which fuel it replaces. In addition, the study revealed that the payback periods were increasing order with respect to fuels: electricity, firewood, LPG, charcoal, and kerosene. The payback period of the solar water heater with G.S.–Al collector was determined using 10% compound annual interest, 5% maintenance cost, 5%, inflation in fuel prices and maintenance cost. The study also concluded that many companies in India manufacture solar water heaters at that time but they were not popular in the domestic sector because of their high cost.

3.0 Description of Experimental Set-Up

The thermosyphon solar water heating system was stationed in the open field of the Bus-Park, Bosso Campus, Federal University of Technology, Minna. Niger State. Nigeria, to allow for effective tracking of the sun. The system, consisted of four flat plate solar collectors, a hot water storage tank, a cold water storage tank and connecting pipes. The collectors were connected in series through the supply headers, each employing eight evenly spaced parallel 12.5 mm copper pipes embossed by semi – circular grooves formed in the flat plate. Some pertinent technical details are given in Table 1.

Mercury – in – glass thermometers were installed into the water streams at the following locations along the circuit by the help of robber propping and glue.

1: The water inlet pipe of the first collector. The thermometer measures the first collector inlet water temperature.

2: 3: 4: The water outlet pipe of the first, second and third collectors respectively. These thermometers measure the outlet water temperatures of the first, second and third collectors and by extension the water inlet temperature of the second, third and fourth collectors respectively.

5: The water outlet pipe of the fourth collector to the hot water storage tank. The thermometer measures the outlet water temperature of the fourth collector and by extension that of the collector array.

6: The hot water storage tank's hot water inlet and cold water outlets. While thermometer '6' measures the temperature of the hot water coming from the collector array to the top of the hot water storage tank.

7. Measures the temperature of the 'cold' water coming from the hot water storage tank to the collector array .The average of these two temperature readings is what gives the bulk water temperature of the tank.

8: The hot water storage tank's water outlet pipe. The thermometer measures the tank's outlet hot water temperature or any drawn – off to the loads.

9: The hot water storage tank's cold water inlet pipe. The thermometer measures the water temperature coming into the hot water storage tank from the overhead cold water tank.

Table 1: Technical data of the solar water heating system used in the study.

Description	Specification
a. Solar Collector	
Dimension	1010×1200×90 mm
Header	3/4 " (17 mm inside diameter)
Riser	1/2" (12 mm inside diameter) copper pipe
Number of risers	08
Absorber	Anodised painted black, thickness 2 mm
Insulation	Rockwool, thickness 40 mm
Glass cover	Ordinary glass, thickness 3mm
Frame	25 mm sizes/19 mm bottom hardwood/plywood.
Tilt angle	10° to the horizontal facing due south
b. Storage tank (vertical)	
Dimension	Cubical, 1200×1200x1200 mm^3 1200 litres holding capacity.
Material	Galvanized steel, thickness 2 mm
Insulation	Rockwool, thickness 80 mm enclosed by dampproof polythene sheet.
Cover	Galvanized steel, thickness 2 mm
Volume	1200 L
Fitting	3/4 " or 19 mm copper pipe threaded
c. Connecting pipe	
Material	1" (24 mm inside diameter) copper pipe
Insulation	Aeroflex 3/8" thickness

(Source: Akanmu, 2008.)

On the collector array, the following readings were carried out for the purposes of this study. The temperature readings, the solar radiation intensity readings and the water flow rates which were recorded hourly between the hours of 7:00 am and 6.00 pm each day.

The measurements that were recorded on the hot water storage tank are the bulk temperatures of the water in the hot water storage tank at hourly time intervals using mercury in glass thermometer. The temperatures of water drawn off from a chosen delivery point of the hot water storage tank were also recorded at an equal time interval over the days drawing 200 litres of hot water each time. The first set of tests carried out were those when no hot water was withdrawn from the hot water storage tank. The second sets of tests carried out were done specifically for three days from 12th April to 14th April, 2009. Here draw-offs were done at 9:30, 11:00, 12:30, 14:00, 15:30, 17:00 and 18:30 GMT hours of the day. The overall accuracy of the temperature measurements is estimated at $\pm 1.0^oC$. Data collection were carried out physically in person and recorded in prepared sheets every one hour interval between the hours of seven O'clock in the morning to six O'clock in the evening, Monday to Saturday for the entire duration of the experiments. Solar insolation was measured by means of a digital Solarimeter placed on the same surface inclination with the collector plates array. The accuracy of the measurement is estimated to be ± 1 percent in the entire temperature range employed. Water flow rates were measured by a specially made flow meter. This instrument, based on thermal dissipation tracing was constructed to present minimum hydraulic resistance to flow of 1mm H_20 or less of 1200cm^3/min. It is estimated that the accuracy of this instrument is ± 3 percent in the entire range of conditions employed. The construction of this flow meter is such that it might be calibrated to indicate reverse flow. This option was not utilized in the present experiments.

