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Performance Evaluation Of A 4nos. Serially Connected Flat-Plate Collectors In A Closed Thermosyphon Solar Water Heating System For Use In A Community-Based Environment.

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Abstract

An extensive study was carried out to design, fabricate and investigates experimentally the long-term thermal performance of a closed thermosyphon 4 nos. serially connected flat-plate solar water heating system under a wide range of weather conditions in Minna to determine its suitability to meet the hot water requirement of the community of twenty students. A thermosyphon solar water heating system with four flat plate collectors, connected in series was fabricated, using locally available materials. The design, fabrication and the thermal performance tests of the system were carried out without water-drawn-off load. Results showed that the system is capable of meeting 70 – 100% hot water requirement for bathing in a community based built-environment i n Minna. Thermal efficiency of up to 48% was achieved and an average water temperature in the tank of the range 45^{o}C to 90^{o}C was achieved. Detailed thermal efficiencies of the system were determined and presented. The experimental results were compared to the results found in the literatures and they showed good agreement.

Key Words: built-environment , closed thermosyphon, community based, performance evaluation, solar water heating system.

1.0 Introduction

Over the past century fossil fuels and coal have increasingly provided most of our energy needs in the built-environment because these are much cheaper and more convenient to harness and use than energy from renewable sources. Since the occurrence of energy crises of the early seventies, serious concerns had been expressed about the escalating cost of fossil fuels as well as its associated risk and the reality of environmental degradation which have become more apparent as at today than ever before (Kalogirou, 2004). To overcome these challenges, there is a need for long term potential action that has sustainable development (development that meets the needs of the present without compromising the ability of future generations to meet their own needs) as its focus. Renewable energy technology (solar radiation, wind, falling water, biomass, tides, and geothermal) is one of the most efficient and effective solution because it is readily available at reasonable cost, generate new jobs and can be utilised for all the required tasks without causing negative environmental impacts (Dincer, *et al.*, 1998).

However, the solar energy conversion efficiency of a thermosyphon SWH system when flat-plate collectors are engaged is less than 50% because most of the absorbed solar energy are lost due to heat loss into the ambient environment (Klein et al. 1976). For this reason, the working temperature of the collector plates should not be very high so as to enable the system attain high performance efficiency. To improve the performance of the thermosyphon SWH system, much research effort had been directed to the development of collector technology using water as the working fluid (Iwuoha, 2004; Danshehu *et al.,* 2004). Through good thermal contact between the thermal absorber and the risers and the headers, the thermal efficiency can be raised. The performance of the thermal absorber is one crucial factor in achieving a high overall energy yield. To address the challenges highlighted above about the thermosyphon SWH system, this research problem had been formulated. Consequently, a mild steel flat-plate solar collector, connecting copper pipes, and mild steel storage tank that is operating as a closed thermosyphon system had been designed, constructed, and tested. Its performance evaluation was carried out and then compared to thermosyphon SWH system designed, fabricated, and tested in regions of similar climatic conditions to Minna.

Table 1: List of Symbols

Nomenclature			
A_C	collector area (m^2)	**Greek letters**	
C_p	specific heat capacity of water (J/kg ^{0}C)	ε	emissivity
F_R	collector heat removal factor (dimensionless) coefficient	(τα)	collector transmittance–absorptance
F	collector factor (dimensionless)	η	collector efficiency
G	instantaneous solar radiation (W/m^2)	σ	Stephan–Boltzmann constant (W/m^2 K^4)
(h)	time (h)		
h	convection heat transfer coefficient (W/m^2 ^{0}C)	**Subscripts**	
h_r	radiation heat transfer coefficient (W/m^2 ^{0}C)	a	ambient
$I(\tau\alpha)_{(ac)}$	absorbed energy by cover (W/m2)	b	back
K_{air}	air thermal conductivity (W/m ^{0}C)	c	cover or collector
L	plate spacing (m)	f_i	collector inlet fluid
$\dot{m}$	flow rate per unit area of collector (kg/s/m^2)	f_o	collector outlet fluid
Nu	Nusselt number (dimensionless)	L	overall
ODE	ordinary differential equation	p	plate
$\dot{Q}$	heat generated (W)	pc	partly cloudy
t	time (s)	R	heat removal
T	temperature (^{0}C)	s	sunny or sky
U	heat coefficient (W/m^2 ^{0}C		
TRNSYS	Transient System (An Energy System Simulation Programme).		

