Journal of Engineering and Applied Sciences 1 (1) : 7-13, 2006

Flow Design and Collector Performance of a Natural Circulation Solar Water Heater

Bukola O. Bolaji
Department of Mechanical Engineering, Federal University of
Technology P. M. B. 704, Akure, Nigeria

Abstract: This study shows the design and experimental analysis of flow inside the collector of a natural circulation solar water heater. The water heater was constructed and tested at Ado-Ekiti, Nigeria on Latitude 7.5°N. The results show that the system performance depends very much on both the flow rate through the collector and the incident solar radiation. A typical day analysis of the system shows that collector efficiency is high especially around mid-day when the solar collector receives the highest energy. During the test, the results showed that the system exhibited optimum flow rate of 0.1 kg s.m^2 at a maximum collector efficiency of 68.5%. Also, the average daily efficiency of the system was 57.7% and the maximum water temperature obtained was 83.5°C, while the maximum ambient temperature obtained was 34.5°C.

Key words: Solar water heater, natural circulation, solar collector, fluid flow

INTRODUCTION

Heating of water for domestic purposes is a simple and effective way of utilizing solar energy. A solar collector intercepts the incident solar radiation, converts it into heat andfinally transfers this heat to a working fluid for an end use system. The natural or free circulation solar water heating systems are most applicable in smaller installations. These are natural choice for domestic solar hot water systems. The circulation of water between the solar collectors and the heat store is by gravity or thermosyphon action, whereas in the forced convection system, an electric pump is used for the water circulation which adds to the cost, energy consumption and complexity of the system.

According to[1], all natural circulation systems are self-regulating; the greater the energy received, the more vigorous the circulation. The force that induces the circulation by overcoming the resistance of the system components is due to the difference in density of the hot water in the flow pipe and density of the cold water in the return pipe. The design of the flow pipe and heat transfer surface of the solar collector should be executed with the objective of achieving a high efficiency with low friction losses.

Numerous studies have been performed on natural circulation solar water heating system. In 1979 in United State, National Bureau of Standards Programme monitored five types of pumped solar energy water heating systems along with a natural circulation water heating system. It was noted that the best performance was obtained from the natural circulation unit[2]. In another study in United State, reported by[3], the indirect natural circulation water heating systems achieved higher solar fractions in comparison to the equal sized pumped systems. According to[4], higher flow rate leads to higher collector efficiency factor. However, it also leads to higher mixing in tank and therefore, a reduction in the overall solar water heating system efficiency.

Fanney and Klein[5] performed side-by-side experimental investigations to evaluate the influence of the flow rate on the thermal performance of two direct solar domestic hot water systems. The first system was a direct solar hot water system utilizing a natural circulation return tube to the storage tank. The return tube discharges the hot fluid at the top of the storage tank. The second system was a direct solar hot water system in which the tank was fitted with a stratification-enhancing return tube designed to reduced internal tank fluid mixing. All experiments were subjected to the same environmental conditions and were subjected to the same load profile. Results of the first system show improvements in the overall system performance as a result of lowering the collector fluid flow rate. For the second system, results show insignificant difference in overall performance for conventional and reduced flow rates. Fanney and Klein[5] also investigated the thermal performance of an indirect solar domestic hot water system employing an external counter-flow heat exchanger to transfer heat from the solar collector to the potable water. The results of their investigation showed that the system exhibited no optimum flow rates at either side.

Hollands and Brunger[6] performed a theoretical investigation to determine the optimum collector flow rate in solar domestic hot water systems having an external counter flow heat exchanger. Their analysis was based upon the assumption that the overall exchanger conductance can be held fixed while the flow rate are varied in the search of an optimum flow rate. This assumption requires the design of the heat exchanger to vary with flow rate. Based on analytical investigation, they showed that optimum flow rates exist on both sides of the heat exchanger. Hollands and Brunger concluded that the optimum value of the collector flow rate is independent of the amount of solar radiation, the tank-side heat exchanger inlet temperature and the ambient temperature.