4.0 Experimental observations and discussion.

The increasing rate of change of the collectors' fluid outlet temperature, collectors' fluid inlet temperature, and bulk water temperature of the tank between 7.00 to 14.00 GMT hours during all the seasons (Figures 2.0 to 4.0) could be attributed to the increasing level of radiation for the same duration of time of the day (Figures 11.0 to 13.0) for which the daily temperature of the fluid reaches its highest by 14.00 GMT hours. This is inferred to have led to the temperature increase of the stored water in the tank, and consequently the temperature increase of the incoming fluid to the collectors. Therefore, the highest temperature of the outgoing fluid is observed to be at this same time (Taherian et al., 2010). By extension, it is thought that this causes increase in the mean temperature of the working fluid and therefore, the absorber is expected to have attained its maximum temperatures at this time (14.00 GMT hours). The mean error percentages of 4%, 6% and 7% (Figures 2 to 4) reported for the experimental values of collectors' fluid outlet temperature, collectors' fluid inlet temperature, and bulk water temperature of the tank respectively lend credence to this behaviour.

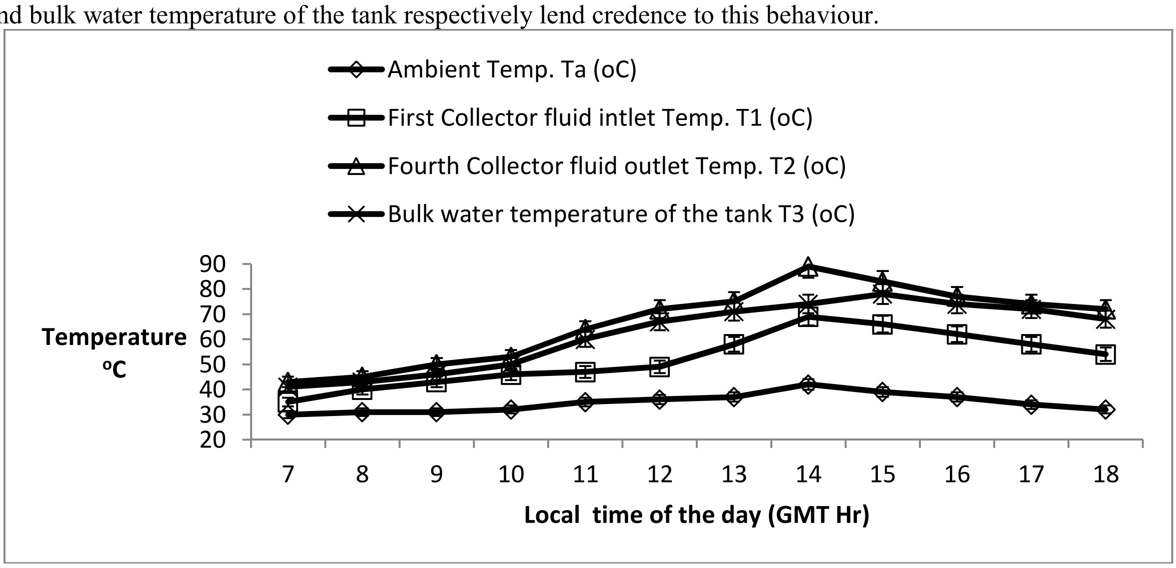

Figure 2. Dry season mean hourly variation with the temperature profile of the thermosyphon solar water heating system
(Source: From Field Test 2008.)

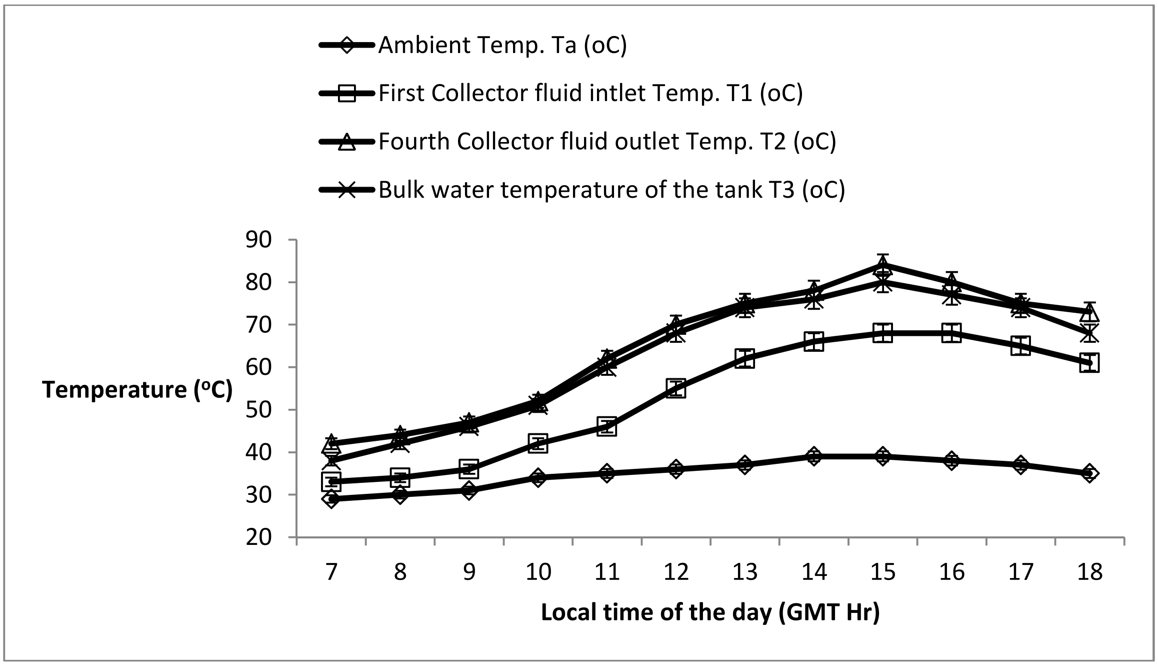

Figure 3. Wet season mean hourly variation with temperature profile of the thermosyphon solar water heating system.
(Source: From Field Test 2008.)

