Performance Evaluation of Solar - Operated Thermosyphon Hot Water System in Akure

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Abstract

Two passive solar - operated hot water systems were designed, constructed using local materials and tested at Akure on latitude 7.25° N. The storage tank of one of the systems was not insulated whilst in the other system, the storage tank was insulated and smaller diameter pipes with many passes were used which gave even spread of water along the absorber, thereby increasing the heat removal from the collector by the working fluid. The later which is an improvement on the former system is designated as the "improved system", whilst the uninsulated system is designated as the "existing system". Efficiency curves show that the improved system had higher thermal efficiency and performed better than the existing system. During the test period, a maximum hot water temperature of 52.5°C was obtained in the existing system whilst that of the improved system was 76.5°C.

Keywords: Solar power; Thermosyphon water heating system, Passive solar system, Improved system

Nomenclature

A_c	Collector area, m^2
C_b	Bond conductance
C_p	Specific heat capacity, J/kg K.
D	Outside diameter of tube, m
D_i	Inside diameter of tube, m
F	Standard fin efficiency for straight fins
F'	Collector efficiency factor
F"	Collector flow rate, m^2/s
F_R	Collector heat removal factor
G	Flow rate per unit collector area kg/sm^2
h_i	Inside heat transfer coefficient, W/m^2 K.
I	Rate of total radiation incident on absorber W/m^2
Q_c	Rate of convective losses from the absorber, W
Q_k	Rate of conduction losses from the absorber, W
Q_L	Combined heat loss, W
Q_u	Useful heat energy collected, W
Q_ρ	Rate of reflection losses from the absorber, W
T_a	Ambient temperature, K
T_c	Temperature of the collector absorber, K
T_i	Fluid inlet temperature to the collector, K
t	Thickness of plate
U_L	Overall heat transfer coefficient of the absorber, W/m^2 K
W	Distance between the tubes
α	Absorption coefficient of the absorber
η	Efficiency of the collector, %
ρ	Reflection coefficient of the absorber
τ	Total transmisivity

1 Introduction

The high cost of conventional sources of energy and the fast rate at which they are being depleted should be a course of concern for energy users and managers. Although there is disagreement as to how long the world's fossil fuels reserve would last, there is no disagreement with the fact that these energy sources are depleting quite rapidly. Hence as fossil fuels are becoming more difficult to obtain, the search for alternative energy sources becomes necessary.

Solar energy is the most attractive energy source for the future. Solar energy is more evenly distributed over the earth's surface than fossil fuels and the amount of energy available for conversion is several orders of magnitude greater than the present world requirements. For instance, the earth receives annually, energy from the sun amounting to 1 x 10^{18} kWh. This is equivalent to more than 500000 billion barrels of oil or about 1000 times the energy of known reserves of oil or more than 20000 times the present annual consumption of energy of the whole world (Garg, 1982). Moreover, solar energy is a renewable source of energy which is also free from pollution hazards associated with nuclear energy development.

The parts of the world lying between 35° N and 35° S which have at least 2000 hours of bright sunshine per year is normally accepted to be suitable for utilization of

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energy from the sun (Chandra and Oguntuase, 1986). Nigeria satisfies this requirement, hence positive results are expected from solar energy utilization. The most successful applications of solar energy in this country are in areas of domestic hot water supply, space heating and cooling, electricity generation for operating TV sets, lighting and water pumping.

Solar water heaters represent one of the easiest, most practical applications of solar energy on an individual and medium scale basis. Heat from the rays of the sun is easily captured using several methods but the most suitable for solar water heating application is the flat - plate collector. This is essentially a heat exchanger in which the radiant energy of the sun is converted to low - grade thermal energy which manifest as enthalpy increase of the working fluid.

The thermosyphon water heating system is a natural choice for domestic solar hot water system. All thermosyphon systems are self-regulating in that the greater the energy received, the more vigorous the circulation. The simplicity and reliability of the system give it a significant advantage over active systems. Its thermal performance has been shown to be comparable with equivalent active systems and when pump power costs are considered, energy and cost savings can be superior (Uhlemann and Bansal, 1985).

There is a great demand for hot water for agricultural, industrial space heating and cooling applications and for domestic uses especially hot water of between 40°C and 70°C which are temperatures quite easily attainable by solar water heaters. The large scale utilization of thermosyphon solar water heating systems will result in considerable savings of energy in residential buildings as water heating can consume 45% to 55% of household energy (Ojosu and Komolafe, 1989).

