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Performance Evaluation of a Solar Water Heater in Yola, Nigeria

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Abstract: *Performance evaluation of a constructed SWH has been done. It is found that the SWH can provide hot water at about 60^{o}C up to 5:00 pm local time at an efficiency of about 40%. The collector efficiency factor and the heat removal factor at average values were found to be about 0.64 and 0.56 respectively which indicates a satisfactory design with approximate overall heat transfer coefficient of about 4.05 Wm^{-2o}C^{-1}. The SWH may be use at homes, hospitals and places where at most 60^{o}C of hot water may be needed.*

Keywords: *solar water heater, performance, heat loss coefficient, collector efficiency, heat removal factor*

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I. INTRODUCTION

Electrical energy utilization is increasingly rapid in today's modern world, but its supply is inadequate. As a result, peoples' increasing demands, particularly for hot water are barely met. Alternative means of satisfying these needs may be necessary if it is affordable and easily accessible. A solar water heater (SWH) that uses the direct energy of the sun makes a better alternative. The fact that solar energy is renewable, free and non exhaustible, is enough guarantee for continuous supply of hot water where they are needed. Studies have shown that solar water heating systems are now famous in their utilization to provide hot water for homes, industries and hospitals [1, 2].

However, providing the supply from a locally produced SWH at 60^{o}C up to about 5:00 pm local time may particularly be an issue. This ability may probably be tied down to device design and/or availability of solar insolation. Nevertheless, the nature and type of materials used in their construction may also affect their effectiveness. Most locally made collectors for water heating make use of galvanized pipes and plates to avoid corrosion and these materials have low thermal conductivity compared to copper and aluminum. The use of galvanized pipes on the other hand, affects the possibly number of riser pipes that can comfortably be accommodated on a given collector area due to their rigidity at bending. In this work, performance evaluation of a SWH constructed from copper pipes with increased number of riser pipes has been done. Necessary parameters and figure of merits that determine its effectiveness were also evaluated.

II. MATERIALS AND METHODS

2.1 Solar water heater description

The SWH evaluated has the following design parameters: Collector area A_c = 1.402 m^2, black painted absorber made from 0.5 inch diameter bended copper pipe of length l = 1.5 m, spaced 0.1 cm and pin unto a black painted aluminum sheet of thickness 0.5 inch. The cylindrical storage tank has a diameter of 0.27 m and containing 60 liters of water. The SWH is well insulated with 6 cm thickly packed saw dust at the bottom and sides of the collector box as well as around the storage tank. The flat plate collector was oriented horizontally (at the latitude of the location) to the incident solar radiation and positioned facing south for optimum collection of radiation.

2.2 Data collection

The incident solar radiation intensity and ambient temperature data was collected from Nigerian Environmental Climatic Observation Programme (NECOP) instrument installed at Modibbo Adama University of Technology (MAUTECH) Yola. The values of the glass surface, absorber, air between absorber and glass, inlet and outlet water temperatures were measured by thermometers with precision of 0.5^{o}C from the solar water heater placed at the installed instrument location for three days of experiment

2.3 Collector theory

When solar radiation of intensity H is incident and transmitted through a glass cover of transmittance τ and absorbed by a black steel sheet surface of absorptance α, the quantity of heat generated by the surface is given [3] by:

$$Q_u = \tau\alpha H A_c - Q_{loss} \tag{1}$$

These losses consist of those from absorber plate p through the glass cover c to the air a lost by conduction, convection and radiation given by:

$$Q_{loss} = q_{p-a} + q_{a-c} \tag{2}$$

where q_{p-a} is the loss from plate to air through conduction, convection and radiation and q_{a-c} is the loss from glass cover through convection and radiation [3] by:

$$q_{pa} = h_{p-a}(T_p - T_a) + h_{p-c}(T_p - T_c) + \frac{\sigma(T_p^4 - T_c^4)}{\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_c}} \tag{3}$$

$$q_{ca} = h_{c-a}(T_c - T_a) + \varepsilon_c \sigma T_c^4 - \varepsilon_c L \tag{4}$$

where h_{p-a} (= 0.3 Wm^{-2} by conduction), h_{p-c} and h_{c-a} are the respective heat transfer coefficients from plate to air, plate to glass cover and glass cover to air; T_p, T_a and T_c are the respective plate, air and glass temperatures; ε_p (0.92) and ε_c (= 0.95) are the emittance of plate and glass respectively and L is the long wave radiation from the sky that entered through the glass cover. The loss by conduction through the bottom is usually very small due to insulation and can be neglected in some cases.

