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Design and Performance Features of a Domestic Thermosyphon Solar Water Heater for an Average-Sized Family in Nsukka Urban

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Abstract: This research reports the results of the performance evaluation of a thermosyphon solar water heater developed at the National Center for Energy Research and Development, University of Nigeria, Nsukka. Both numerical and experimental methods were used in the analysis for the optimum performance of the system. The result shows that on a clear day, a thermosyphon solar water heater of collector area 3.4 m^2 and 150 L storage capacity performing at a collector efficiency of 60% can deliver hot water of up to 80°C temperature for the domestic services of an average-sized family at Nsukka.

Key words: Thermosyphon solar water heater, water heating load, flat plate collector area, collector efficiency

INTRODUCTION

A thermosyphon solar water heater is one of the most economic devices to meet both domestic and industrial hot water needs. These systems are widely used domestically in many parts of the world, such as Australia, India, Middle East and Japan (Shariah and Lof, 1997). However, the case is still different in Nigeria where installation of solar water heaters has not become fashionable inspite of the fact that her near equatorial geographical location positions her for an all year-round insolation. Various research work in this area indicate that it is possible to design and install a thermosyphon solar water heater that can meet either in full or in part the hot water requirement for residential use (Norton and Probert, 1982; Lock, 1962). Similar works that have been done in this regard in Nigeria did not quantify the hot water need of an average-sized family and the required design features of a thermosyphon solar water heater that can service this need (Agbo *et al*., 2005; Bello *et al*., 1990).

At the moment, most homes in urban areas use electric ring boiler for the purpose of water heating. Some others depend on kerosene and wood for heating. These options have their attendant adverse environmental and economic effects. The need to therefore introduce a cost-effective and sustainable alternative or supplement has in recent times become imperative. The ever-increasing cost of electricity in Nigeria in addition to its unsteady supply coupled with the present-day cost and scarce nature of our crude are pointers to this assertion.

Thermosyphon solar water system is light and compact and does not require much expertise for maintenance. They are the simplest and the cheapest heating systems that can easily be adopted for home use especially in the rural areas. Countries such as Israel has long adopted thermosyphon system in her national energy mix to meet domestic hot water requirements (Norton and Probert, 1982). This work is part of an on-going research effort at the National Centre for Energy Research and Development, University of Nigeria, Nsukka to fully maximize the potentials and benefits of thermosyphon solar water heaters in Nigeria. It intends to show the possibility of adopting solar water heaters for domestic uses in Nigeria at large and in Nsukka in particular given the average family size and the ambient conditions. Both experimental and theoretical approaches were adopted to obtain the optimum collector area that will serve the hot water need of the family as specified.

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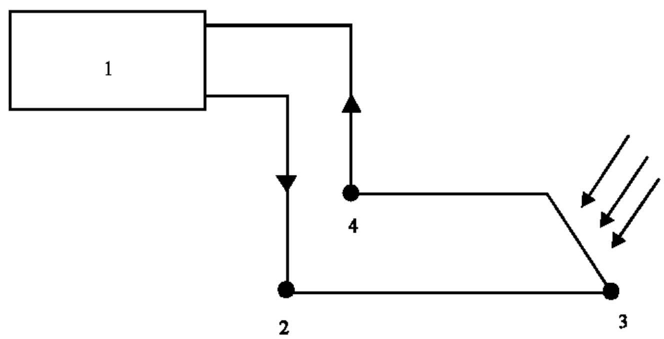