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 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. Furthermore, Kudish et al (1985) measured the thermosyphon flow rate directly by adapting a simple and well-known laboratory technique, a constant level device, to a solar collector in the thermosyphon for the determination of instantaneous collector efficiency as a function of time of the day. Their findings were utilised in constructing a standard efficiency test curve, which suggested that the technique was suitable for testing collectors of thermosyphon system.

Morrison and Braun (1985) employed modelling to study the operation characteristics of thermosyphon SWH with vertical and horizontal storage tank. The outcome of their study suggested that the system performance of both vertical and horizontal storage tank differed and that performance was maximized when the daily collector volume flow was approximately equal to the daily load flow. Hobson and Norton (1989) developed a characteristic curve for determining solar fraction for a directly heated thermosyphon SWH by using data from a 30 day test. They discovered that their calculated values agreed with the computed values from the numerical simulation. The analysis adopted by Hobson and Norton could be described as a simple but relatively accurate design method for direct thermosyphon solar energy water heaters. Shariah and Shalabi (1997) optimized the design parameters for a thermosyphon SWH system for Amman and Aqaba (two Jordanian cities) by employing TRNSYS simulation program. Their findings suggested that though, the solar fraction of a system installed in Aqaba (hot climate) is less sensitive to some parameters than the solar fraction of a similar system installed in Amman (mild climate). Nevertheless, it could be inferred that 10 to 25% solar fraction of the system can be achieved when each studied parameter is chosen properly.

Karaghouli and Alnaser (2001) analysed the thermal performance of the thermosyphon water heater unit with a view to demonstrating its applicability in Bahrain by using data of several sunny, cloudy and hazy days under varying daily solar intensities, and the daily outside temperature ranges between 19-25°C. The results showed that the system has an average efficiency of 38% with storage tank temperature above 50°C. Chuawittayawuth and Kumar (2002) presented details of experimental observations of temperature and flow distribution in a natural circulation solar water heating system and its comparison with the theoretical models. They discovered that the measured profile of the absorber temperature near the riser tubes (near the bottom and top headers) conforms well with the theoretical models. Moreover, the values at the riser tubes near the collector inlet were found to be generally much higher than those at the other risers on a clear day, while on cloudy days, these temperatures were uniform.

2.1 Theoretical Background

The solar water heater under study is consisted of four flat plates solar collectors of 2.25 m^2 aperture area each installed at a 19^0 latitude tilt facing South and connected to a well insulated galvanized steel stand alone storage tank. The details of the system are described in Akanmu, W.P; (2011).

The governing differential equations should be separately written for the absorber, the glass cover and the working fluid, and then solved as a system of equations.

The enthalpy change of the glass cover equals the absorbed energy from the sun plus the absorbed energy by convection via the absorber plate plus the absorbed energy by the cover through absorber radiation minus the outgoing energy via convection with the ambient minus the outgoing energy through radiation to the surrounding ambient,

$$(\dot{m}C_P)_C \frac{dT_C}{dt} = I(\alpha C) + h_{P-c}\left(T_p - T_c\right) + hr_{p-c}\left(T_p - T_c\right) + h_{c-a}(T_a - T_c) + hr_{c-a}(T_a - T_c) \quad (1)$$

