International Journal of Physical Sciences Vol. 7(22), pp. 2891-2896, 9 June, 2012
Available online at http://www.academicjournals.org/IJPS
DOI: 10.5897/IJPS11.1570
ISSN 1992-1950 ©2012 Academic Journals

Full Length Research Paper

Analysis of thermal efficiency of a passive solar water heater

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Accepted 23 May, 2012

The analysis of thermal efficiency of a passive solar water heater is presented. The heater which has potential applications in agro-industries and homes, consisted of a single-glazed flat plate solar collector made up of an absorber plate and a transparent sheet of glass; water storage tanks and the stand. The absorber plate was made of mild steel which is a very good conductor of heat. Copper tube was used to form a loop on the mild steel absorber. Water in the loop is heated by the radiant energy trapped by the absorber. The system was tested experimentally under daytime load conditions at Nsukka, Nigeria, over the ambient temperature range of 21 to 31°C, and a daily global irradiation range of 8.3 to 17.4 MJ m^{-2}. Peak temperature rise of the heated water was about 83°C, while the maximum daily average useful efficiency was about 42%. It was deduced that the system can be operated successfully for agro-industries and home applications.

Key words: Solar, water, efficiency, temperature.

INTRODUCTION

Thermal energy has wider applications in the human's life. In the past few decades water heating systems with natural circulation have been in use in many parts of the world and have been studied by some researchers (Close, 1962; Ong, 1976; Rasavi et al., 2003). The amount of heat delivered by a solar water heating system depends primarily on the amount of heat delivered by the sun at a particular place (the insolation). In tropical regions the insolation can be relatively high, for example 7 kWh/m^2/day (Ojike, 2011). Even at the same latitude, the average insolation can vary a great deal from location to location due to differences in local weather patterns and the amount of overcast. Solar water heaters can operate in any climate. These systems use the sun to heat either water or a heat-transfer fluid, such as a water-glycol antifreeze mixture, in collectors generally mounted on a roof. The heated water is then stored in a tank similar to a conventional gas or electric water tank. Passive systems move household water or a heat-transfer fluid through the system without pumps. Passive systems have no electric components to break. This makes them generally more reliable, easier to maintain, and possibly longer lasting than active systems. Passive systems can be less expensive than active systems, but they can also be less efficient.

Performance varies depending, in part, on how much solar energy is available at the site, but also on how cold the water coming into the system is. The colder the water, the more efficiently the system operates (Doe, 1996). Natural circulation solar water heating systems (also called passive systems) are the simplest and most widely used solar energy collection and utilization devices. They are intended to supply hot water for domestic, commercial and industrial uses, and are based on natural circulation or thermosiphon principle. They supply hot water at a temperature of about 60°C and consist of a collector, storage tank, and connecting pipes (Kalogirou, 2009). These systems heat potable water or a heat transfer fluid and use natural convection to transport it from the collector to storage. To take into account periods of low solar radiation levels, storage tanks are normally sized to hold about two days' supply of hot water. Connecting lines must be well insulated to prevent heat losses and sloped to prevent formation of air pockets which would stop circulation. At night, or whenever the

