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Analysis of the performance profile of the NCERD thermosyphon solar water heater

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Abstract
The work reported here is the performance profile of a thermosyphon solar water heater developed by the National Centre for Energy Research and Development (NCERD), University of Nigeria, Nsukka. The performance evaluation was based on the mathematical models that describe the test system and some measured experimental data. The effect of some of the design and operating parameters that have been shown to affect the system's performance was investigated. The parameters considered included the number of glazing covers, glazing cover thickness, tube spacing and the nature of absorber plate material. The performance results indicate that the test system has a maximum average daily collector efficiency of 0.658 and a mean system temperature of 81°C. The efficiency of the collector drops to an average seasonal value of 0.54 with a negligible variation across the three climatic seasons was covered in the study. With a tube spacing not exceeding 10 cm, the performance of the system is optimized irrespective of the nature of the absorber plate material. We found that the number of glazing covers affects the top-loss coefficient of the system depending on the type of absorber plate used. Multiple glazing shows a negligible contribution especially for low temperature application. The glazing cover thickness does not affect the performance of the system significantly.

Keywords: thermosyphon solar water heater, collector efficiency, performance models, simulation

1. Introduction

Solar water heating finds application in hot water provision in homes, hostels, hotels, hospitals, and industries such as the textile, paper, and food processing industries. It has been established (Klein *et al.*, 1976; Garg, 1987; Gupta and Garg, 1968; Buckles and Klein, 1980) that for a well-designed, and well-operated natural circulation water heater, high water temperature is achievable which can meet the full domestic hot water need or at least be used as a supplement to the conventional means of hot water generation. In many countries of the world like Israel, Australia, India, Japan, Greece and the United States, different designs of solar water heaters have been installed and commercialized (Enibe, 2000).

At the moment, water heating in Nigeria is done using conventional electric power and fuel wood. These sources of power have adverse health, economic as well as environmental impacts on the populace. The demand for energy is consistently increasing as a result of the energy crisis of the 1970's, population increase and modernization. The need to therefore embrace a cost-effective and sustainable alternative to our depleting conventional energy sources has become imperative.

The efficiency of a solar water heating system can be optimized if the peculiarities of the location are considered in adopting an optimum design and operating parameters (Garg, 1987). Solar water heater designs and performance studies carried out in different locations of the globe such as the USA (Farber, 1959), Israel (Faiman, *et al.,* 1979), Australia (Morrison and Tran, 1992) and China (Wang, 1979)) reflect the prevailing climatic conditions of the locations among other parameters. Earlier work in this area done in Nigeria (Bello *et al.,* 1990; Danshehu *et al.,* 1998) used data points for a few days (less than one week) which according to Duffie and Beckman (1974), is not adequate for performance evaluation of a thermosyphon solar water heater.

The present study is designed to help in developing and optimizing performance parameters of interest for solar water heater designs in Nigeria and Nsukka in particular.

2. Mathematical models of a thermosyphon solar water heater

The performance variables (design, operating and meteorological parameters) are related mathematically to describe the various performance models or parameters of the system (US DOE, 2000). The development of mathematical models for solar water heaters has tremendously reduced the empiricism associated with the solar water heater design and performance evaluation (Kreider, 1982).

The first mathematical model for performance evaluation of a natural circulation solar water heater was made by Close (1962). Other models (Duffie and Beckman, 1974; Sohda and Tiwari, 1981) have also been developed as improvements on this initial work.

As an improvement, Sodha and Tiwari (1981) developed a mathematical model that not only predicts the performance of thermosyphon systems but also considers the effect of the hot water withdrawal rate. This was a major limitation of most other models (Garg, 1987). These models were employed for this work and the parameters of interest summarized in Table 1.