This study is an attempt to investigate the effects of insulting the water storage tank and increasing the volume of water passage through the collector, on the performance of thermosypon solar - water heating systems.

2.0 Materials and Methods

2.1 Theoretical Considerations

The energy balance equation on a flat-plate collector is given as :

$$\tau I A_c = Q_u + Q_k + Q_c + Q_R + Q_p \quad (1)$$

The heat loss terms $Q_K + Q_C$ and Q_R are usually combined into one term, Q_L and given as

$$Q_L = Q_k + Q_c + Q_R \quad (2)$$

The reflected energy from the absorber is given as

$$Q_p = \tau \rho I A_c \quad (3)$$

Equation (1) becomes

$$\tau I A_c = Q_u + Q_L + \tau \rho I A_c$$

or

$$Q_u = (1-\rho)\tau I A_c - Q_L \quad (4)$$

For an absorber,

$(1-\rho) = \alpha$, hence

$$Q_u = \alpha\tau I A_c - Q_L \quad (5)$$

It is usual to express Q_L as:

$$Q_L = U_L A_c (T_c - T_a) \quad (6)$$

From equation (5) and (6),

$$Q_u = \alpha\tau I A_c - U_L A_C (T_c - T_a)$$

or

$$Q_u = A_c\left[(\alpha\tau)I - U_L(T_c - T_a)\right] \quad (7)$$

$$q_u = Q_u / A_c$$

$$= \left[(\alpha\tau)I - U_L(T_c - T_a)\right] \quad (8)$$

Hence,

$$\eta = q_u / I$$

$$= \left[(\alpha\tau) - U_L(T_c - T_a)/I\right] \quad (9)$$

According to Adegoke (1987), equation (9) is awkward to use because T_c is difficult to determine experimentally. The equation can, however, be made manageable by introducing a correction factor to both right hand terms that will allow the use of more readily determined fluid inlet temperature to the collector. Hence,

$$\eta = F_R\tau\alpha - F_R U_L\left[\frac{T_i - T_a}{I}\right]$$

$$= F_R\left[\tau\alpha - U_L\left(\frac{T_i - T_a}{I}\right)\right] \quad (10)$$

F_R is a correction factor such that efficiency, as calculated by equations (9) and (10) are the same.

Hourly efficiency.

$$\eta_h = \frac{q_u}{I} \quad (11a)$$

Daily efficiency,

$$\eta_d = \frac{\sum q_u}{\sum I} \quad (11b)$$

$$q_u = F_R\left[I(\tau\alpha) - U(T_i - T_a)\right] \quad (12)$$

$$F_R = \frac{GC_p}{U_L}\left(i - e^{\left[U_L F'/GC_p\right]}\right) \qquad (13)$$

Where G = flow rate per unit collector area (kg/sm^2). To represent equation (13) graphically it is convenient to define a new variable. $F'' = F_R/F'$, known as the "collector flow rate". F″ is a function of the single variable $U_L F'/GC_p$. Fig. 1 reproduced from Dufflie and Beckman (1974), shows the relationship between F″ and the function $GC_p/U_L F'$.

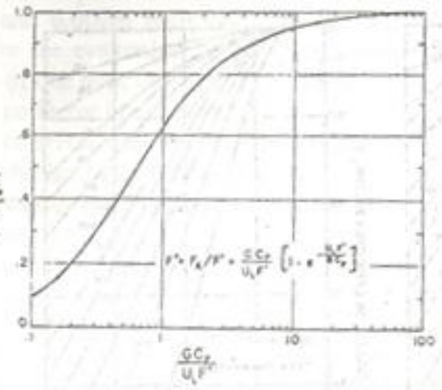

Fig. 1: Collector flow factor as a function of $GC_p/U_L F'$ (Source: Duffie and Beckman (1974))

$$F' = \frac{1/U_L}{W\left[\frac{1}{U_L\left[D + (W-D)F\right]} + \frac{1}{C_b} + \frac{1}{\pi D_i h_i}\right]} \qquad (14)$$