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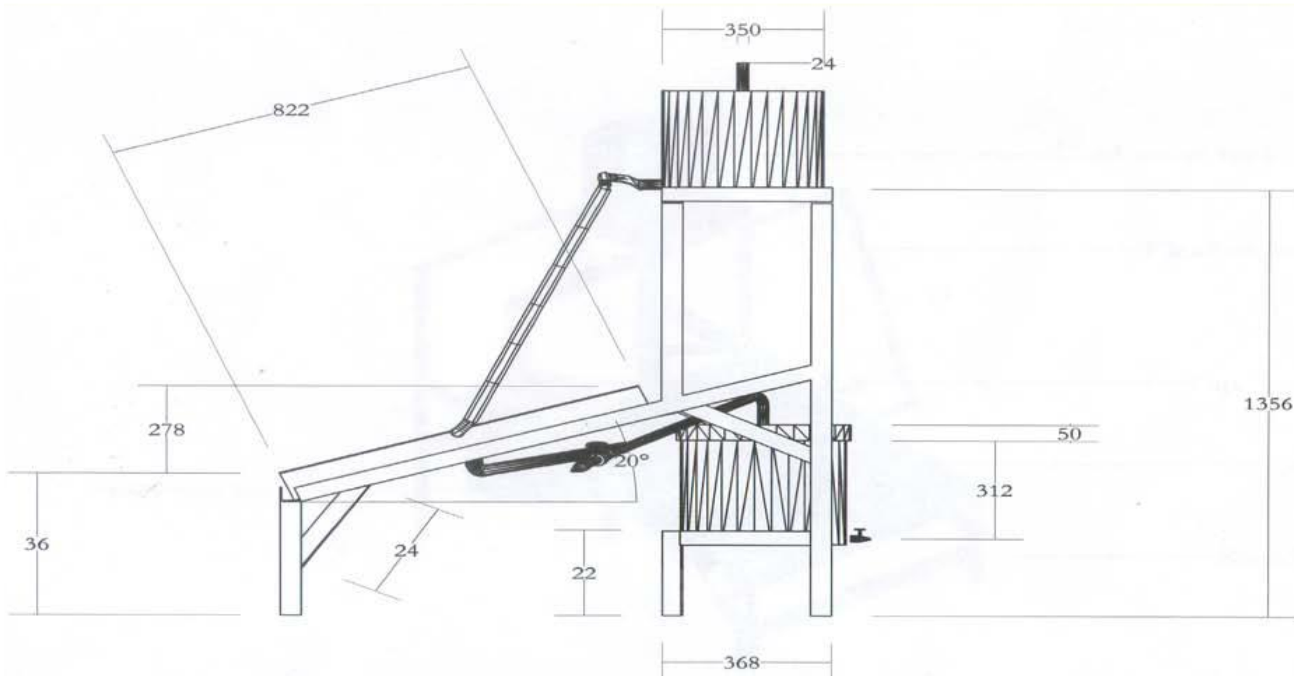

Figure 1. Side view of the solar water heater (in mm).

collector is cooler than the water in the tank the direction of the thermosiphon flow will reverse, thus cooling the stored water, unless the top of the collector is placed well below (about 30 cm) the bottom of the storage tank (Kalogirou, 2004).

In this study the thermal efficiency of a passive solar water heater is undertaken. The solar water heater has two storage tanks and is used for cold and warm waters, respectively.

MATERIALS AND METHODS

The solar water heater used in this study was designed and fabricated at the National Centre for Energy Research and Development, University of Nigeria, Nsukka. It consists of a solar collector which is made up of an absorber plate and transparent sheet of glass; water storage tanks and the stand. The absorber plate was made of mild steel which is a very good conductor of heat. It is malleable and relatively cheap. Copper tube was used to form a spiral loop and placed on the absorber plate. The tube was held in place with steel rings to the absorber plate. This gives the copper tube and the steel plate stability.

Water in the loop is heated by the radiant energy trapped by the absorber. The choice of copper for the tube was informed by its excellent heat conducting properties. It is very malleable, ductile and resistant to corrosion. Both the tubes and mild steel sheet which make up the absorber plate were painted black to increase absorbance and retention of absorbed heat. Glass wools were used to insulate the space between the hot water tank and its outer jacket to minimize heat losses from the water tank while styro-foam was used to insulate the flexible hoses. The two storage tanks for hot and cold water respectively were 1.05 m apart and constructed with 0.4 m thick galvanized iron to prevent corrosion. Water flow through the system is controlled by manual taps attached at joints connecting the pipes to and fro solar collector with the tanks. When the tap that connects the cold water tank and solar collector was switched on, cold water flows through the copper pipes to the hot water tank. While flowing through the copper tube, water is heated up by the heat energy absorbed from the absorber plate through the copper loop. The flow is continuous till solar radiation has approaches zero usually in the evening. Flow rate in the system is directly proportional to solar radiation intensity, the more intense the solar radiation the higher the flow rate. The whole set up was erected on steel support as shown in Figure 1.