Since the solar water heater used was inclined at an angle equal to the latitude of the location (Yola) the collector is therefore considered a horizontal surface with respect to the incident solar radiation. Hence for free convection, h_{p-c} can be determined using the Nusselt number *Nu* in air space between parallel plates with Grashof number given [4,5] by:

$$Nu = \frac{h_{p-c} l}{k} \tag{5}$$

where *Nu* for horizontal surface is: $Nu = 0.152 Gr^{0.281}$ and the Grashof number is:

$$Gr = \frac{g\beta(T_p - T_c) l^3}{v^2} \tag{6}$$

where g is the acceleration due to gravity (9.8 ms^{-2}), β is the coefficient of thermal expansion (1/T$_\beta$), h_{p-c} is loss from the glass cover, l (0.07 m) is the spacing between absorber and glass cover, k is the thermal conductivity of air and v is the kinematic viscosity of air.

$$T_\beta = \frac{T_p + T_c}{2} \tag{7}$$

where T_c is the temperature of glass cover.

The convective heat transfer coefficient under *V* wind speed from glass to air is given by:

$$h_{c-a} = 2.8 + 3.0\, V \tag{8}$$

The long wave radiation is estimated using [6]:

$$L = 1.31 \left(\frac{10 e_a}{T_a}\right)^{\frac{1}{7}} \sigma T_a^4 \tag{9}$$

where e_a is the vapour pressure at screen height (=1013 mbar).

When the loss in energy Q_{loss} is calculated then the useful energy is easily found from equation (1).

The useful heat energy rate derivable from the collector can also be written [3] as:

$$Q_u = \tau\alpha A_c H - A_c U_L (T_p - T_a) \tag{10}$$

Equation (10) has been used to determined the overall heat loss coefficient from the knowledge of Q_u and $(T_p - T_a)$

Hence the thermal efficiency is determined from:

$$\eta_{th} = \frac{Q_u}{H} \times 100\% \tag{11}$$

However the heat absorbed by the working fluid is equivalent to the useful heat derivable from the collector [3]:

$$Q_u = \dot{m} c_p (T_o - T_i) = A_c[\tau\alpha H - h(T_p - T_a)] \tag{12}$$

where $\dot{m}$ is the mass flow rate given by: $\dot{m} = A_p \rho_w v$ and v is the velocity of flow through the copper pipe.

Alternatively, the useful heat rate can be written in terms of the fluid temperature T_f [3] as:

$$Q_u = A_c F' [I(\tau\alpha) - U_L(T_f - T_a)] \tag{13}$$

where F' is the collector efficiency factor and T_f is the average value of the inlet and outlet temperatures given by:

$$T_f = \frac{T_i + T_o}{2} \quad (14)$$

The average value is necessary because of the non uniformity of the temperature of the fluid within the collector pipes and its being higher at the outlet than at the inlet.

The thermal resistance R between the working fluid and absorber together with other expressions for the collector factors [3]are as follows:

$$R = \frac{(T_p - T_f)}{Q_u} = \frac{(T_p - T_f)}{\dot{m}c_p(T_o - T_i)} \quad (15)$$

$$F' = \frac{1}{(1 + RU_L)} \quad (16)$$

$$F_R = \frac{\dot{m}c_w}{A_c U_L}\left[1 - exp\left(\frac{-A_c F' U_L}{\dot{m}c_w}\right)\right] \quad (17)$$

where F' and F_R are the collector efficiency factor and the heat removal factor respectively.

III. RESULTS AND DISCUSSION

Table 1 gives the calculated values of Grashof number, Nusselt number used in determining the heat transfer coefficient from the absorber plate to the glass cover using equations (5, 6 and 7) for day 1, 2 and 3. The average values of the heat transfer coefficients are 2.80, 2.77 and 2.73 Wm^{-2} respectively for the days. These values which are relatively constant are a reflection of the characteristics of the SWH.