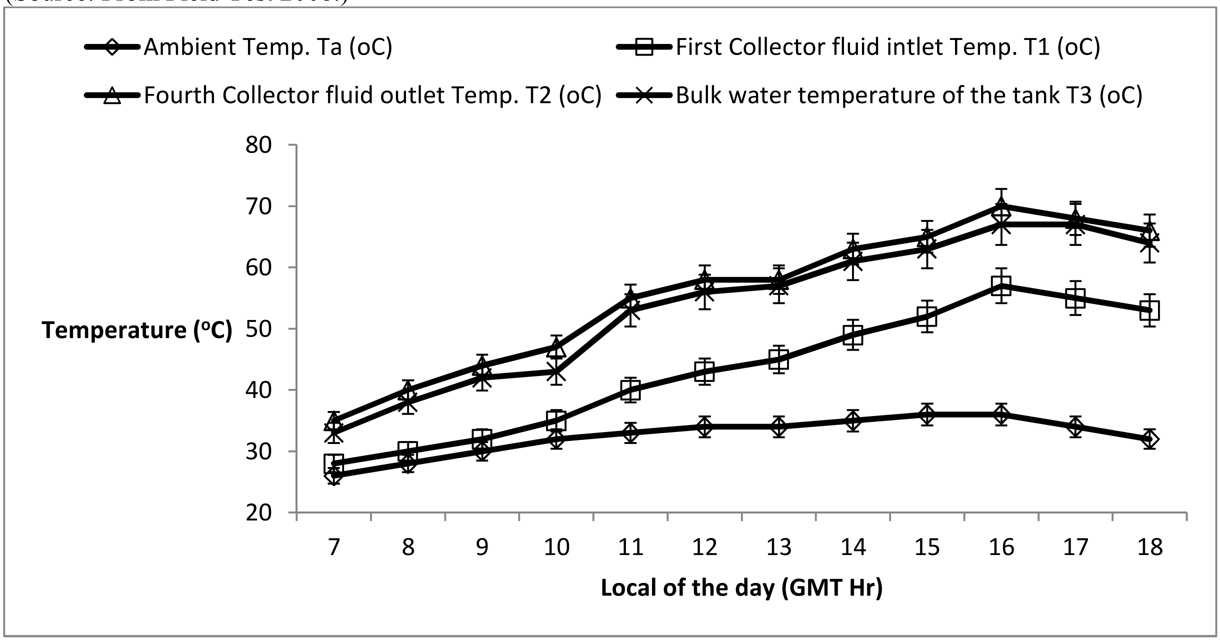

Figure 4. Harmatan season mean hourly variation with the temperature profile of the thermosyphon solar water heating system.
(Source: From Field Test 2008.)

As the incident radiation experiences progressive increase there is a corresponding increase in the useful energy gained. This energy is responsible for driving by convection buoyancy the system fluid flow, depending on the thermal properties of the fluid. Consequently, behind the rate of change of the intensities, there was a little drag of the rate of change of the useful energy obtained and this small time delay was observed for all the seasons. This fact causes the water heater to act like a temporary heat store such that, at the time the collector was absorbing maximum solar radiation (Figures 2 to 4), the response delay driving the system causes water in the tank to attain the maximum temperature much later (about one hour after the system had absorbed the highest solar radiation). This phenomenon eventually causes changes in the inlet and outlet temperatures of the collector as well as the fluid bulk temperature as depicted in Figures 2 to 4. The circulation is discontinued in the collectors when the radiation from the sun is small. Since flow is as a result of buoyancy force, when there is not enough solar radiation present on the surface of the collector, the flow stops. This temperature difference between outlet and inlet is found to be 10 ^{o}C for this study. These changes are shown for all the seasons in Figures 5 to 7 and as expected, the maximum fluid flow occurred in the dry season by 14.00 GMT hours.