The system is single-glazed and for maximum solar radiation collection, collectors are always tilted with respect to the latitude of the location they will be cited (Duffie and Beckman, 1991). However, studies on flat plate collectors have shown that a practical approach to flat plate collector is to tilt the collector along north-south direction at an angle from the horizontal to the local latitude plus 10° to 15° (Reece, 1981; Duffie and Beckman, 1991; Agbo and Okoroigwe, 2007).

Thus, collector tilt angle β, is given as

$$\beta = \text{local latitude} + 15° \quad (1)$$

Where Local latitude for Nsukka = 6.8°

Water was introduced into the cold water tank positioned at the top of the device via a funnel placed on top of the tank. The water immediately flows through a flexible hose into the copper tubes of the absorber plate in the casing. Solar radiation striking the surface of the transparent glass penetrates and heats up the water in the tube. The heated water can then be collected through a header which is incorporated to the hot water tank. The device is mounted in an area where there are no trees or shade of any sort so as to maximize the solar radiation striking the solar collector. During operation, the temperatures of both the cold (Tm1) and warm water (Tm3), the absorber plate (Tm2), and the ambient were measured using I-Bk thermocouples. They were measured using four (4) k-type thermocouples fixed at different points and connected to

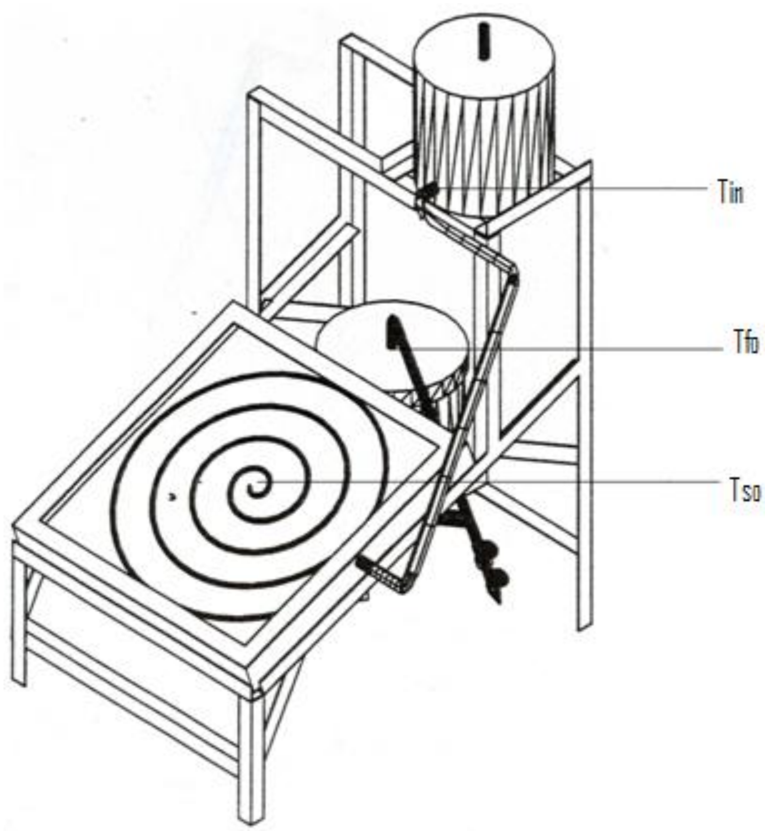

Figure 2. The system showing the position of the thermocouples.

temperature meter (Patos Type k DE-305 Digital Thermometer with accuracy of 0.1°C) as shown in Figure 2 while the amount of insolation at any given time was obtained from the Centre for Basic Space Studies, University of Nigeria, Nsukka. The centre measures the solar radiation over the area the study was done and has data bank on weather elements.