Beckman *et al.*,[7] performed annual simulations to monitor the thermal performance of direct solar domestic hot water systems operated under several control strategies. Among these strategies were reduced constant collector flow rates and variable collector fluid flow rates. They concluded that an improvement in the thermal performance of the system occurs at reduced constant flow rate. Slightly smaller improvements were observed if the flow rate was varied to obtain a specified collector outlet temperature or if the flow rate was varied to achieve a constant temperature rise across the collector.

Various studies reviewed above have shown the important of flow rate to the collector performance of the solar water heating system. In this study, the fluid flow system of a natural circulation solar water heater is designed and constructed with the aim of improving the collector efficiency. Also, the influence of the flow rate on the collector is evaluated.

MATERIALS AND METHODS

Flow system design: A density difference created by the temperature gradients causes the fluid being heated to flow without any pump. This type of fluid flow due to density gradient is usually termed the natural circulation. The magnitude of this flow and the resulting velocity of the fluid flow can be calculated on the basis of simple physical principles.

Figure 1 shows the schematic diagram of a natural circulation solar water heater, consisting of a collector, a storage tank (installed above the collector) and the connecting tubes. When solar radiation falls on the collector, it brings a temperature difference between the lower and upper ends of the collector. The temperature difference causes a density variation given rise to buoyancy forces. The effective pressure difference due to bouyancy force responsible for the total closed loop cycle in the natural circulation system is made up of two parts as follow:

$$\Delta p_t = \Delta P_1 + \Delta P_2 \quad (1)$$

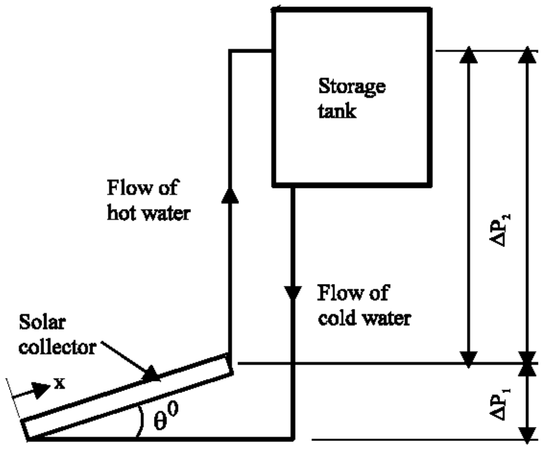

Fig. 1: The schematic diagram of nature circulation solar water heater

Where ΔP_1 = pressure difference due to the buoyancy force in the collector
ΔP_2 = Pressure difference due to the density variation in the connecting tubes.

The buoyancy pressure in the collector is calculated through integration over the length of the collector

$$\Delta P_1 = g\mathrm{Sin}\theta\int_0^L \left[\rho_{fi} - \rho_{(x)}\right]dx \quad (2)$$

Where $\rho_{(x)}$ = density of water at the location from the inlet of the collector
ρ_{fi} = density of water corresponding to temperature of water at the inlet of the collector.

Considering the density variation over the height H to be constant, the buoyancy force pressure ΔP_2 can be written as:

$$\Delta P_2 = \left(\rho_{fi} - \rho_{fo}\right)gH \quad (3)$$

Substituting Eqs. 2 and 3 in Eq. 1, we have

$$\Delta P_t = g\mathrm{Sin}\theta\int_0^L \left[\rho_{fi} - \rho_{(x)}\right]dx + \left(\rho_{fi} - \rho_{fo}\right)gH \quad (4)$$

Over small temperature changes, the variations in density with temperature can be written as:

$$\rho_{(t)} = \rho_o\left(1 - \beta t\right) \quad (5)$$

where β = coefficient of volume expansion and is the density at 0°C.
Substitution of Eq. 5 in Eq. 4 yields

$$\Delta P_t = g\beta\rho_o\left[\mathrm{Sin}\theta\int_0^L\left(T_{(x)} - T_{fi}\right)dx + H\left(T_{fo} - T_{fi}\right)\right] \quad (6)$$

The total pressure losses ΔP_s in the system can be written as $\Delta P_s = \Delta P_c + \Delta P_z$