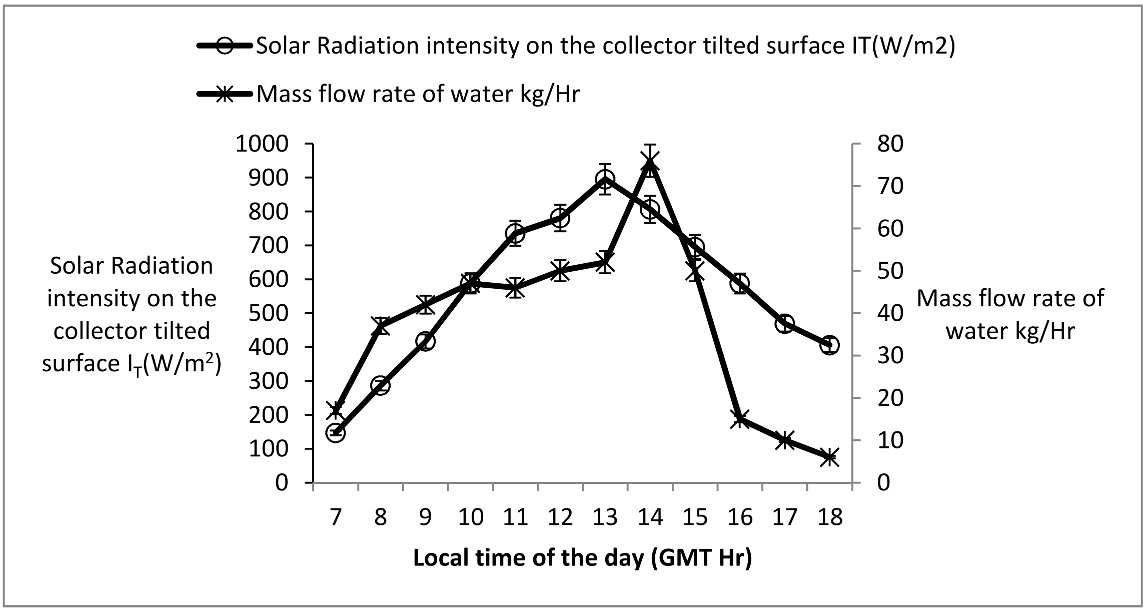

Figure 5. Dry season mean hourly variation with mass flow rate of water along the down comer pipe of the thermosyphon solar water heating system and the solar radiation intensity.
(Source: From Field Test 2008.)

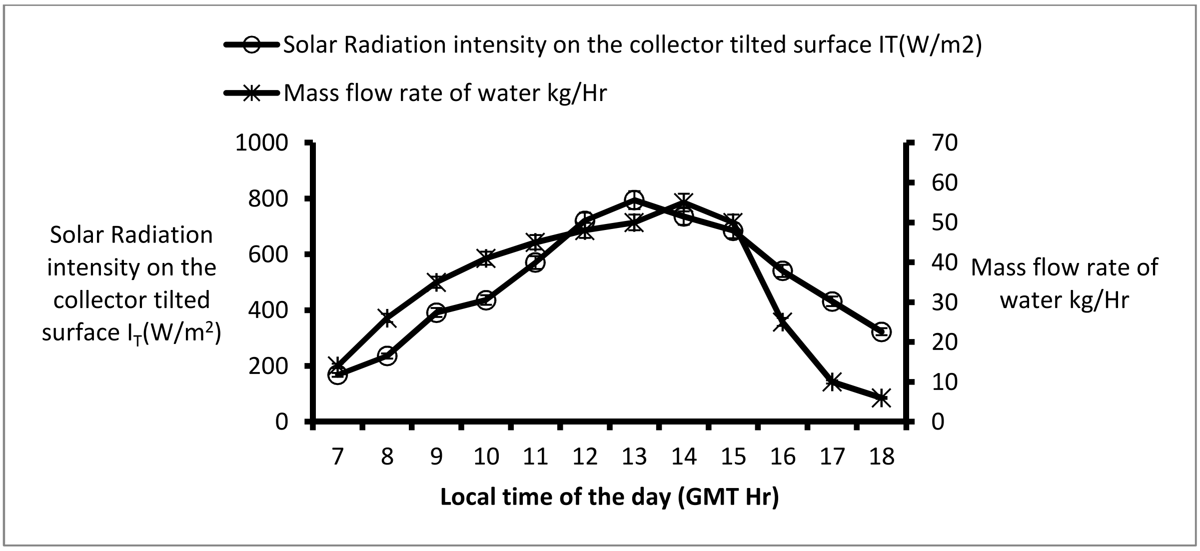

Figure 6. Wet season mean hourly variation with mass flow rate of water along the down comer pipe of the thermosyphon solar water heating system and the solar radiation intensity.
(Source: From Field Test 2008.)