Methodology for determination of efficiency

The efficiency of the solar water heater used was measured based on the existing literature that a measure of solar water heater performance is the collector's collection efficiency η, defined as the ratio of the useful energy gain Q_u over some specified time period to the incident solar energy G_t over the same time period (Duffie and Beckman, 1991):

$$\eta = \frac{\int Q_u dt}{A_c \int G_T dt} \quad (2)$$

where

$$Q_u = A_c F_R[S - U_L (T_{fi} - T_a)] \quad (3)$$

$$S = (\tau\alpha)_{av} G_T \quad (4)$$

$$UL = U_T + U_B + U_e \quad (5)$$

$$U_T = \left[\frac{N}{\frac{Ca_{ir}}{T_p}\left[\frac{T_p - T_a}{N+f}\right]^e} + \frac{1}{h_w} \right]^{-1} + \frac{\sigma (T_p + T_a)(T_p^2 + T_a^2)}{\left[(\varepsilon_p + 0.00591Nh_w)^{-1} + \frac{[2N + f - 1 + 0.133\varepsilon_p]}{\varepsilon_g} - N\right]} \quad (6)$$

$$f = (1 + 0.089h_w - 0.1166h_w\varepsilon_p)(1 + 0.07866N) \quad (7)$$

$$Ca_{ir} = 520(1 - 0.00005\beta^2) \quad (8)$$

$$e = 0.43 \ (1 - \frac{100}{T_p}) \quad (9)$$

$$U_B = \frac{K_s}{L_s} \quad (10)$$

$$U_e = (UA)_{edge} / A_c \quad (11)$$

$(UA)_{edge}$ = (k_s/L_s) × collector perimeter × collector thickness (12)

A_c is the collector area, T_{fi}, T_{fo} and T_a are fluid inlet, fluid outlet and ambient temperatures respectively; K_S is the thermal conductivity and L_s is the thickness of the bottom insulator. $(\tau\alpha)_{av}$ is average transmittance-absorptance product (Duffie and Beckman, 1991), N is the number of glass covers, h_w is the convective heat-transfer

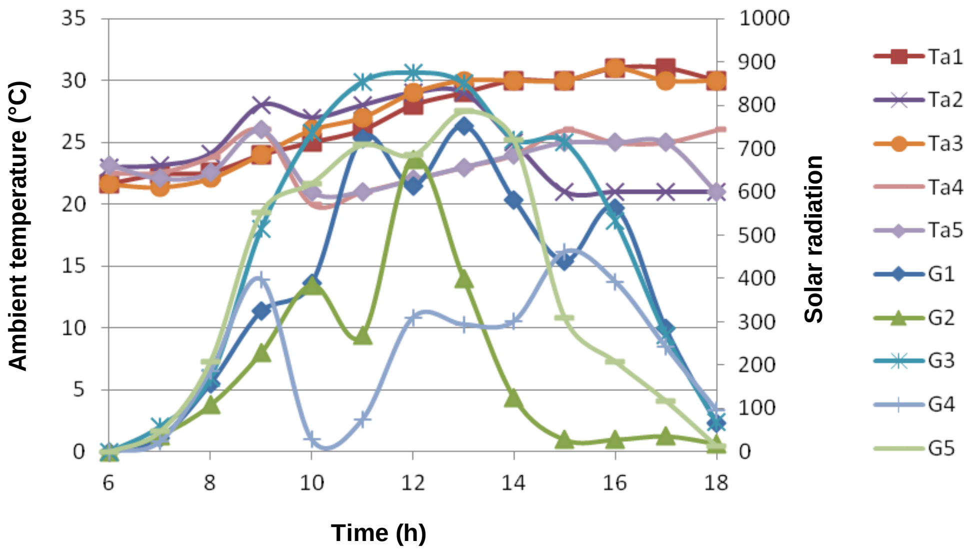

Figure 3. Graph of solar radiation and ambient temperature against time.