Where ΔP_c = Pressure losses in the collector

ΔP_z = pressure losses in the connecting tubes

Therefore, $$\Delta P_s = \Delta P_c\left[1 + \left(\frac{\Delta P_z}{\Delta P_c}\right)\right]$$

$$\Delta P_s = \Delta P_c\left(1 + r_p\right)$$

Where : $$r_p = \frac{\Delta P_z}{\Delta P_c}$$

In the stationary conditions of the flow, the total buoyancy pressure ΔP_t is equal to the total pressure losses ΔP_s, therefore,

$$\Delta P_t = \Delta P_c\left(1 + r_p\right) \quad (7)$$

Substitution of Eq. 7 in Eq. 6 yields

$$g\beta\rho_o\left[\mathrm{Sin}\theta\int_0^L\left(T_{(x)} - T_{fi}\right)dx + H\left(T_{fo} - T_{fi}\right)\right] = \Delta P_c\left(1 + r_p\right) \quad (8)$$

Considered temperature distribution in the collector to be linear, therefore,

$$T_{(x)} - T_{fi} = \left(T_{fo} - T_{fi}\right)\left(\frac{x}{L}\right) \quad (9)$$

Hence: $$\int_0^L\left(T_{(x)} - T_{fi}\right)dx = \left(T_{fo} - T_{fi}\right)\left(\frac{L}{2}\right) \quad (10)$$

Substitution of Eq. 10 in Eq. 8 yields

$$g\beta\rho_o\left(T_{fo} - T_{fi}\right)\left(\tfrac{1}{2}L\,\mathrm{Sin}\theta + H\right) = \Delta P_c\left(1 + r_p\right) \quad (11)$$

To obtain the relationship between the temperature and the mass flow rate m′, the equation for useful heat energy collected Q_u can be used[1].

$$Q_u = A_c F_R\left[I\alpha\tau - U_L\left(T_{fi} - T_a\right)\right] \quad (12)$$

Where, A_c = Collector area (m^2)

F_R = Useful heat energy collected (W)

U_L = overall loss coefficient of the collector ($Wm^{-2}K^{-1}$)

The energy collected is converted to the thermal energy of water in the pipes, thus

$$Q_u = \dot{m}C_p\left(T_{fo} - T_{fi}\right) \quad (13)$$

Then $$\dot{m}C_p\left(T_{fo} - T_{fi}\right) = A_c F_R\left[I\alpha\tau - U_L\left(T_{fi} - T_a\right)\right]$$

Therefore, $$\left(T_{fo} - T_{fi}\right) = \frac{A_c F_R}{\dot{m}C_p}\left[I\alpha\tau - U_L\left(T_{fi} - T_a\right)\right] \quad (14)$$

Elimination of $(T_{fo} - T_{fi})$ from Eq. 11 and 14 yields

$$\dot{m} = \frac{A_c F_R}{\Delta P_c}\left[\frac{g\beta\rho_o}{\left(1 + r_p\right)C_p}\right]\left[I\alpha\tau - U_L\left(T_{fi} - T_a\right)\right]\left(\tfrac{1}{2}L\,\mathrm{Sin}\theta + H\right) \quad (15)$$

The mass flow rate of natural circulation can be calculated using Eq. 15 andthe collector efficiency is obtained by using the relation

$$\eta = \frac{Q_u}{A_c I} \quad (16)$$

Substitution of Eq. 13 and 14 in Eq. 16 yields

$$\eta = F_R\left[\alpha\tau - U_L\frac{\left(T_{fi} - T_a\right)}{I}\right] \quad (17)$$

since F_R, $\alpha\tau$ and U_L are constant, therefore,

$$\eta \propto \frac{\left(T_{fi} - T_a\right)}{I} \quad (18)$$

The expression $(T_{fi} - T_a)/I$ is referred to as collector performance coefficient.