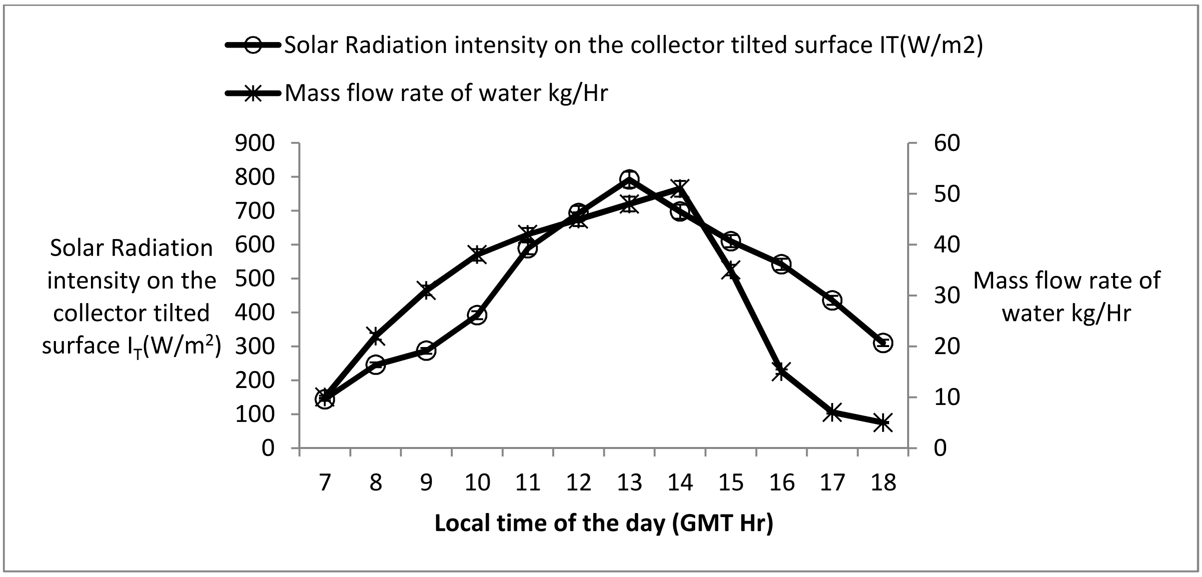

Figure 7. Harmatan season mean hourly variation with mass flow rate of water along the down comer pipe of the thermosyphon solar water heating system and the solar radiation intensity.
(Source: From Field Test 2008.)

The solar radiations at the tilted collectors, the inlet and outlet collectors' temperature, as well as the bulk water temperature were measured throughout the year. From this data, the outlet and inlet collectors' temperature difference, useful energy and the instantaneous efficiencies were calculated. The solar collectors' outlet and inlet temperature difference, the storage tank temperature and the ambient temperature for a mean dry season day is plotted in Figure 14 which shows the ability of the system in providing hot water suitable for household use under varying weather conditions. The storage tank water temperature reached 78°C just before sunset. The amount of useful energy and the incident solar radiation for the three seasons is presented in Figure 8 to 10 .

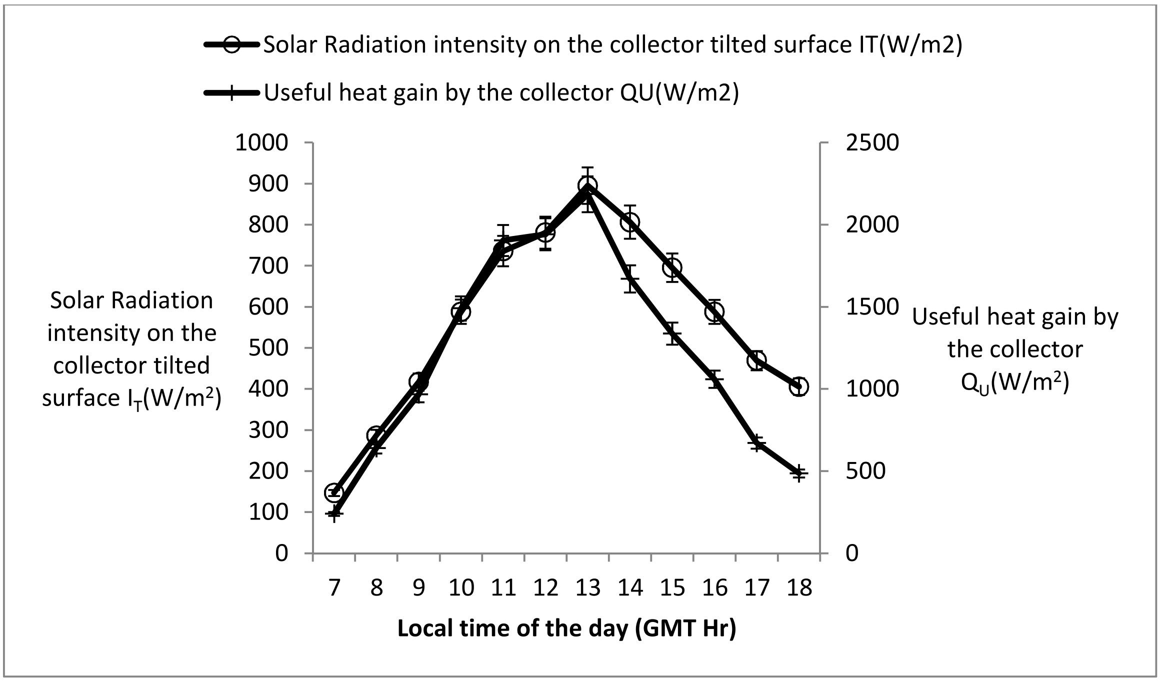

Figure 8. Dry season mean hourly variation with solar radiation intensity, and useful heat by the collectors of the thermosyphon solar water heating system.
(Source: From Field Test 2008.)