Where

$$\mathrm{hr}_{p-c} = \left(\sigma\left(T_p + T_c\right)\left(T_p^2 + T_c^2\right)\right) / \left(\left(1/\varepsilon_p\right) + \left(1/\varepsilon_c\right) - 1\right) \quad (2)$$

The convection heat transfer coefficient of the absorber plate and the glass cover is (Tiwari, G. N; Singh, U; Nayak, J. K., 1985)

$$h_{p-c} = NuK_{air}/L \quad (3)$$

The convection heat transfer coefficient of the absorber plate and the ambient can be obtained by (Tiwari, G. N; Singh, U; Nayak, J. K., 1985)

$$h_{c-a} = 5.7 + 3.8V \quad (4)$$

Also, the radiation heat transfer coefficient of the absorber plate and the ambient is:

$$\mathrm{hr}_{c-a} = \varepsilon_c \sigma (T_c^2 + T_s^2)(T_c + T_s) \quad (5)$$

Where (Tiwari, G. N; Singh, U; Nayak, J. K., 1985)

$$T_s = 0.0552\ T_a^{1.5} \quad (6)$$

2.1.1 The governing equations for the absorber plate

The energy changes of the absorber plate equals the absorbed energy from the sun minus the outgoing energy via convection to the glass cover minus the outgoing energy through radiation to the glass cover minus the outgoing energy through the insulation minus the energy transferred to the working fluid.

$$(\dot{m}C_P)_p \frac{dT_p}{dt} = I(\tau_c.\alpha_p) + h_{P-c}(T_c - T_p) + hr_{p-c}(T_c - T_p) + U_b(T_a - T_p) + U_b(T_a - T_p) + \dot{m}_f C_{Pf}(T_{fi} - T_{fo}) \quad (7)$$

2.1.2 The governing equations for the working fluid

The only governing equation for the working fluid is the useful energy, which is transferred from the absorber plate, and that is: the incoming radiation minus energy loss when the collector temperature is assumed to be at $T_{p.}$ (Tiwari, G. N; Singh, U; Nayak, J. K.,1985)

$$Q_u = A_C F_R [G(\tau\alpha) - U_L(T_{fi} - T_{fo})] \quad (8)$$

The thermal efficiency of a flat plate solar collector can be depicted as the linear graph dependent on the outgoing useful energy of the collector, the amount of incoming sunlight and the thermal loss. The instantaneous efficiency of the collector is defined as the ratio of the gained useful energy to the radiated energy onto the collector surface:

$$\eta = Q_U / A_C G \quad (9)$$

The instantaneous efficiency of solar collectors is affected by many different factors such as the materials used in manufacturing the collector, the type and configuration of absorber plate and riser tubes, the properties of glass cover and the weather conditions; thereby, it can be written in the form of the following efficiency function. (Tiwari, G. N; Singh, U; Nayak, J. K: 1985):

$$\eta = F_R(\tau\alpha) - F_R U_L (T_i - T_a)/G \quad (10)$$

Where $F_R(\tau\alpha)$ determines how the energy is absorbed and $F_R U_L$ determines the way the energy is lost. In Eq. (10), η is the dependent variable and $[(T_i - T_a)/G]$ is the independent variable. Therefore, in the efficiency diagram, $F_R(\tau\alpha)$(is where the curve intersects with y-axis and $-F_R U_L$ is the slope of the efficiency diagram. When sloped lines intersect the horizontal axis, it means that the outgoing useful energy from the collector is crosses and is called the stagnation status. The useful energy obtained from the collector can be calculated by measuring the flow rate of the fluid from the collector and the inlet and outlet temperatures.

$$Q_U = \dot{m} C_p (T_o T_i) \quad (11)$$

Therefore,

The set of differential equations can then be represented in Simulink graphical user interface (GUI) in the form

$$\eta = \dot{m} C_p (T_o - T_i)/A_C G \quad (12)$$

Of simulation blocks and connecting links. Due to its intricate structure and multiplicity of sub-systems, the block diagram has not been shown here. Simulations can be run for various weather conditions.