The experimental setup: The schematic diagram of the natural circulation solar water heater is shown in Fig. 1. The system consists of a flat-plate solar collector (Fig. 2), storage tank (Fig. 3) and connecting pipes. The absorber steel plate of the solar collector was formed, like a corrugated sheet to accommodate the water pipes and headers in the grooves to maintain good contacts with the pipes (Fig. 2). Each pipe is 1 m long and has an inner diameter of 17 mm and outer diameter of 20 mm. The pipes are placed close together horizontally with a space of 83 mm in between and welded at both ends to the header pipes of 22 mm internal diameter, 25 mm outside diameter and 700 mm long each.

The absorber–water pipe assembly formed an inner box, which in turns is mounted in an outer box, the space between the absorber-water pipe assembly and outer box is filled with wood shaven as insulating material. The front surface of the box is then covered with 4 mm thick clear plain glass and air gap between the plate and the glass cover is 76 mm. The overall dimension of flat-plate solar collector is 1130 x 830 x 190 mm and the effective glazing area is 0.7 m^2.

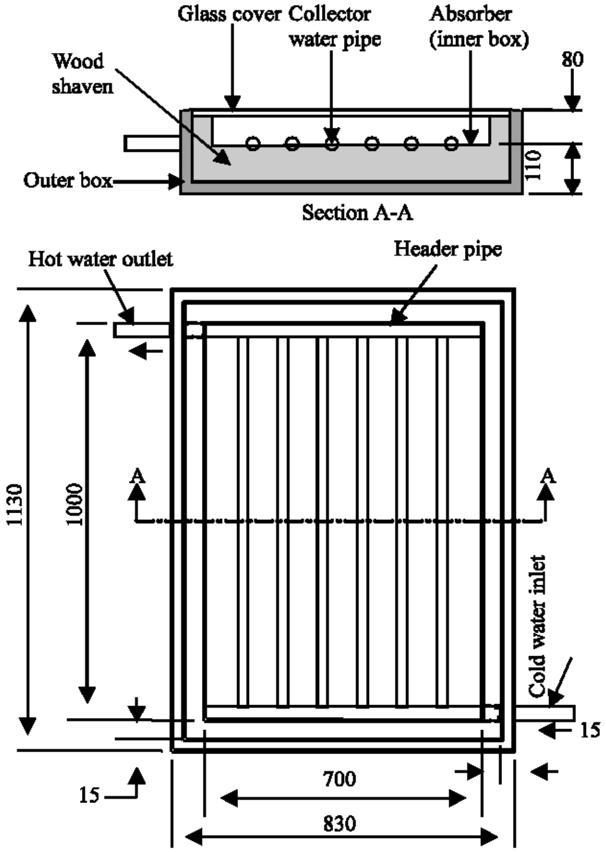

Fig.2: Flat-plate solar collector with water pipes

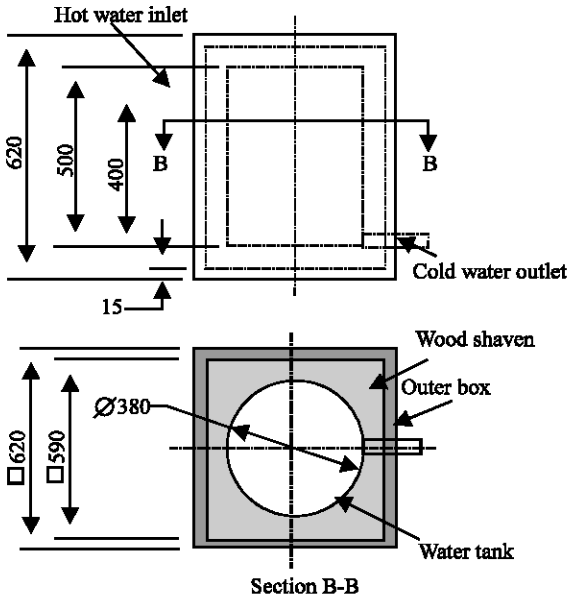

Fig. 3: Storage tank

The connection between flat-plate collector and the storage tank are in two parts; the return pipe and the flow pipe. The return pipe connects the outlet of the storage tank and the inlet of the collector together, while the flow pipe connects the outlet of the collector and the inlet of the storage tank together (Figs. 2 and 3).