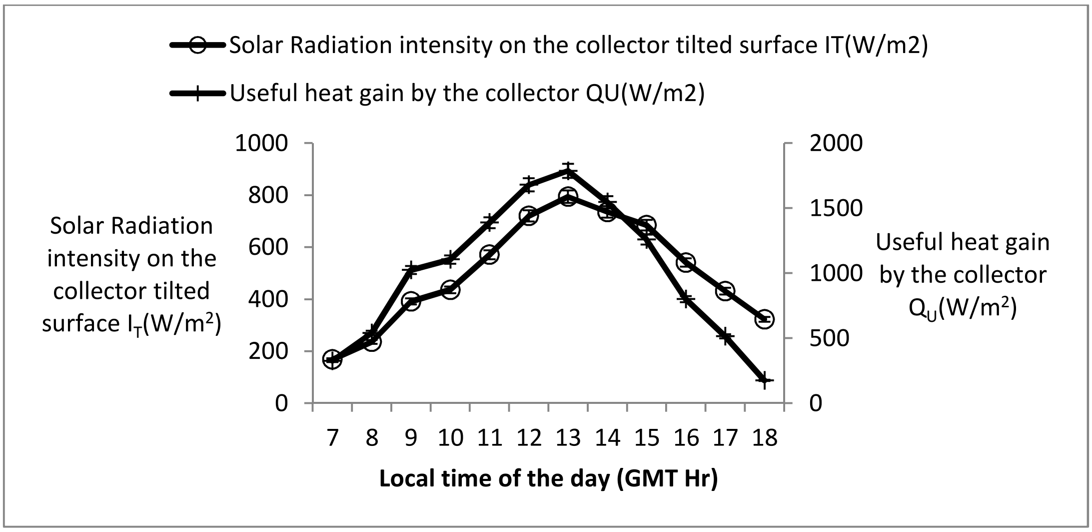

Figure 9. Wet season mean hourly variation with solar radiation intensity, and useful heat by the collectors of the thermosyphon solar water heating system.
(Source: From Field Test 2008.)

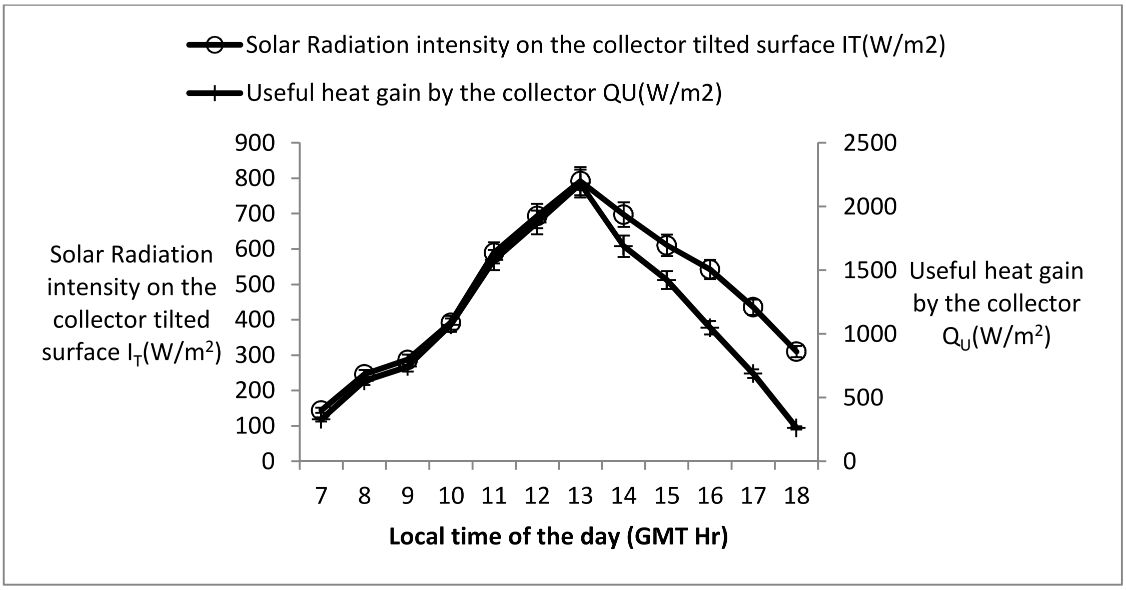

Figure 10. Harmatan season mean hourly variation with solar radiation intensity, and useful heat by the collectors of the thermosyphon solar water heating system.
(Source: From Field Test 2008.)