Fig. 2 shows the graph plots of F' versus tube spacing for various conditions from which F could be obtained

$$F = \frac{\left[\tanh m(W-D)/2\right]}{m(W-D)/2} \qquad (15)$$

$$m = \left(\frac{U_L}{Kt}\right)^{1/2} \qquad (16)$$

$$C_b = \frac{K_b b}{t_b} \qquad (17)$$

where,

K_b = thermal conductivity of the bond

b = bond length

t_b = average thickness of bond

$$(\tau\alpha) = \frac{\tau\alpha}{\left[1-(1-\alpha)\rho_d\right]} \qquad (18)$$

Referring to equation (10), at high values of (T_i – T_a), the heat loss coefficient, U_L begins to loss its linearity since radiation from the collector increase as the fourth power of temperature difference. However, for values of $[(T_i - T_a)/I]$ below 0.264 equation (10) is essentially that of a straight line (ASHARAE, SP No 40). Hence plotting the collector efficiency, η, against the performance coefficient, the performance of the collector under various conditions could be deduced.

2.2 *The Experimental Thermosyphon System Setup*

Fig. 3 shows the layout of the experimental system with uninsulated water tank. Each of the systems consists of: a flat-plate collector; storage tank and connecting pipes. The improved thermosyphon solar water heating system was installed side by side with the existing system at the experimental site and both systems were subjected to the same environmental and weather conditions.

The absorber steel plate of the solar collectors were formed like corrugated sheet to accommodate the water pipes and headers in the grooves to maintain good contacts with the pipes. The pipes of the existing system, each 1.7 cm internal diameter, 2.0 cm outside diameter and 100 cm long were spaced 8.9 cm apart and welded at both ends to the headers which were each 2.2cm internal diameter, 2.5 cm outside diameter and 70cm long. In the improved system, the outside diameter of the collector water pipes was reduced from 2.0 cm to 1.7 cm, their number increased from 6 to 9 and the spacing decreased from 8.9 cm to 5.5 cm to give a more even spread of water along the absorber so that the total heat removal by the working fluid is increased despite the fact that the volume of water circulated in the collector at a time is only marginally increased.

In both systems, the absorber – water pipe assembly are contained in and inner box which in turn is mounted in an outer box with the spaces between the boxes (at the bottom and sides), filled with dry sawdust as insulating material. The top of the collector is covered with one sheet of 0.4 cm thick clear glass with the space between the absorber – water pipe assembly and the cover glass being 7.0 cm. The overall dimensions of the collectors was 113 cm x 83 cm x 19 cm with effective aperture areas of 0.7m^2. In each of the systems, a 56 – litre tank, which was not insulated in the existing system but insulted in the improved system, was used as storage tank.

The flat – plate collector is always tilted and orientated in such a way that it receives maximum solar radiation during the desired season of use. The best stationary orientation is due south in the northern hemisphere and due north in southern hemisphere. In this position the inclination of the collector to the horizontal plane for the best performance is sometimes presumed to