2.1 Collector efficiency

The collector efficiency as a measure of collector performance can be predicted from a steady state energy balance on the absorber plate. It is expressed as the ratio of the useful energy gain over any time period to the incident solar energy over the same time period (Duffie and Beckman, 1974).

$$\eta_c = \frac{Q_u}{A_c I_o} \quad (1)$$

I_o is the insolation received on the collector surface. Q_u is the useful energy absorbed by the collector which relates the collector overall-heat loss coefficient, U, collector efficiency factor, F^1, collector fin efficiency, F, and the effective transmittance-absorptance product, $(\iota\alpha)_e$ as:

$$Q_u = A_c F^1 \left[I_o (\iota\alpha)_e - U_L (T_m - T_a) \right] \quad (2)$$

$$Q_u = A_c F_R \left[I_o (\iota\alpha)_e - U_L (T_i - T_a) \right] \quad (3)$$

2.2 Hot water withdrawal rate from storage tank

Following the assumptions of Sodha and Tiwari (1981), the energy balance equation for the thermosyphon solar water heater during sun-up hours can be written as:

$$W \frac{dTm}{dt} + U(T_m - T_a) + B\dot{M}(t) c_P (T_m - T_i) = I_o (\tau\alpha)_e F^1 A_c \quad (4)$$

The rate of withdrawal of water from the storage tank at constant temperature M_c can be determined using the above expression by putting. $\frac{dTm}{dt} = 0$

Thus:

$$\dot{M}_c = \frac{1}{(T_m - T_i) C_P} \left[(\tau\alpha)_e F^1 A_c I_o - U(T_m - T_a) \right] \quad (5)$$

W, U, and T_m are the total heat capacity of the system, overall heat-loss coefficient from the system and the mean system temperature respectively. B is a constant which can be taken as 1 if water is drawn from the middle of the tank and 2 if it drawn from the top of the tank.

3. NCERD thermosyphon solar water heater

A thermosyphon solar water heater developed at the National Centre for Energy Research and Development (NCERD), University of Nigeria, Nsukka was used for the study. The system consisted of a single-glazed absorber plate coated with dull-black commercial paint. The flat-plate absorber was inclined at 7^0 to the horizontal and facing due south (latitude of Nsukka). It was made from 1.6mm thick galvanized iron sheet and had absorbing area of $2.28m^2$. Storage tank capacity of 150 litres was fitted with insulated pipeline connections for the circulation of the working fluid from the collector to the tank and vice versa. The system under discussion is passive and thus had no pumps or controls.

The system's performance was monitored from December to February to cover the dry and Harmattan seasons and in July to reflect the trend in the peak of the rainy season. The measured data included the following: temperature of the hot water from the storage tank, the global solar radiation and the ambient temperature. These values were taken on a two-hourly basis. The temperature was measured using a simple mercury-in-glass thermometer and a pyranometer (model: Einstrahlungssensor Spektron 100, TRITEC Energie GmbH, 79104 Freiburg) was used for measuring the global solar radiation. During the tests period, no hot water was taken from the system.

Using the measured experimental data obtained from the system and other meteorological and design parameters, various performance parameters were evaluated. The evaluation procedure was based on the system's characteristic equations and models already presented in section 2.

Table 1 is a summary of the test system's performance parameters evaluated for the purpose of the performance test of the system.

4. Results, discussion and conclusion

4.1 Temperature profile of the system

Figure 1 shows the hourly temperature profile of the solar water heater from 8.00 hrs. to 18.00 hrs. under different climatic conditions. The system on a clear day in the Harmattan season attained a maximum temperature of 81°C, which occurred at 14.00 hrs. This value, however, dropped to 48°C at 18.00 hrs. Within the dry and rainy seasons, the

Table 1: Performance parameters of the NCERD thermosyphon system

Performance parameter	*Calculated value*
Effective transmittance-absorptance product, $(\tau\alpha)_e$	0.88
Heat transfer coefficient between the glass cover and the ambient, h_w	13.3W/m^{2}K
Bond conductance of the bonding material, C_b	1000W/mK
Bottom loss coefficient, U_b	0.5W/m^{2}K
Collector Top-loss coefficient, U_T	6.998W/m^{2}K
Collector overall heat loss coefficient, U_L	7.498W/m^{2}K
Collector fin efficiency, F	0.924
Convective heat transfer for fluid inside flow pipe, h_f	1407.14W/m^{2}K
Heat transfer coefficient between absorber plate and cover glass, H_L	2.445W/m^{2}K
Collector efficiency factor, F^1	0.927

maximum recorded temperature of water from the system was 77°C and 73°C respectively. For these two test days, the temperature gradually dropped with time to 44°C at 18.00 hrs. The results in Table 2 indicate that the system performance across the seasons has a very negligible variation. The consistency follows from the fact that the climatic condition in Nsukka maintains an all-year round abundant radiation (Agbo and Unachukwu, 2007).