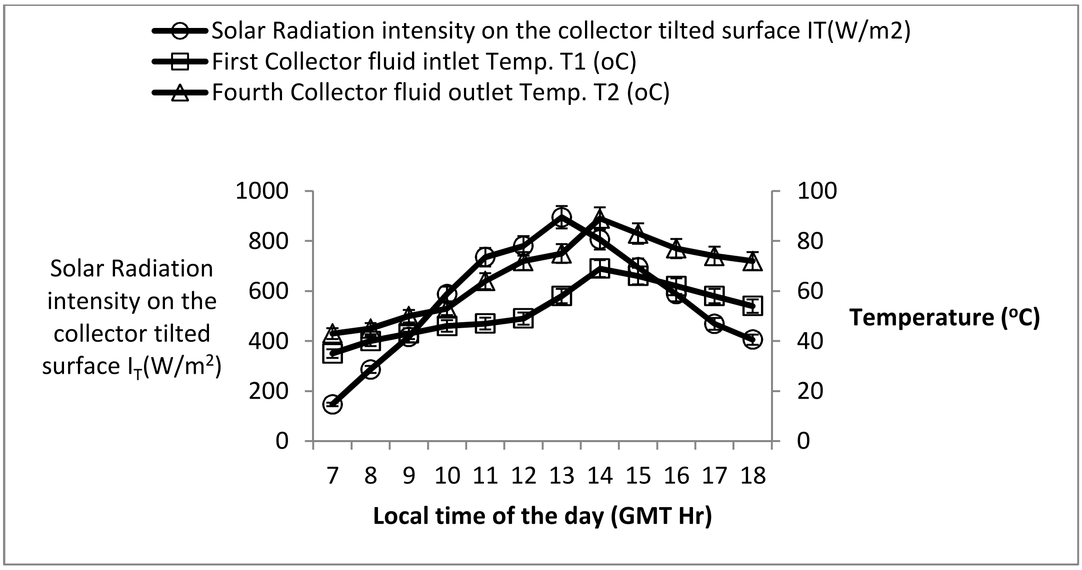

Figure 11. Dry season mean hourly variation with solar radiation intensity, and temperature profile of the inlet and outlet of the collectors of the thermosyphon solar water heating system.
(Source: From Field Test 2008.)

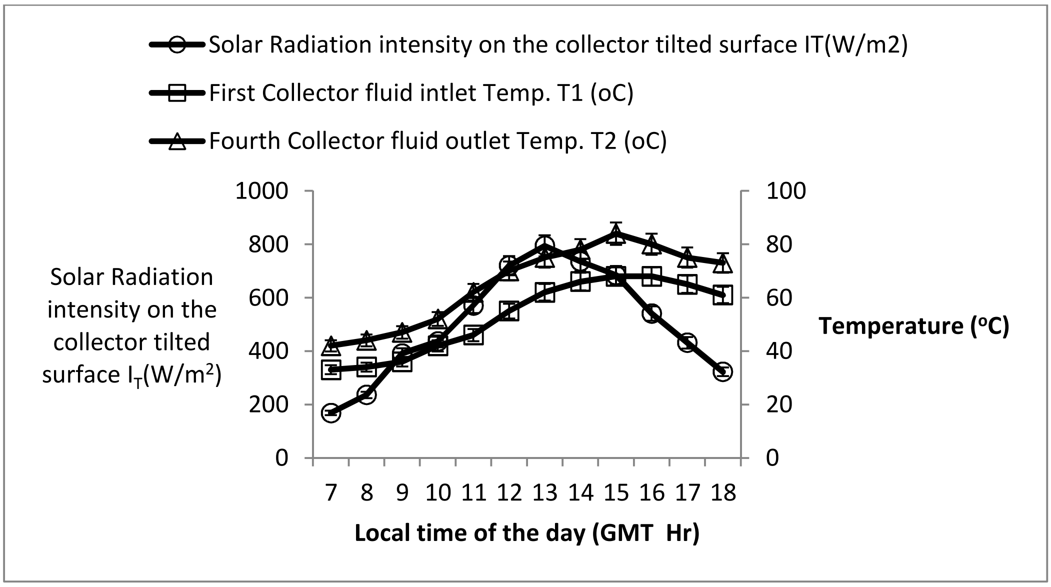

Figure 12. Wet season mean hourly variation with solar radiation intensity, and temperature profile of the inlet and outlet of the collectors of the thermosyphon solar water heating system.
(Source: From Field Test 2008.)

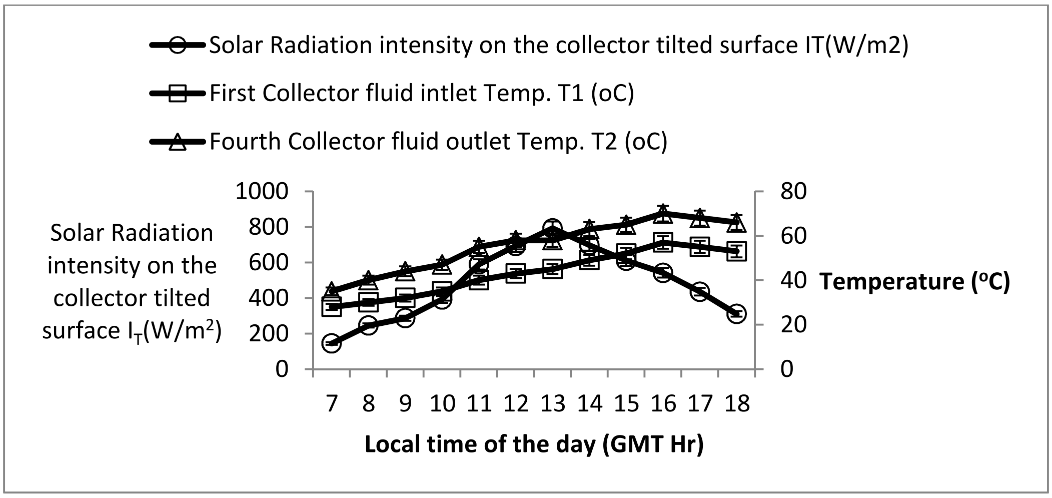

Figure 13. Harmatan season mean hourly variation with solar radiation intensity, and temperature profile of the inlet and outlet of the collectors of the thermosyphon solar water heating system.
(Source: From Field Test 2008.)