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. This was to allow for effective tracking of the sun. The system, once again, 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 12.5mm copper pipes embossed by semi – circular grooves formed in the flat plate. Other pertinent technical details are given in Table1. 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, 7: 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. Thermometer '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.

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 2: Technical Data for the Solar Water Heating System

	ITEM	DETAILS
COLLECTOR	Water flow pipes	8 parallel 1.25cm (½") copper; 1m long
	Supply and drain headers	1.00cm (¾") copper; 1.2m long
	Insulation	4cm Rockwool
	Glass sheet	0.4cm ordinary glass
	Collector plate	1.22 x 1.22m, 1.2mm thick Iron plate painted matt black
	Casing	25mm sizes/19mm bottom hardwood/plywood.
	Water tank	Cubical, 0.5cm thick galvanized steel 1000 litres holding capacity. 8cm Rockwool insulation enclosed by Damp proof polythene sheet
	Connecting Pipes	19mm (¾") Copper pipe with foam insulation

On the collector array, the following readings were carried out for the purposes of performance evaluation. The temperature readings, the solar radiation intensity readings and the water flow rates which were recorded hourly between the hours of 7:00am and 6.00pm 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 set of tests carried out were those when no hot water was withdrawn from the hot water storage tank. The overall accuracy of the temperature measurements is estimated at $\pm 1.0^{o}C$. 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 Results and Discussion

4.1 Efficiency of the Collectors of the Thermosyphon SWH System

Figures 4.1 to 4.3 are the seasons' collector hourly efficiency curves with respect to the local time. The curves generally reveal that initially the efficiency increases gradually from 7.00 GMT hours to 11.00 GMT hours where it peaked at 0.45 collector's hourly efficiency. Between 11.00 to 13.00 GMT hours, there was a gradual decline of efficiency of the collectors' capability. After 13.00 GMT hours, decline of efficiency of the collectors' capability could be described as sharper than that reported between 11.00 to 13.00 GMT hours.

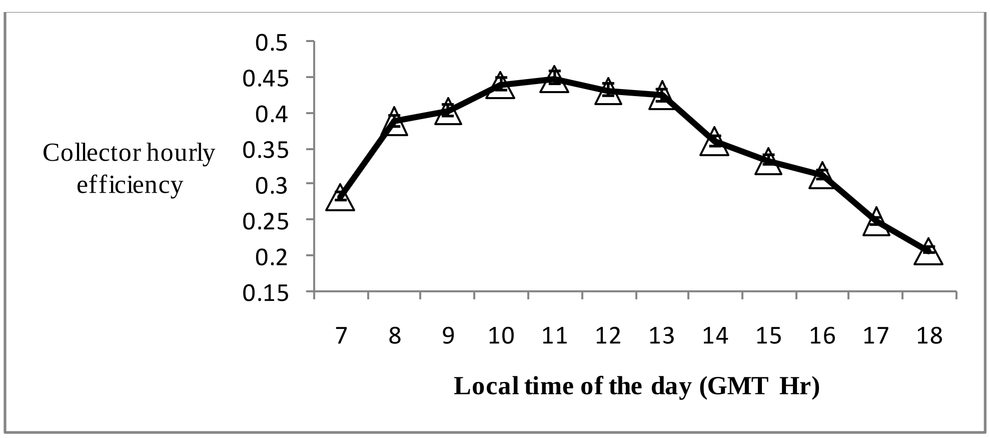

Figure 1: Dry Season Collector Hourly Efficiency of The Thermosyphon Solar Water Heating System.