The effect of the ambient parameters (ambient temperature and solar radiation) indicated a direct variation with the hourly collector efficiency. Generally, as the incident solar flux increases, the overall collector efficiency increases. However, the erratic variations noticed in some of the days agree with the earlier observation of Garg (1987) since the ambient conditions do not necessarily vary with time according to a particular pattern.

Table 2: Performance of the test system under various seasons

Season	Q_u *(W/m^2)*	I_o *(W/m^2)*	η
Harmattan	85 652.456	65 769.28	0.57
Dry	38 762.522	31 447.84	0.54
Rainy	25 257.092	21 455.84	0.52

4.2 Effect of the number of glazing covers

The number of glazing covers has an effect on the system efficiency that is not too pronounced especially at high insolation. Single glazing efficiency is least affected by the level of insolation and the mean system temperature independent of the number of glazing.

Specifically, the collector top-loss coefficient strongly depends on the number of glazing covers and on the absorber plate materials. Figure 2 shows that as the number of glazing cover increases, the top-loss coefficient decreases. For the copper absorber material, there is a decrease of about 34% when two instead of one glazing cover is used. 41% decrease in the-loss coefficient is observed with galvanized steel plate. Copper has a much lower emissivity (ε_p = 0.1) than galvanized steel (ε_p=0.86) thus the reason for the apparent better performance in terms of top-loss coefficient.

4. 3 Effect of glazing cover thicknesses

Table 3 shows the effect of glass cover thickness on the collector efficiency. The efficiency of the collector increases slightly as the glazing cover thickness decreases.

The effect of the glass cover thickness shows a 0.7% increase in collector efficiency when the thickness is halved and 1.2% decrease in efficiency

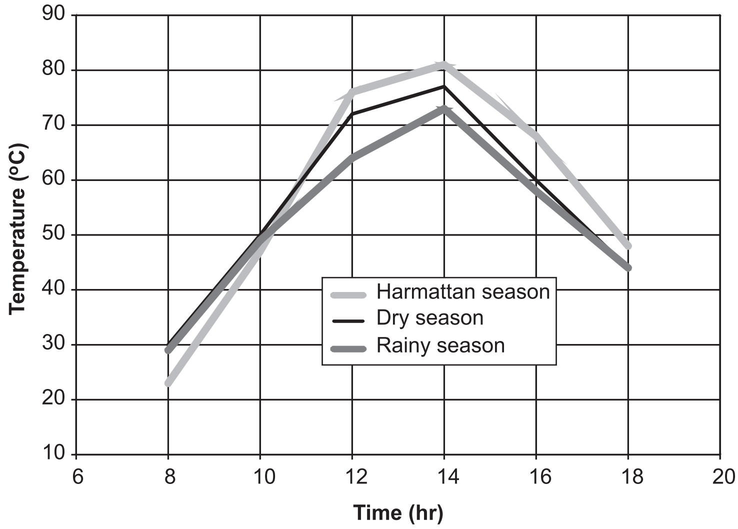

Figure 1: Hourly temperature profile of the NCERD solar water heater for various seasons