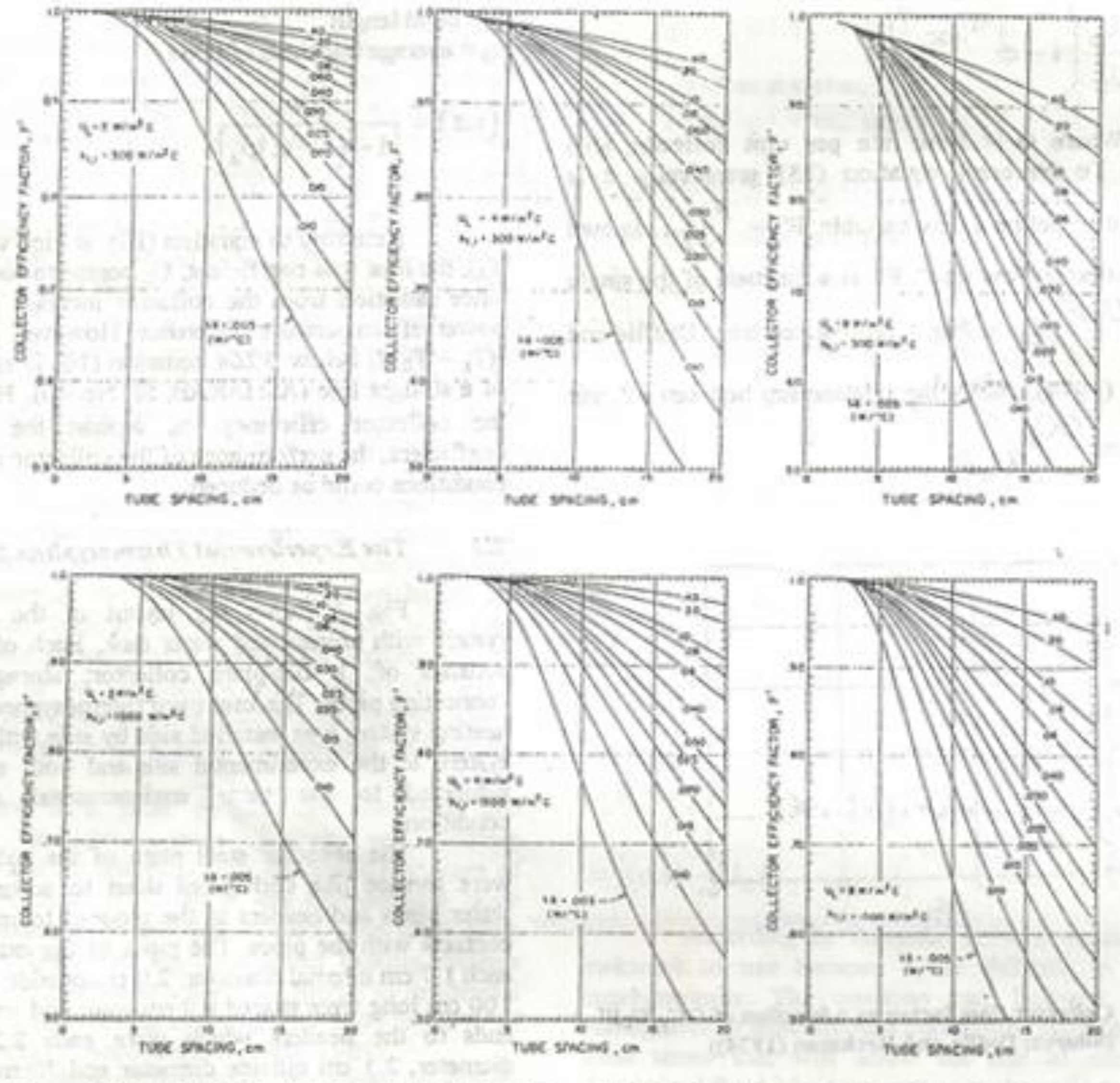

Fig. 2. **Collector Efficiency Factor, F' Versus tube spacing for 2cm diameter tubes for various conditions (Source: Duffie and Beckman (1974))**