Fig. 1: A thermosyphon circuit

Description of a Thermosyphon Solar Water Heater

Figure 1 is a schematic representation of a thermosyphon solar water heater. It consists of three major components, namely: the flat-plate collector, the water storage tank and the connecting or riser pipes. The incident solar radiation is absorbed by the darkened surface of the absorber plate and is transmitted through the plate material to the heat-transfer fluid. The temperature rise of the fluid inside the absorber plate leads to a decrease in its density thus inducing a driving force between the absorber side and the storage tank side due to the density difference. Natural convection occurs following the action of this driving or buoyancy force often referred to as the thermosyphon head and the fluid circulates upward from the absorber through the storage tank and returns to the absorber. No additional mechanical power is required to promote and maintain this circulation. In a thermosyphon, the contained fluid is constrained to flow over a defined part and the overall heat transfer coefficient is a function of the thermal flux (Norton and Probert, 1982; Lock, 1962). For a complete laminar flow, the heat transfer coefficient is constant. Thermosyphon solar water heaters can be classified on the basis of the convective heat transfer regime, the nature of the force field, the existence of boundaries to prevent mass transfer and the number of phases present (Davies and Morris, 1965).

System Parameters

Thermosyphon Head

The thermosyphon driving head can be evaluated from the difference between pressure head in the pipe segments on the inlet and outlet sides of the circuit and the tank (Morrison and Ranatunga, 1980). With reference to points 1, 2, 3 and 4 on Fig. 1, the thermosyphon head, H_t is expressed as:

$$H_t = \frac{\left\lfloor \int_{123} \rho g dL - \int_{341} \rho g dL \right\rfloor}{\bar{\rho} g} \quad (1)$$

where L and $\bar{\rho}$ are the length of developing flow and the average density of water in the system, respectively. The thermosyphon head generated is used to overcome the flow resistance of the water circulation in the loop that is caused by pipe wall friction and other losses due to bends, fittings, etc. in the loop (Huang *et al.*, 2003). In the riser tubes of the loop, the density and thus thermosyphon head depends on the actual temperature distribution over the cross-section rather than the bulk temperature. In most circuits, the flow out of the collector tubes is well mixed in the header and thus the density of the fluid in the connecting tubes can be computed from the bulk temperature, but in the collector tubes the fluid density should be computed by integrating the actual temperature distribution over the cross-section and length of the riser (Morrison and Ranatunga, 1980a).

The density of water can be approximated from the relation:

$$\rho(T) = -4.05x10^{-6}T^2 - 3.906x10^{-5}T + 1.0002556, T \text{ in} C \qquad (2)$$

Friction Head

Flow resistance in thermosyphon systems is attributed to pipe wall friction and other losses due to bends, fittings, etc in the loop. Friction in the collector tubes is complicated by the heat transfer from the wall which may cause a significant difference between the velocity gradients in the driving section of a thermosyphon circuit and in unheated developing flow (Morrison and Ranatunga, 1980b).

On the assumption of a fully developed laminar flow, the friction head can be estimated. Huang (1980) expressed the friction loss due to fluid motion in the collector as:

$$H_f = f_c \frac{lc}{Dc}\frac{V_C^2}{2g} + f_p \frac{lp}{D_p}\frac{V_p^2}{2g} + E_T \frac{V_p^2}{2g} \qquad (3)$$

where Dc is the hydraulic diameter of the absorber plate, V_p is the velocity in the connecting pipe, f_c and f_p are frictional coefficients in the absorber plate and in the connecting pipe, respectively, E_T is the loss factor due to valves, fittings and bends, etc.lc and lp are absorber plate and connecting pipe lengths, respectively. Vc is the fluid velocity in the absorber plate.

As reported by Huang and Hsieh (1985), the flow resistance in the loop can as well be evaluated in the loop as:

$$H_f = A_o \upsilon_w m_w + A_1 m_w \qquad (4)$$

where A_o and A_1 are flow friction parameters that can be determined experimentally by measuring the mass flow rate and the pressure drop of the loop. υ_{mk} is the kinematic viscosity of water.