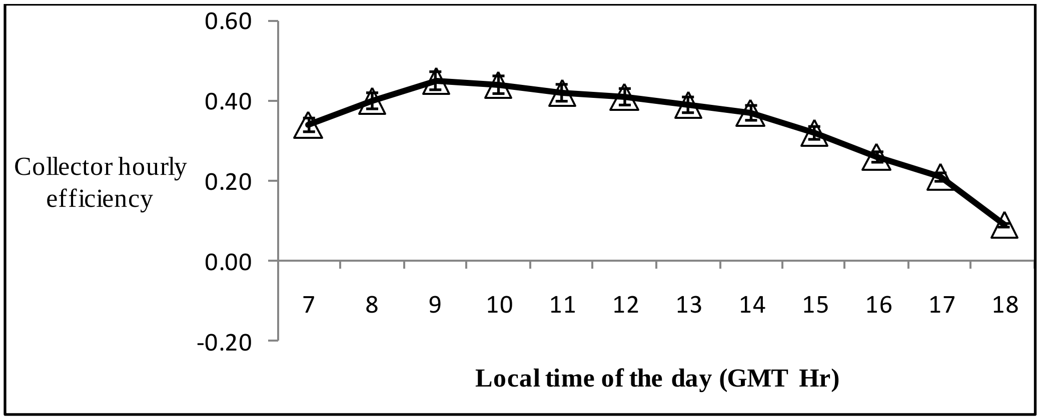

Figure 2: Wet Season Collector Hourly Efficiency of the Thermosyphon Solar Water Heating System.

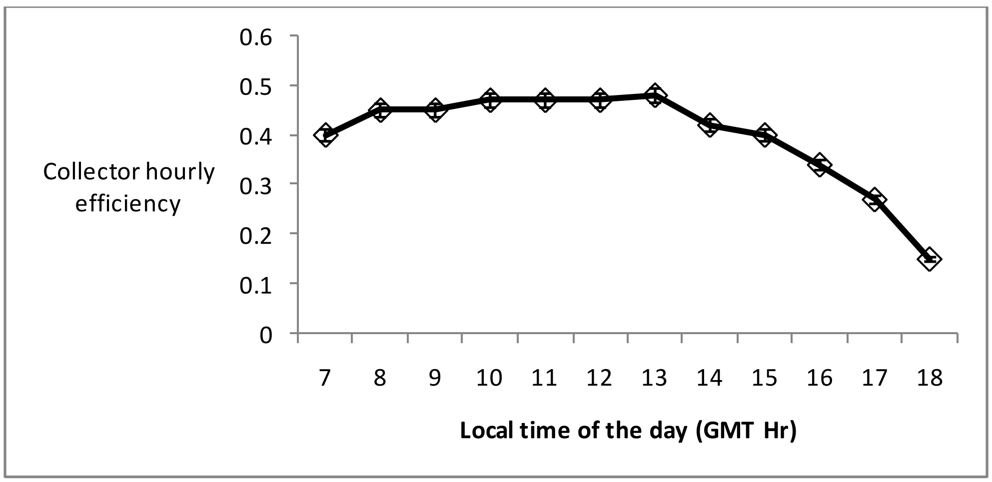

Figure 3: Harmattan Season Collector Hourly Efficiency of The Thermosyphon Solar Water Heating System.