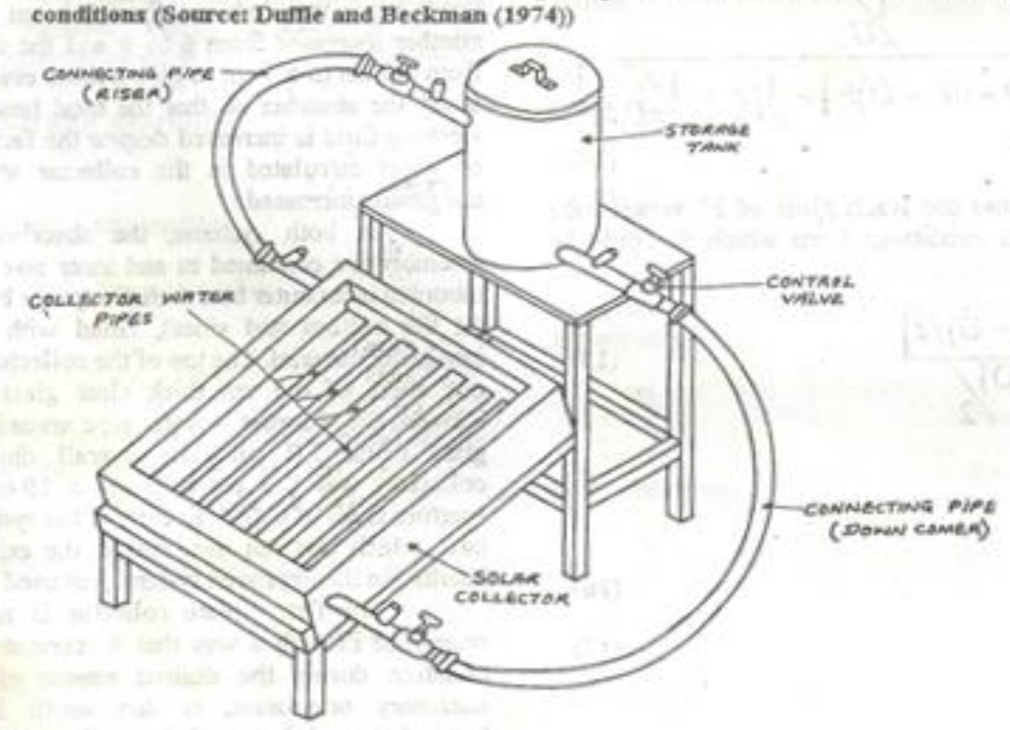

Fig. 3. **The Thermosyphon Solar Hot Water System**

be equal to the local latitude (Ipanyi 1979). Isao (1961) reported that some authors propose somewhat different inclination angles, namely: 0.9 times the latitude; 10° greater than the local latitude; 23.5° greater than the latitude in order to face the winter position of the sun at noon; 1.5 times the latitude. Faber (1961), suggested that the best all year round performance is obtained with a stationary absorber facing due south when its inclination to the horizontal is approximately 10° more than the local geographical latitude. This is the approach used in this work as a tilt angle of 17° was used for Akure location which is on latitude of 7.25°N.

2.3 *Experimental Procedure*

Data acquisition as carried out in November/December 1996 and in January 1997 between 8.00am and 6.00pm each day. The following parameters needed for the evaluation of the system were measured at intervals of one hour during the course of the experiments:

collector inlet water temperature
collector outlet water temperature
storage tank inlet temperature
storage tank outlet temperature
ambient air temperature
ambient wet – bulb temperature
solar irradiation on a horizontal surface.

The incident solar radiation intensity was measured using a portable Kipps Solarimeter. The inlet and outlet temperatures for the collector and the storage tanks as well as the ambient dry – bulb temperatures were measured with mercury-in-glass thermometers. The readings of dry and wet-bulb thermometers were used to compute the relative humidity from humidity slide rule.

3. Results and Discussion

The useful energy gain and the efficiency of the collector were calculated for both the existing an the improved systems using equations (12) and (10) respectively. The hourly and daily efficiencies were calculated using equations (11a) and (11b) respectively.

Fig. 4 shows the hourly variation of the solar insolation and the collector water inlet and outlet temperatures for both systems for a typical hot day. The maximum water temperature obtained is a function of solar insolation, the ambient temperature and the wind speed. However, this maximum temperature occurred after the peak solar insolation for both systems. The temperature differential between the inlet and outlet temperatures for the collector of the improved system is much higher than that for the existing system. This brought about by the re-arrangement of the pipe work in the collector and the insulation of the storage tank which made the inlet temperature to the collector of the improved system generally higher than that of the existing system.

During the test, a maximum water temperature of 53.5°C was obtained on the existing system, whilst that of the improved system was 76.5°C. Compared with the work of Ojosu and Komolafe (1989), whose storage tank and solar collector were combined into one unit, even though the effective collector area was 256% more than the collector area of the improved system, the maximum temperature reached was 70.5°C. In the case of the improved system, the maximum temperature was 76.5°C which is 8.5% higher than the figure of Ojosu and Komolafe (1989).