Table I: Plate to glass cover heat transfer coefficient calculations for day 1, 2 and 3

Time	Day 1 Gr	Day 1 Nu	Day 1 h_{p-c} ($W/m^{2o}C$)	Day 2 Gr	Day 2 Nu	Day 2 h_{p-c} ($W/m^{2o}C$)	Day 3 Gr	Day 3 Nu	Day 3 h_{p-c} ($W/m^{2o}C$)
9	783567.58	6.89	2.71	553881.69	6.25	2.45	568169.18	6.29	2.47
10	781244.18	6.88	2.70	677643.58	6.61	2.60	677643.58	6.61	2.60
11	660621.41	6.57	2.58	661580.91	6.57	2.58	688584.22	6.64	2.61
12	843191.36	7.03	2.76	880647.44	7.12	2.80	880647.44	7.12	2.80
13	1100048.03	7.58	2.98	1043076.48	7.46	2.93	832974.93	7.01	2.75
14	1007638.62	7.39	2.90	1047664.79	7.47	2.94	1168096.21	7.71	3.03
15	1122060.34	7.62	2.99	1055344.61	7.49	2.94	951267.23	7.27	2.86
16	871994.96	7.10	2.79	1075433.29	7.53	2.96	853143.15	7.05	2.77
17	851871.70	7.05	2.77	826482.42	6.99	2.75	723077.19	6.73	2.65
Ave	891359.80	7.12	2.80	869083.91	7.05	2.77	815955.90	6.94	2.73

Tables II, III and IV give calculated values of the quantity of heat loss rate per square meter using equations (3 & 4), the useful energy rate per square meter from equation (1), the mass flow rate from equation (12) and the SWH efficiency from equation (11).

Table II: Temperature difference, radiation intensity, heat loss rates, mass flow rates and SWH efficiency values for day 1

Time	T_o-T_i (°C)	T_p-T_a (°C)	T_c-T_a (°C)	H (Wm^{-2})	q_{pa} (Wm^{-2})	q_{ca} (Wm^{-2})	Q_{loss} (Wm^{-2})	Q_u (Wm^{-2})	$\dot{m}$ (kg/s)	η (%)
9:00	23.00	46.61	29.50	304.63	94.64	107.24	201.88	29.64	0.00031	9.73
10:00	26.00	45.68	29.50	589.23	94.33	101.45	195.78	252.03	0.00232	42.77
11:00	31.50	49.40	25.50	720.60	81.62	150.03	231.65	316.01	0.00240	43.85
12:00	23.00	50.53	32.50	744.92	106.24	113.18	219.42	346.72	0.00360	46.54
13:00	23.50	51.01	42.00	774.78	141.85	56.58	198.43	390.41	0.00397	50.39
14:00	20.50	48.01	38.50	638.79	127.61	59.75	187.36	298.12	0.00347	46.67
15:00	15.50	55.09	43.50	550.71	148.70	72.82	221.52	197.02	0.00304	35.78
16:00	8.50	40.87	33.00	508.42	105.30	49.49	154.79	231.61	0.00651	45.56
17:00	3.00	38.24	32.00	289.28	101.00	39.25	140.25	130.97	0.01043	36.70
Average	19.39	47.27	34.00	569.04	111.26	83.31	194.56	243.61	0.00400	39.78

Table III: Temperature difference, radiation intensity, heat loss rates, mass flow rates and SWH efficiency values for day 2

Time	T_0-T_i (°C)	T_p-T_a (°C)	T_c-T_a (°C)	H (Wm^{-2})	q_{pa} (Wm^{-2})	q_{ca} (Wm^{-2})	Q_{loss} (Wm^{-2})	Q_u (Wm^{-2})	$\dot{m}$ (kg/s)	η (%)
9:00	25.00	31.56	20.00	256.30	58.83	72.38	131.21	63.58	0.00061	24.81
10:00	29.00	39.03	25.00	537.21	77.15	87.89	165.04	243.24	0.00200	45.28
11:00	28.00	38.95	24.50	503.53	75.42	90.54	165.97	216.72	0.00185	43.04
12:00	21.00	51.00	33.50	530.07	110.09	109.71	219.81	183.05	0.00208	34.53
13:00	21.00	55.60	40.00	818.55	135.52	97.82	233.34	388.76	0.00442	47.49
14:00	18.50	53.76	40.00	451.38	135.02	86.29	221.30	121.75	0.00157	26.97
15:00	16.00	55.52	40.50	492.55	137.39	94.20	231.59	142.75	0.00213	28.98
16:00	7.00	51.40	41.00	510.57	138.15	65.26	203.41	184.63	0.00630	36.16
17:00	4.00	41.91	31.00	303.98	98.55	68.44	166.99	64.03	0.00382	21.06
Average	18.83	46.53	32.83	489.35	107.35	85.84	193.18	178.72	0.00275	34.26