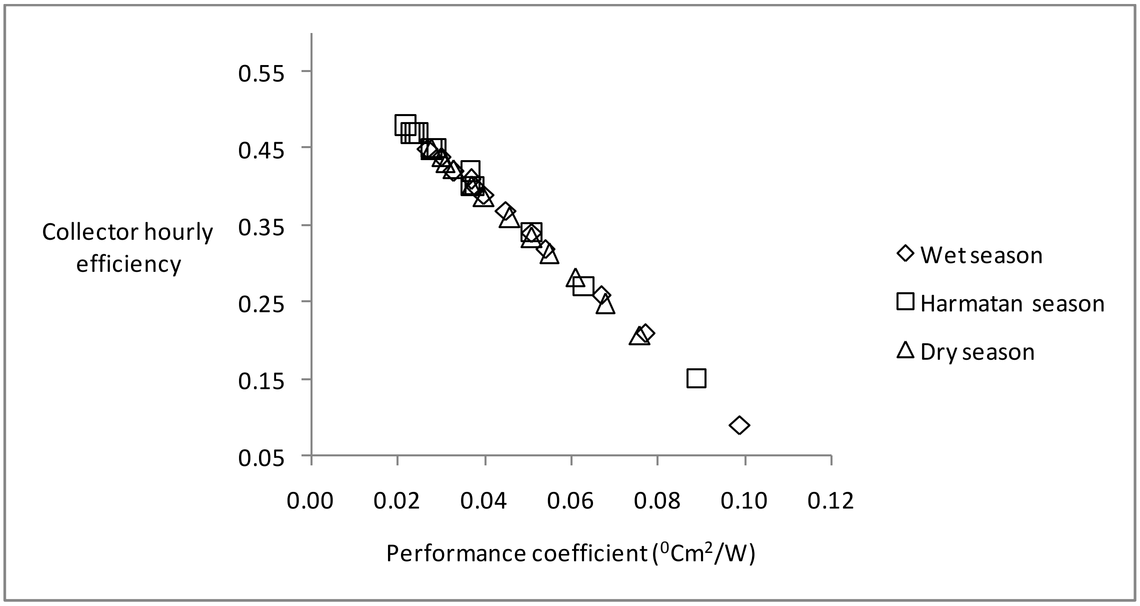

Figure 4: All Seasons' Experimental Thermal Efficiency Graph for the Collectors of the Thermosyphon Solar Water Heating System (Equation of Regression is Y = -4.969x + 0.590; $R^2 = 0.996$).

Relationships between Various Performance Characteristics of the Thermosyphon SWH System

When compared the solar radiation intensity with the useful heat by the collectors of the thermosyphon SWH system at varying times of the day is that there has been variation in the angle of inclination of the sun presented to the collector at various times of the day. Therefore, 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.

4.2 Efficiency of the Collectors in the Thermosyphon SWH System.

From Figure 4 (the efficiency curves of the flat plate collectors of the fabricated thermosyphon for the three seasons), the F_RU_L value of -5.0 obtained from the slope of the graph and $F_R(\tau\alpha)$ value of 0.59 determined by extending the graphical lines to intersect with y-axis in the region of the maximum efficiency imply that the instantaneous efficiency will decrease as the ratio of temperature difference to incident radiation increases. The ratio of the non-linear changes of the instantaneous useful energy obtained during the time the fluid passes through the collector to the instantaneous radiation energy incident on the collector is the mean momentary efficiency (Figures 4.4). Considering Figures 4.4 which were obtained for different seasons, then the highest average daily efficiency of 48% is quite considerable for such thermosyphonic system when compared with other systems already fabricated for other Nigerian cities (Danshehu *et al.*, 2004). Since the working fluid is water, its temperature varies with respect to the amount of available insolation at a given period of the day and therefore at 13.00 GMT hours when the radiation is at its highest, the system efficiency is less than after and before 13.00 GMT. When comparing with another experimental investigation carried out by Chuawittayawuth and Kumar (2002), the results of the current study become more credible. Chuawittayawuth and Kumar (2002), also showed that the maximum outlet temperature happens in the afternoon. High outlet temperatures obtained in this study can be attributed to the design of the collectors and their efficiency enhancement because of better absorbing semi-selective surface.

5.0 Conclusions

The solar water heating system has been analysed, 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 (1.20m x 1.20m) flat plate collectors connected in series has exhibited ability when 1000 litres of water was:

- Heated to a maximum temperature of 76^0C in a favourable weather condition and deliver same for use.
- Heated to a maximum temperature of 52^0C in an unfavourable weather condition.
- Delivered hot water at as high temperatures as 45^0C by 7.00am in the mornings.
- Met an appreciable volume of hot water demand especially between the hours of 11.00am to 5.00pm daily and throughout the year.
- 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.

- 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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