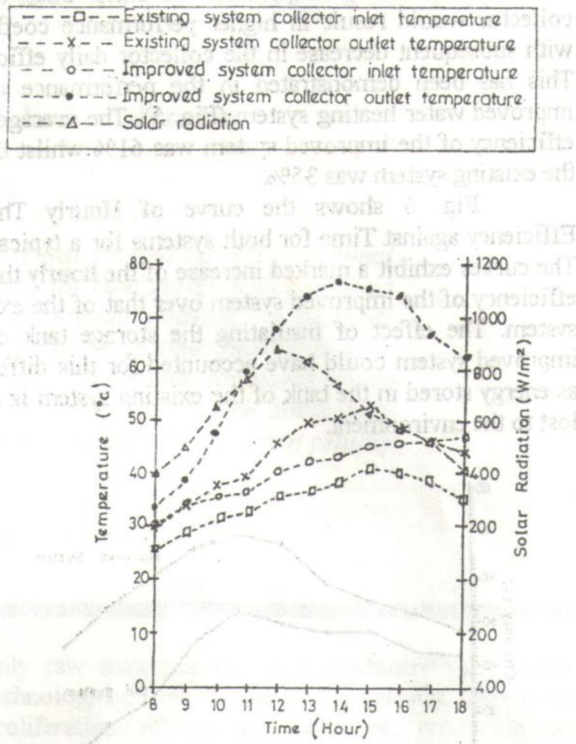

Fig. 4. Typical Daily Temperature Profile of the Solar Water Heater showing Hourly Variation for 11:12:96.

The Collector Performance Coefficient [$(T_I - T_a)$], was evaluated for each day and graphs of Thermal Efficiency, 0, against Collector Performance Coefficients were drawn as shown in Fig. 5. The plot was based on performance analysis for ten days between 27 November 1996 and January 1997. The collector daily efficiency was found to increase with decreasing collector performance coefficient.

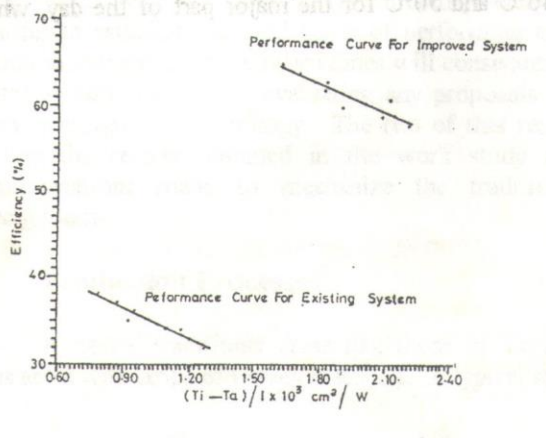

Fig. 5. Overall collector Performance Curve of Flat Plate Solar Water Heater.

In practice, human beings have little or no control over the environmental temperature and the rate of insolation of solar energy. However the temperature of the fluid entering the collectors can be controlled by insulating the inlet pipe to the collector and the storage tank. Hence with the same level of ambient temperature and solar radiation, increased temperature of fluid inlet to the collector would result in higher performance coefficient with subsequent decrease in the collector daily efficiency. This has been demonstrated in the performance of the improved water heating system (Fig. 5). The average daily efficiency of the improved system was 61% whilst that of the existing system was 35%.

Fig. 6 shows the curve of Hourly Thermal Efficiency against Time for both systems for a typical day. The curves exhibit a marked increase of the hourly thermal efficiency of the improved system over that of the existing system. The effect of insulating the storage tank of the improved system could have accounted for this difference as energy stored in the tank of the existing system is easily lost to the environment.

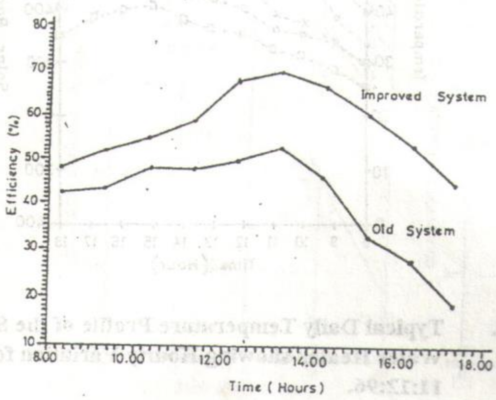

Fig. 6. Typical Day Hourly Variation of Collector Efficiency (12:12:96).

4. Conclusion

Comparison between the improved solar-water heating system and the existing system shows that the improved system has performed better. The existing system could only generate hot water at temperatures between 40°C and 50°C for the major part of the day, whilst the improved system could generate hot water at temperatures between 60°C and 70°C. A maximum water temperature of 53.5°C was obtained during the tests in the existing system whereas that of the improved system was 76.5°C.

Insulation of the storage tank and improved flow paths for the working fluid in the solar collector are contributory factors to the improved performance of solar operated thermosyphon water heating systems.

5. Acknowledgement

The support of the Mechanical Engineering Department of the Federal University of Technology, Akure, in this studies is acknowledged. Also acknowledged is the Department of Meteorology, for making their observatory field available as the venue for the tests.

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