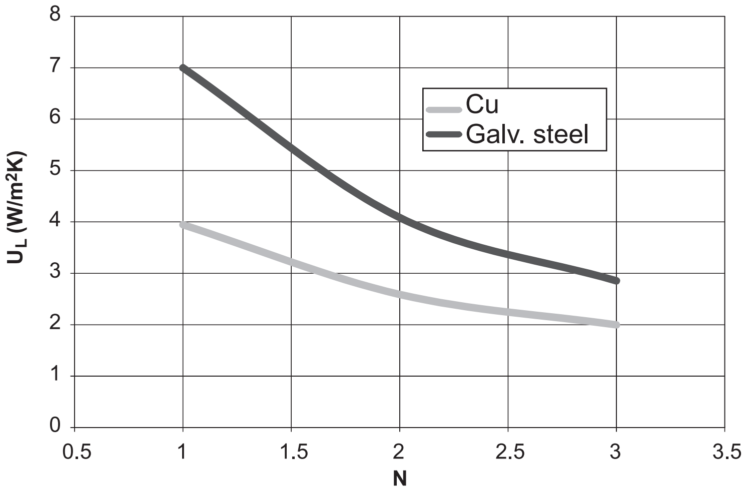

Figure 2: Variation of top-loss coefficient with number of glazing covers, N

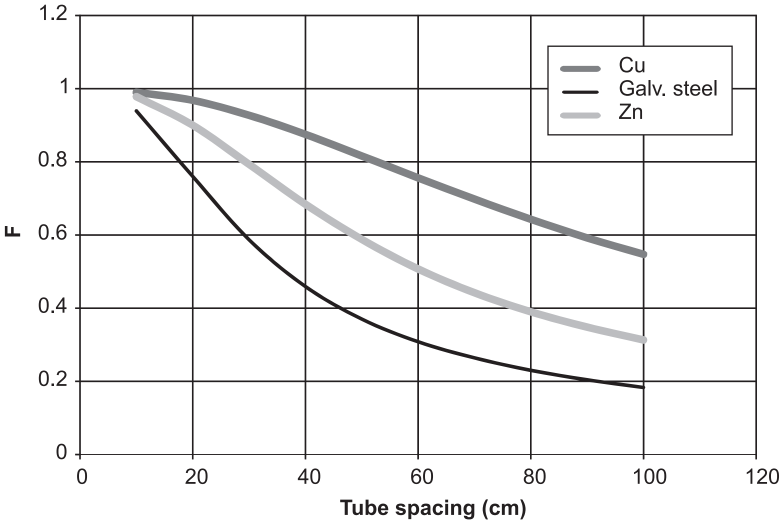

Figure 3: Fin efficiency, F against tube spacing for various absorber plate materials

Table 3: Variations of collector efficiency with glass cover thickness, L_g

Lg (x 10^{-2}m)	$(\iota\alpha)e$	Qu (W/m²)	η
0.1	0.891	393.999	0.764
0.2	0.889	393.042	0.763
0.3	0.886	391.609	0.760
0.4	0.884	390.654	0.758
0.5	0.881	389.221	0.755
0.6	0.879	388.265	0.753
0.7	0.876	386.832	0.751
0.8	0.874	385.877	0.749
0.9	0.872	384.922	0.747
1.0	0.869	383.486	0.744

when doubled. As the glass cover gets thinner, the conductive heat transfer between the absorber plate and the fluid increases, which consequently increases the collector efficiency and the mean system temperature. The time required for heating is also shortened (Takeo and Hamdy, 2002). However, it is important to use plate and cover materials with a small thickness as permitted by factors such as durability, strength and ruggedness of the collector.

4.4 Effect of collector tube spacing

Figure 3 presents the tube spacing effect on the fin efficiency for various absorber plate materials. It reveals that among the three absorber plate materials, copper shows the best performance. Zinc performs better than galvanized steel of the same thickness. However, at a certain tube spacing (<10cm), the fin efficiencies for the three absorber materials are almost equal. Thus, with this tube spacing, the performance of the collector is independent of the type of absorber plate used. This suggests that the performance of the collector with zinc or galvanized steel absorber plates can attain the same efficiency as copper given the proper tube spacing.

5. Conclusion

The performance of the NCERD thermosyphon solar water heater has been evaluated for the three main seasons of the year. The effects of some of the design parameters have been investigated. The test system has a maximum average daily collector efficiency of 0.658. This drops to an average seasonal value of 0.54 with a negligible variation across the three climatic seasons covered in the study. Maximum hot water temperature of 81°C was obtained from the test system. For spacing between flow tubes that is within 10 cm the system's performance is optimized irrespective of the nature of the absorber plate material. The top-loss coefficient is affected by the number of glazing covers depending on the type of absorber plate used. The use of multiple glazing cover has a negligible effect on the system's performance especially for low temperature application.

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