Collector Efficiency

Collector efficiency is a measure of the collector performance, which can be described in a number of ways. 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; Sambo and Bello, 1990).

$$\eta_c = \frac{Q_u}{A_c I_o} \qquad (5)$$

The useful energy carried away by liquid flowing through the collector is the difference between the energy absorbed on the absorber plate and the heat lost from it through the front cover and back surface of the collector. The Hottel-Whiller equation relates the useful energy gain of the collector with the inlet water temperature, ambient temperature and outlet water temperature as follows (Garg, 1987; Yeh *et al.*, 2003):

$$Q_u = A_c F_r \left[I_o (\iota\alpha)_e - U_L (T_i - T_a) \right] \qquad (6)$$

$$Q_u = A_c F^1 \left[I_o (\iota\alpha)_e - U_L (T_m - T_a) \right] \qquad (7)$$

The effective collector area, A_c is related to the tube number, n, centre-to-centre tube spacing, w and tube length, l as:

$$A_c = nwl \qquad (8)$$

The effective absorptance-transmittance product $(\tau\alpha)_e$ for a cover system of N identical plates is given as (Duffie and Beckman,1974):

$$(\tau\alpha)_e = \frac{\tau\alpha}{1-(1-\alpha)\rho_d} + (1-\tau_\alpha)\sum_{i=1}^{N}\alpha_i\tau^{i-1} \quad (9)$$

For a collector of 1 glass cover,

$$(\tau\alpha)_e = \frac{\tau\alpha}{1-(1-\alpha)\rho_d} + (1-\tau_\alpha)\alpha_1 \quad (10)$$

where τ_a is the transmittance due to absorption only given as $\tau_a = e^{-ky}$, y is the thickness of the glass cover, k is the extinction coefficient of the glass cover, α_1 is the ratio of the overall loss coefficient to the loss coefficient for glass.

The collector overall heat loss coefficient is the sum of the top and bottom loss coefficients.

$$U_L = U_T + U_B \quad (11)$$

The bottom loss coefficient, U_B derives from the thermal conductivity, K_S and the thickness, L_s of the bottom insulator as:

$$U_B = \frac{K_S}{L_S} \quad (12)$$

Following the basic procedure of Hottel and Woertz, Klein developed an empirical equation for the top loss coefficient, U_T as (Yeh *et al.*, 2003):

$$U_T = \left[\frac{N}{\frac{Ca_{ir}}{T_p}\left[\frac{T_p - T_a}{N+f}\right]^e} + \frac{1}{h_w}\right]^{-1} + \frac{\sigma(T_p + T_a)(T_p^2 + T_a^2)}{\left[(\varepsilon_p + 0.00591Nh_w)^{-1} + \frac{\left[2N + f - 1 + 0.133\varepsilon_p\right]}{\varepsilon_g} - N\right]} \quad (13)$$

where $f = (1 + 0.089h_w - 0.1166h_w\,\varepsilon_p)(1 + 0.07866N)$, $C_{air} = 520(1 - 0.00005\beta^2)$, $e = 0.43\left(1 - \frac{100}{T_p}\right)$, β is the collector tilt and σ is the Stephan Boltzmann constant.

The convective heat-transfer coefficient h_w, for air flowing over the outside surface of the glass cover depends primarily on the wind velocity, v and can be determined from (Duffie and Beckman, 1974).

$$h_w = 5.7 + 3.8v \quad (14)$$

Solar Water Heater Configuration and Sizing

The optimum size of a solar water heater to meet a particular service hot water need depends on a combination of factors, including the investment cost on the system, cost of alternative energy, collector orientation, climate and temperature of the cold water supply. The primary concern in the design is the determination of the collector area, which optimizes the system from an economic standpoint (Garg, 1987). This, in turn requires knowledge of the relationship between solar load fraction and collector area.