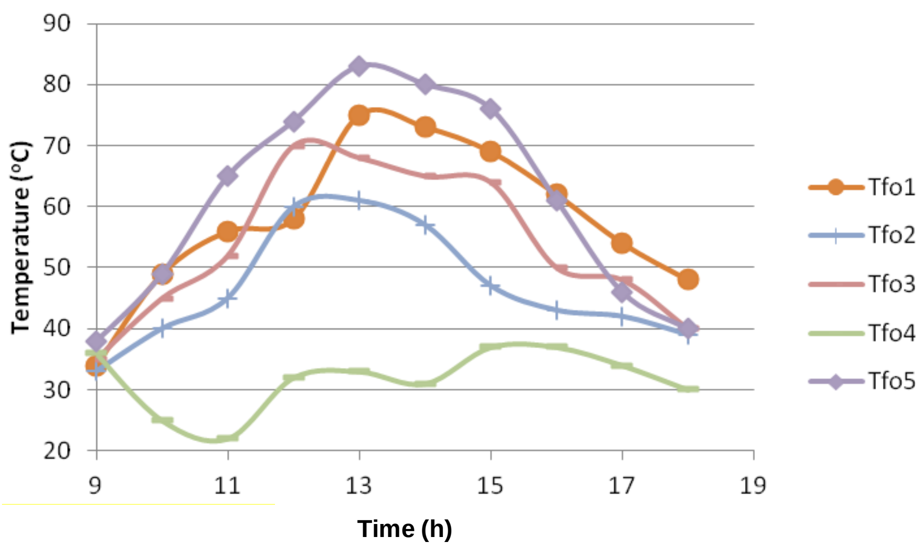

Figure 4. Graph of collected hot water.

coefficient, ε_g and ε_p are the transparent cover and the absorber plate emissivity respectively. β is the collector tilt and σ is the Stephan Boltzmann constant and F_R is as given in Duffie and Beckman (1991). These equations were therefore used to generate the efficiency of the system.

RESULTS AND DISCUSSION

Figure 3 is the graphical representation of the hourly solar radiation and ambient temperatures of March, 17th to 21st 2010 which were the periods the study was done. In the graphs, Ta is the ambient temperature; The subscripts 1, 2, 3, 4, 5 represent 17th, 18th, 19th, 20th 1nd 21st March, respectively; G is the solar radiation. The ambient temperature varies in sympathy with the solar radiation rising as the solar radiation reaches its peak. Then as the solar radiation decreases the ambient temperatures were still high till late evenings due to the cloudiness of the area which trapped the heat wave (Duffie and Beckman, 1991). It is observed that the hourly solar radiation is maximum between the hours of 12:00 and 14:00 when the sun is vertically overhead while lowest at early morning and late evening hours of the day, respectively. From Figure 3 the solar radiation on the day 4 (G4) went down to zero around 10 am in the morning due to rainstorm which formed a thick cloud that prevented solar radiation. From the figure, ambient temperature varied between 21 and 31°C.

Figure 4 shows the variation of collected hot water temperature (T_{fo}) from the collector with time. Comparing

Table 1. Solar water heater efficiency.

Time	η1	η2	η3	η4	η5
8-9	0.28	0.27	0.51	0.40	0.44
9-10	0.32	0.37	0.46	-1.15	0.47
10-11	0.44	0.27	0.47	-0.14	0.49
11-12	0.43	0.43	0.46	0.37	0.47
12-13	0.32	0.32	0.44	0.34	0.47
13-14	0.21	0	0.41	0.27	0.45
14-15	0.08	0	0.42	0.35	0.28
15-16	0.12	0	0.38	0.35	0.09
16-17	0	0	0.23	0.28	0
17-18	0	0	0	0	0
Average	0.22	0.38	0.33	0.27	0.52

Figures 3 and 4 it can be observed that the hot water temperature fluctuates steadily in sympathy with the solar radiation. Table 1 shows the hourly and daily average efficiency (η) of the solar water heater. The average daily efficiency for the system ranged from 0.22 (day 1) to 0.52 (day 5) throughout the duration of the study. The average efficiency is within the range for passive solar collectors (Duffie and Beckman, 1991 and Okonkwo, 1993).

Conclusion

Radiation data generated during the study show that peak temperature rise of the heated water was about 83°C, while the maximum and average useful efficiency were about 22 and 52%, respectively. These results show that the system can be operated successfully for agro-industry and home applications.

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