Table IV: Temperature difference, radiation intensity, heat loss rates, mass flow rates and SWH efficiency values for day 3

Time	T_0-T_i (°C)	T_p-T_a (°C)	T_c-T_a (°C)	H (Wm^{-2})	q_{pa} (Wm^{-2})	q_{ca} (Wm^{-2})	Q_{loss} (Wm^{-2})	Q_u (Wm^{-2})	$\dot{m}$ (kg/)	η (%)
9:00	24.50	29.73	20.50	281.15	59.87	57.81	117.68	95.99	0.00094	34.14
10:00	30.00	37.62	25.00	572.30	76.73	79.08	155.81	279.14	0.00222	48.78
11:00	29.50	37.62	25.50	742.00	78.37	75.97	154.34	409.58	0.00332	55.20
12:00	31.50	49.19	33.50	728.61	109.55	98.40	207.95	345.79	0.00262	47.46
13:00	26.50	44.92	31.50	736.50	101.15	84.19	185.33	374.41	0.00338	50.84
14:00	19.50	53.05	44.50	778.68	152.22	53.66	205.87	385.92	0.00473	49.56
15:00	19.50	45.89	36.00	497.06	117.76	62.08	179.84	197.93	0.00242	39.82
16:00	13.00	40.46	32.00	501.74	101.68	53.12	154.80	226.52	0.00416	45.15
17:00	6.00	36.66	27.00	307.13	83.09	60.64	143.73	89.69	0.00357	29.20
Average	22.22	41.68	30.61	571.69	97.83	69.44	167.26	267.22	0.00304	44.46

The low mass flow rates for the three experimental days may generally be due to low solar radiation received at the time of experiment (as indicated by their average values) or due to the diameter of the pipes used; but in either case, a slightly greater than 55°C on an average between the inlet and outlet temperatures of water were collected up to 5:00 pm (Table IV). This can see from Tables II-IV how the difference in inlet and outlet temperatures narrowed down around the 17:00 hour (5:00 pm local time) to few degrees differential indicating that the water was indeed at temperatures greater than 55°C. Moreover, the average values of the efficiencies have shown direct increasing relationship suspected with the average solar radiation received on the three experimental days. In facts, Table IV has shown increase in efficiency and radiation, but paradoxically accompanied by decrease in heat loss rates. This is actually desirable, perhaps might have come from some hidden causes.

Table V gives average values of the plate, fluid, inlet and ambient temperatures for the different days along with the SWH parameters. The low values obtained for F' and F_R is an indication of poor design, but it should be expected as it is not a factory in the first place.

Table V: Parameters of the SWH for Day 1, 2 and 3

Day	T_p	T_f	T_{in}	T_a	U_L	R	F'	F_R	T_{min}	T_{max}
1	70.61	60.92	51.22	37.23	4.01	0.19	0.57	0.52	57.74	146.69
2	68.06	58.64	49.22	32.92	4.15	0.15	0.62	0.53	46.94	149.80
3	60.28	55.17	44.06	34.71	4.00	0.09	0.74	0.63	53.42	147.82

The maximum and minimum plate temperatures T_{min} and T_{max} obtained from the ratio of the minimum and maximum radiation absorbed by plate to the overall heat loss coefficient for that day is also presented in Table V. These values when averaged together produce an approximate value of 100°C and when compared to the average hot water temperature T_f of approximately 58°C, a glimpse of how much the heat loss rate had been. That is: $U_L \times (100-58) = 170\ Wm^{-2}$.

IV. CONCLUSION

It is possible to locally produce a SWH that can provide hot at about 60°C by 5:00 pm and at the same time operating at less than AM 1 solar radiation. This ability could be attributed to the copper pipes used and the increased number of riser pipes per collector area that resulted from decreased pipe spacing. The absorber plate doesn't have to be from steel sheets. The SWH is therefore recommended for home use as auxiliary water heater.

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