The flat-plate collector is orientated in such a way that it receives maximum solar radiation during the desired season of use. According to[1], the best stationary orientation is due south in the Northern Hemisphere. In this position the inclination of the collector to the horizontal plane for the best all year round performance is approximately 10° more than the local geographical latitude. This approach was used in this work as a tilt angle of 17.5°N was used for Ado – Ekiti, Nigeria location that is on latitude 7.5°N. The absorbing surfaces were painted with matt black paint. The absorbing plate and the absorbing surface of the pipes absorb solar radiation and the absorbed heat is then transmitted to the water in the pipes. Under the mode of natural convection the water flows through the pipes by the thermosyphonic force and enters the storage tank.

RESULTS AND DISCUSSION

The Natural circulation solar water heater was tested for 12 days in the month of November, 2003 at intervals of one hour between 8.00 and 18.00 h each day. The incident solar radiation intensity was measured using pyranometer. The water inlet and outlet temperatures for the collector and storage tank as well as ambient air were measured with mercury-in-glass thermometers with a precision of 0.5°C. The useful energy gain, the mass flow rate and the efficiency of the collector were calculated using Eq. 12, 15 and 16, respectively.

The hourly variation of the ambient air, collector water inlet and outlet temperatures and solar radiation for two days in November 2003 are shown in Table 1 and 2. This results show that the maximum water temperature obtained is a function of solar insolation and the ambient air, therefore, this maximum temperature occurred after the peak solar insolation. During the test, a maximum water temperature of 83.5°C was obtained while the maximum ambient temperature for the day was 34.5°C. This shows that the hot water temperature was 49°C (142%) higher than ambient temperature. Fig. 4 shows the variation of the collector efficiency with the collector performance coefficient $(T_{fi} - T_a)/I$. The plot was based on performance analysis for twelve days in November 2003. The collector efficiency was found to increase with decreasing collector performance coefficient.

Table 1: Results obtained in the natural circulation solar water heater on 12th November, 2003

	Collector temperature (°C)				
Local Time (h)	Inlet	Outlet	Ambient temperature (°C)	Relative Humidity (%)	Solar radiation (Wm^{-2})
8.00	31.0	34.0	26.0	94.0	488
9.00	35.5	40.5	26.5	88.0	592
10.00	375.0	50.5	28.5	81.5	746
11.00	40.0	53.5	30.5	73.0	864
12.00	43.5	73.0	31.0	73.5	977
13.00	46.0	80.5	31.5	69.0	925
14.00	46.5	81.0	33.0	68.5	840
15.00	48.0	79.5	34.0	65.0	732
16.00	49.0	77.5	33.5	60.0	673
17.00	50.5	67.0	32.0	64.0	629
18.00	52.5	64.0	31.5	69.0	623

Table 2: Results obtained in the natural circulation solar water heater on 21st November, 2003

	Collector Temperature (°C)				
Local Time (h)	Inlet	Outlet	Ambient temperature (°C)	Relative humidity (%)	Solar radiation (Wm^{-2})
8.00	34.5	44.0	27.5	96.0	571
9.00	36.5	50.5	28.0	92.0	456
10.00	39.0	58.0	29.5	88.5	662
11.00	42.5	64.5	30.5	80.0	712
12.00	44.5	71.0	31.0	87.0	894
13.00	45.5	81.0	32.5	72.0	993
14.00	48.0	83.5	34.0	66.0	938
15.00	49.5	82.0	34.5	62.0	783
16.00	51.0	80.0	34.5	62.5	645
17.00	52.0	68.5	33.0	67.0	682
18.00	53.5	66.0	32.5	75.0	564