There are various possible approaches by which a solar water heater can be sized. First is the rule of thumb method. This method according to the US Department of Energy (US, DOE, 2000) stipulates that about 2 m^2 of collector area is suitable in a domestic solar water heater for each of the first two family members and 0.7 m^2 for each additional family member if the location is in the Sun Belt. However, the rule of thumb method does not reflect the cost of competing fuels and the effect of the environment on the system; thus introducing errors in the sizing of the system (Kreider, 1982). Secondly, simple hand calculation or calculation by a hand-held calculator can be used for sizing a solar water heater. This approach remains valid and is one of the simplest ways of designing a solar water heater. Computer aided design method is a modern way of properly designing a solar water heater for a particular application. In addition, it will help in studying the dynamic performance of the system under given climatic conditions. Various design models have been developed; the most accurate and sophisticated being TRNSYS (acronym for A Transient system simulation Program). Others include the F-chart method, SOLCOST method, SLR and GFL methods (Garg, 1987).

Heating Load Determination

The domestic hot water demand or load varies from family to family or from community to community depending on the number of persons to use the water, the inlet water temperature, the volume of water needed and the desired hot water temperature limit. Because solar water heater performance is extensively sensitive to both the size of the load and its time distribution, the load must be estimated on a monthly or hourly basis (Sheng, 1986).

The monthly domestic water heating load, L can be calculated by the expression (Sheng, 1986):

$$L = N_d N_P V_p \rho C (T_O - T_n) \quad (15)$$

where N_p is the number of persons to use the water, N_d is the number of days in the month, V_p; is the volume of hot water required per person (Ls), C is the specific heat capacity of water (4.19 KJ kg^{-1} °C) and ρ is the density of water (1 kg L^{-1}). T_o and T_n are the demand hot water temperature and the inlet water temperature, respectively.

MATERIALS AND METHODS

A thermosyphon solar water heater developed at the National Centre for Energy Research Development, University of Nigeria, Nsukka was used for the experiment. The system consists of a single-glazed absorber plate coated with dull-black commercial paint. It is made from 1 mm thick galvanized iron sheet and has absorbing area of 2.28 m^2. A storage tank capacity of 150 L is fitted with insulated pipeline connections for the circulation of the working fluid (water) from the collector to the storage tank and vice verse. The system is passive, thus had no pumps or controls.

The performance profile of the heater in terms of the hot water temperature delivered and the collector efficiency is obtained. The collector efficiency was calculated based on the Hottel-Whiller model with the following as input parameters: global solar radiation I, ambient temperature,T_a the hot water temperature obtained from the system,T_m and the useful energy absorbed by the collector,Q_u.

Using the values of the available average daily global solar radiation on a clear day at Nsukka (15 MJ m^{-2} day), the cold water temperature from the mains (30°C), the collector efficiency (60%), required hot water temperature (80°C), an average family size of 8 persons and the volume of hot water required by the family (150 L per day) together with other physical constants contained in Eq. 4, the size of the collector (area) that will meet the 100% hot water need of the family was calculated.

The value of the average daily total insolation on the south-facing collector surface at a tilt of 7° (latitude of Nsukka) is estimated using the radiation conversion factor, R (1.1).

The water-heating load for the test month (January) is calculated from Eq. 15 as:

$$L = 31 x 8 x \frac{150}{8} x 1 x 4.19 x (80 - 30) = 974175 \text{ KJ}$$

The load demand per day is therefore given as:

$$\frac{974175 \text{ KJ}}{31 \text{ days}} = 31425 \text{ KJ day}^{-1}$$

Hence, the required collector area is obtained as in Eq. 5:

$$A_c = \frac{31425 \text{ KJ day}^{-1}}{0.6 \times 15,000 \text{ KJ m}^{-2} \text{ day} \times 1.1} = 3.2 \text{ m}^2$$

RESULTS AND DISCUSSION

Table 1 is a detailed analysis of the performance of the NCERD solar water heater for the test days taken. It presents the temperature profile of the solar water heater from 8.00 to 18.00 h. The system attained a maximum temperature of 82°C on an average clear day and this occurred between 13.00 and 15.00 h. This value however dropped with ime to about 50°C at 18.00 h. The observed heat losses notwithstanding, the water temperature recorded at the end of the day still meets the comfort level temperature of about (45°C) for bathing. The water temperature in the early hours of the morning is below comfort level; a situation calling for an improved design to take care of the losses. These losses can partly be attributed to the back-flow effect during the night hours which has been reported (Duffie and Beckman, 1974) to be a common feature of thermosyphon solar water heaters. Given a proper choice of an insulator, insulator thickness and pipe work geometry, the losses can be minimized reasonably. Losses encountered as a result of the back-flow effect during the night hours can be minimized if a control valve is introduced to make for one directional flow (Bello *et al.*, 1990).