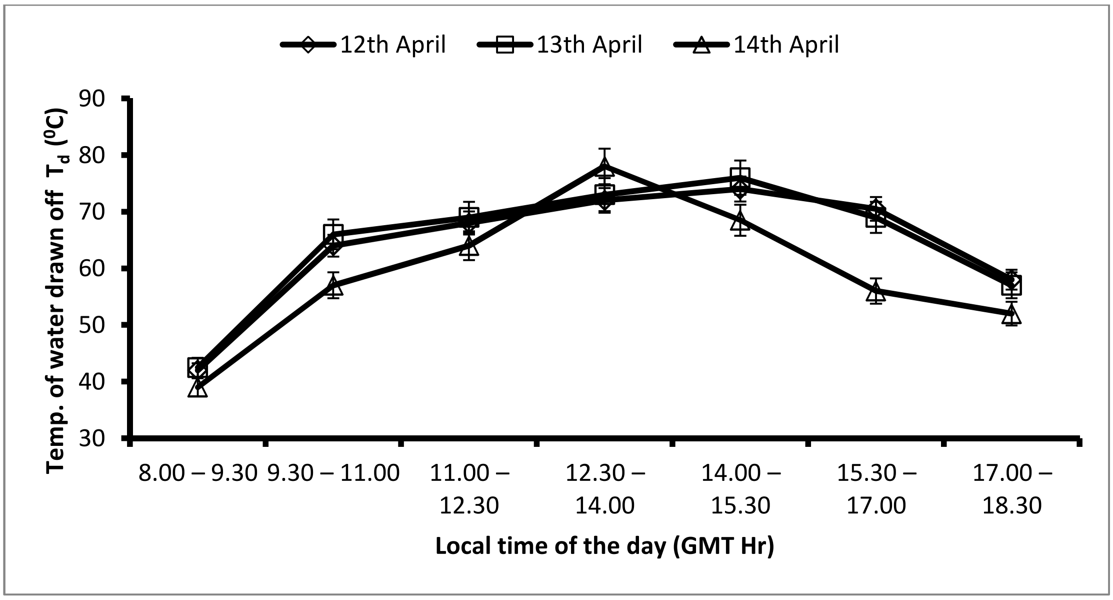

Figure 14. Temperature
(Source: From Field Test 2008.)

It is noted that the insolation increases from 7.00 GMT until it reaches its maximum value (895, 794, 697 W/m^2) at 13.00 GMT hours for the dry, wet, and harmattan seasons, then it begins to decrease. The useful energy follows the same pattern. The difference between the incident energy and the useful energy represents the collectors' thermal loss. The collector efficiency, which is the ratio of useful energy to solar radiation, should follow the same trend as the insolation and useful energy. It increases until 13.00 GMT hours and then decreases. This is shown in Figure 8.0 to 10.0. As it can be seen from the Figures, the insolations for each of these seasons vary and therefore the useful energy is expected to vary as well. Therefore auxiliary heat would be needed on wet and harmattan seasons' days. In spite of low useful energy during these seasons, the collector efficiency is in the normal range on the days of these seasons, which shows that the solar collectors can capture heat at low insolation or in the presence of diffused radiation only. The attainment of the highest insolation at 13.00 GMT hours irrespective of seasons could be attributed to the fact that the angle of inclination of the sun to the collector's tilted surface is highest at this time (Alfa *et al.,* 2004). Consequently, the reduction in the solar radiation intensity before or after 13.00 GMT hours could be said to be responsible for the reduction in the useful heat energy gain observed before or after this time. Furthermore, the attainment of the highest insolation and useful heat gain in the dry season could be attributed to the fact that there is the occurrence of the least cloud cover in the sky during this season in comparison to others.

5.2 Conclusions

The option of adopting solar water heaters to meet the hot water needs of Nigeria is viable. It is more cost-effective, environmentally friendly and sustainable in comparison with the option of using electricity. The solar water heating system has been analyzed, designed, fabricated from locally available materials and installed to supply hot water needs fully or partially to meet the need of twenty students. From the results obtained in the performance test carried out, the solar water heating system with 4Nos (1.20 m x 1.20 m) flat plate collectors connected in series has exhibited ability when 1000 litres of water was:

(1) Heated to a maximum temperature of 76^0C in a favourable weather condition and deliver same for use.
(2) Heated to a maximum temperature of 52^0C in an unfavourable weather condition.
(3) Delivered hot water at as high temperatures as 45^0C by 7.00 am in the mornings.
(4) Met an appreciable volume of hot water demand especially between the hours of 11.00am to 5.00 pm daily and throughout the year.
(5) The thermal performance of the natural circulation thermosyphon solar water heating system is comparable to that of a well-controlled forced circulation active solar water heating system. Thermosyphon systems have no parasitic power or maintenance requirements for a pump and controller, and are therefore an attractive alternative for helping to meet the hot water load in a variety of locations. Whereas the long term thermal performance of active systems may be estimated using the f-chart method, the unique control strategy inherent in the operation of a natural circulation thermosyphon system can be used to develop a design tool for predicting its long term performance.
(6) Even though, a substantial heat loss could occur from the long run of pipes connecting the storage tank to the panel if not properly insulated, the thermal performance of the hot water heating system can be approximately predicted based on the thermal characteristics of the collector array and storage tanks without a consideration of the connecting piping

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