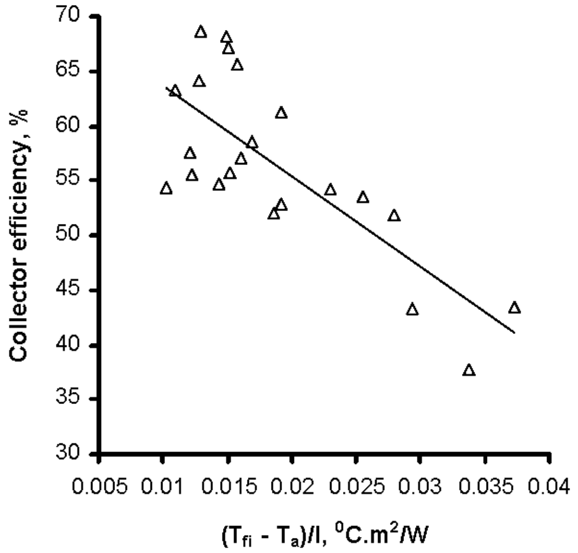

Fig. 4: Variation of the collector efficiency with performance coefficient $(T_{fi} - T_a)/I$

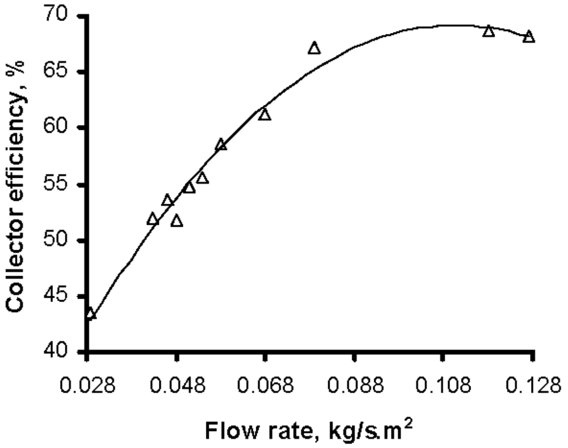

Fig. 5: Daily variation of efficiency as a function of water flow rate through the collector for 21st November, 2003

Fig. 5 shows a typical daily variation of efficiency as a function of the water flow rate per m^2 of collector area. The curve shows the effect of the flow rate on the collector efficiency. The efficiency increases as the flow rate increases until it reaches its maximum value of 0.1 kg/s per m^2 of collector area after which any additional increase in the flow rate no longer affects the performance of the collector. The collector efficiency at the optimum flow rate was 68.5%.

The curve of collector efficiency versus solar radiation (Fig. 6) shows that the efficiency increased with increased solar radiation. This is a clear indication of the dependence of the system performance on the total daily insolation. During the test, the average daily efficiency of the system was 57.7%. Fig. 7 shows the curve of a typical day thermal efficiency against time for 21st November 2003.

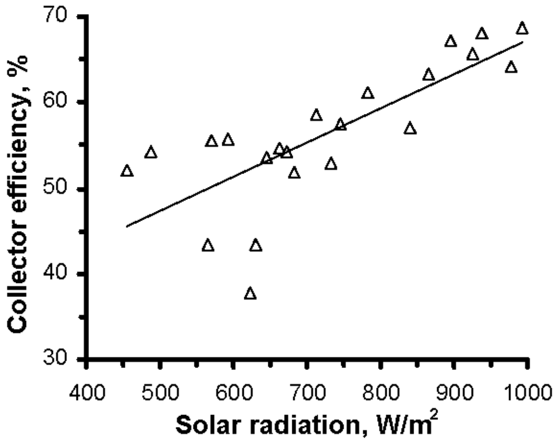

Fig. 6: Collector efficiency versus incident solar radiation

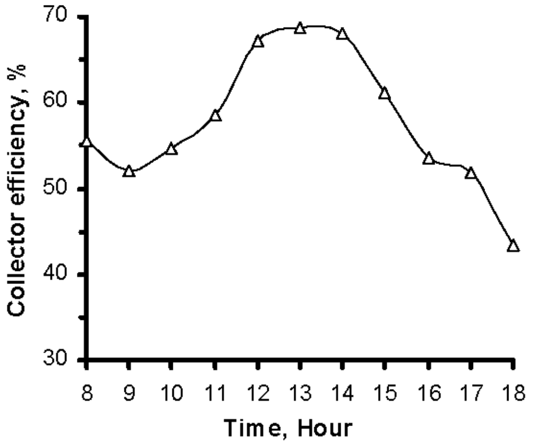

Fig. 7: The curve of collector efficiency against time for 21st November, 2003.