Collector efficiency as shown in the attached table reflects the performance of the system taken over intervals as shown. The results show that the collector efficiency drops with time as the system temperature increases. This can be explained based on the fact that the loss factor [$U_L(T_m$-$T_a)$] increases with increasing system temperature thus resulting in the overall drop in collector efficiency. The maximum collector efficiency recorded is 0.778 and the minimum value is 0.210. Following from this, the efficiency can be improved if the loss factor is minimized by a suitable choice of both the design materials and the specifications. The effect of ambient parameters (ambient temperature and solar radiation) shows a direct variation with the hourly collector efficiency. This agrees with the result of earlier works done in Nigeria (Agbo *et al.*, 2005; Sambo and Bello, 1990).

The optimum collector area that will serve the daily hot water need of an average-sized family in Nsukka is 3.2 m^2. However, this value can be increased or decreased depending on a specified family size, volume of hot water needed among other parameters. Based on the size of the collector area, all other design features of the water heater are derived.

Table 1: Measured and calculated parameters for the collector unit analysis reserch

Time	T_a/°C	T_m/°C	I/W/m^2	ω	Cosθ_c	Cosα_z	R	IR	IR (τ_∞)	U_L (T_m-T_a)	Q_u/W/m^2	η
8	24	27	383.6	+60	0.4649	0.4166	1.12	429.63	379.793	22.494	755.173	0.771
10	27	40	479.5	+30	0.8052	0.7543	1.07	513.07	453.554	97.474	752.596	0.643
12	30	51	547.9	0	0.9298	0.8780	1.06	580.77	513.401	157.458	752.307	0.568
14	33	76	958.9	-30	0.8052	0.7543	1.07	1026.02	907.002	322.414	1235.562	0.528
16	34	71	506.8	-60	0.4649	0.4166	1.12	567.62	501.776	277.426	474.177	0.366
18	31	50	41.1	-90	0	-0.0449	*	Total = 3117.11			Total = 3969.815	
8	25	26	150.7	+60	0.4659	0.4183	1.11	167.28	147.876	7.498	296.697	0.778
10	29	40	657.5	+30	0.8070	0.7568	1.07	703.53	621.921	82.478	1140.145	0.711
12	32	66	109.6	0	0.9319	0.8807	1.06	116.18	102.703	254.932	0	-
14	32	44	835.6	-30	0.8070	0.7568	1.07	894.09	790.376	89.976	1480.337	0.726
16	28	40	123.3	-60	0.4659	0.4183	1.11	136.86	120.984	89.976	65.537	0.210
18	28	34	27.4	-90	0	-0.0442	*	Total = 2017.94			Total = 2982.716	

CONCLUSIONS

The option of adopting solar water heaters to meet the hot water needs of families in Nsukka and Nigeria at large is viable. It is more cost-effective, environmentally friendly and sustainable in comparison with the option of using electricity. The choice of the optimum collector area is one of the principal factors considered in the design of solar water heaters. This optimum value is obtained theoretically as a function of the volume of hot water needed, the input and output water temperature and the ambient parameters.

Both the experimental and theoretical results obtained show that with a thermosyphon solar water heater of collector area 3.2 m^2, water temperature up to 80°C can be obtained to service the hot water needs of an average family in Nsukka. This result can equally apply to other environments with radiation pattern similar to that of Nsukka.

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