The efficiency is high especially around mid-day when the solar collector receives the highest energy, but it is low in the morning and late afternoon due to the low incident radiation during this period. This shows that the greater the energy received, the more vigorous the circulation and the better the system performance.

CONCLUSIONS

The flow system of a natural circulation solar water heater was designed and the system was constructed and tested at Ado – Ekiti, Nigeria on latitude 7.5°N. The results obtained shows that the water temperature in the system is a function of solar radiation and the ambient air. A typical day analysis of the system shows that collector efficiency is high especially around mid-day when the solar collector receives the highest energy. Experimental results also reveal that the performance of the solar water heater depends very much on the flow rate through the collector. The collector efficiency increases as the flow rate and the incident solar radiation increase. Therefore, the greater the energy received the more vigorous the water circulation and the better the system performance. During the test, the results showed that the system exhibited optimum flow rate of 0.1 kg/s.m^2 at a maximum collector efficiency of 68.5%. Also, the average daily efficiency of the system was 57.7% and the maximum water temperature obtained was 83.5°C, while the maximum ambient temperature was 34.5°C. The performance of natural circulation solar water heater can be improved by using smaller diameter pipes in the collector and increasing the number of these pipes to give even spread of water along the collector absorber. This will also reduces the spaces between the water pipes, minimises the heat losses and increases the heat gain.

ACKNOWLEDGEMENT

The author wishes to acknowledge the assistance of Miss Daramola, B. former student of Federal Polytechnic Ado – Ekiti, Nigeria in Carrying out this work.

NOMENCLATURE

A_c - collector area (m^2)
C_p - specific heat capacity (Jkg^{-1}K^{-1})
F_R - collector heat removal factor
H - height of water level in the tank above the collector (m)
I - incident radiation on the collector (Wm^{-2})
L - length of the collector (m)
m - flowrate per unit collector area (kgs^{-1}m^{-2})
P - pressure (Nm^{-2})
Q_L - combined heat loss, (W)
Q_u - useful heat energy collected (W)
T - temperature (K)
U_L - overall loss coefficient of the collector (Wm^{-2}K^{-1})

Greek

α - absorption coefficient of the absorber
β - coefficient of volume expansion
θ - collector tilt angle to the horizontal (degrees)
η - collector efficiency (%)
τ - transmissivity

Subscripts

a - ambient
c - collector
f - fluid
i - inlet
L - losses
o - outlet
u - useful
x - arbitrary point

REFERENCES

1. Adegoke, C.O. and B.O. Bolaji, 2000. Performance evaluation of solar-operated thermosyphon hot water system in Akure. Intl. J. Eng. Eng.Technol., FUTAJEET, 2: 35- 40.
2. Uhlemann, R. and U.K. Bansal, 1985. Side by side comparison of pressurised solar water heating system with a thermosyphonic flow. The Intl. Solar Energy Society., 34: 317-328.
3. Bansal, N.K. and K. Uhlemann, 1986. Thermosypon water heating system. Reviews of Renewable Energy Resources. Wiley Eastern Limited, New Delhi, India, 3: 189-196.
4. Duffie, J.A. and W.A. Beckman, 1991. Solar Engineering of Thermal Processes. 2nd (Edn.). John Wiley and Sons New York.
5. Fanney, A.H. and S.A. Klein, 1988. Thermal performance comparisons for solar hot water systems subjected to various collector and heat exchanger flow rate. Solar Energy, pp: 1-11.
6. Hollands, K.G.T. and A.P. Brunger, 1992.“Optimum flow rates in solar water heating systems with a counter flow exchanger. Solar Energy, pp: 15-19.
7. Beckman, W.A., J. Thorton, S. Long and B.D. Wood, 1994. Control problem in solar domestic hot water systems. Solar Energy pp: 233- 236.