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ANNUAL PERFORMANCE EVALUATION OF SPIRAL TYPE SOLAR WATER HEATER USING LINEAR REGRESSION MODEL

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ABSTRACT

The main challenges of designing a solar water heating system is the determination of the performance of the system for at least one year since solar radiation received from the sun varies from day to day and month to month. So most researchers are limited to testing their solar water heaters for a small period of time and use these test as basis for the performance. To be satisfied with any solar system it must be tested for at least a year. Thus, there is the need to have a realistic model that can predict the annual performance of the solar system considering all days of the year. A solar water heating system using flat plate collector was designed, constructed at the old site clinic of Bayero University, Kano. The system comprises of a collector and a storage tank, the collector has an area of 1.62m^2. The spiral collector system was tested for 80 days (11 weeks) and performance data were recorded. This data was analysed to find the relationship between performance of the system and the solar radiation intercepted. An empirical model was then developed using the performance data collected for the spiral type solar water heating system. This empirical model can be used to predict the annual performance of the solar water heating system using weather data obtained from metrological centres. The model was found to accurately predict the system performance with a maximum weekly error of 11% and a total error based on the 11 weeks of data collected of 1.55 kWh/m^2 corresponding to an error of 2.2%. It was also found out that the energy collected for a spiral type solar collector varies linearly with the solar radiation intercepted and the efficiency is independent on the solar radiation intercepted.

Keywords: *Solar Collector, Hot water, Annual Performance, Copper Tube*

1. INTRODUCTION

The Sun produces enormous amount of energy which reaches the earth surface and can be utilized for many applications such as production of heat for domestic applications (Solar water heating and cooking), Power generation, processing of agricultural products e.t.c. Water is one of the most essential needs to living organisms. Nigeria receives about 5.08 x 10^{12} kWh of free energy per day from the sun (Sambo and Doyle, 1986). If solar devices with just 5% efficiency are used to cover only 1% of the country's surface area, then 2.54 x 10^6 kWh/day of electrical energy can be obtained from solar energy; this amount of electrical energy is equivalent to 4.66 million barrels of oil per day. The increasing demand for energy and the rising cost of fossil fuels and their associated environmental impacts necessitate the need to find sustainable cost effective and environmentally friendly energy technologies to satisfy our demand for energy. Solar energy is the most attractive source of energy since it is readily available and can serve both the domestic and industrial heating needs. It will also reduce the overdependence on fossil fuels especially in developing countries like Nigeria.

Many domestic and industrial applications require hot water and the conversion of solar energy to heat by heating water is easy and straight forward. Currently domestic and industrial applications hot water is produced by either using fossil fuels directly or electricity. Heating water consumes nearly 20% of total energy consumption for an average family. Solar water heating systems are the cheapest and most easily affordable clean energy available to homeowners that may provide most of hot water required by a family. It is required for taking baths, washing clothes and utensils, and other domestic purposes in both the urban and rural areas. Hot water is also required in large quantities in hotels, hospitals, hostels, and industries such as textile, paper, food processing, dairy, and edible oil (Nahar, 2002). Using the sun's energy to heat water is not a new idea. Harnessing the sun as a clean and renewable source of energy has proven to be a challenge over the centuries and in modern times has fallen off in favor of other technologies which are easier to commercialize (Samo et al. 2012).

To convert solar energy into thermal energy, collectors are employed which consist of the collector system consists of heat exchanger (plate and heat exchanger pipes) placed in a box-cased by insulation materials to minimize heat loss and transparent material placed on the top of the box at suitable distance in-order to capture and transfer heat into the box and to minimize top heat loses. Mostly three types of solar collectors for water heating are available in the market: flat plate collectors (FPC), evacuated tube collectors (ETC), and compound parabolic collectors (CPC) (Verma et al., 2020). Many studies have been done both internationally and in Nigeria on the development of various designs and configuration of Solar Water heating devices (Rhushi et al., 2011; Martin et al., 2011; Jamar et al., 2016). These include active and passive systems. Passive systems do not require a pump to circulate the water through the system and thus has no parasitics and are easier to maintain. In passive systems the thermosyphon principle is employed in which the difference in the density of a heated fluid and that of a cold one is employed.

Over the years researchers have focused on the novel ways to improve the collector performance and efficiency by employing different techniques of extracting as much energy as possible: Tracking the sun (Rhushi et al., 2011; Hosni and Abu, 2012), Use of passive heat transfer enhancement techniques such making rough surfaces, corrugation, and coatings (El-Sebaii and Al-Snani, 2010), finned surfaces and twisted pipes (Martin et al., 2011; Sadhishkumar and Balusamy, 2014; Ameen et al., 2015), Use of heat pipes (Sivakumar et al. 2012, Ismail and Abogderah, 1998)

Other researchers considered using different layout of the collector tube, The use of a spiral tube have been shown by researchers to improve the efficiency and it also makes construction easier since most tubes especially copper tubes comes in a spiral form and thus, this configuration will reduce the time and cost of making the collector and will avoid the use of joints in the collector or reduce the number of joints. For thermosyphon systems it must be ensured that the thermosyphon effect can take place and pump the water if the collector is made in the form of a spiral since it will have only one inlet and out let unlike the conventional configuration which has many pipes in parallel. In view of this Danshehu (2001), designed, constructed and evaluated the performance of 100 liters spiral-type solar water heater. The performance was compared with the conventional U-coil collector configuration. Also Kabiru, (2010) developed a 500 litre spiral-type solar water heater using aluminium tubes and galvanized iron sheets. These studies have shown that it is possible to develop a passive system based on the spiral configuration. Selvadhurai. et al. (2019) conducted numerical simulation using TRNSYS and compared the performance of a spiral and U-coil collector. Result showed that at noon, the performance of the spiral type is better than that of the parallel flow. Maheshwaran and Murugavel (2013) conducted an experimental study of the performance of a spiral type of passive solar water heater and obtained a maximum efficiency of 65.98% in Kovilpatti, India. Jawad et al. (2022) studied both numerically and experimentally a doubled spiral tube arrangement with inner coating of the pipe in Babylon, Iraq and reported a maximum temperature difference of 25.2^{o}C. Al-Hadithi and Tayeeb (2022) tested the real time performance of a spiral type solar water heater in the month of M~~m~~ay in Fallujah, Iraq and found out that an increase in up to 40% efficiency is obtainable compared to published values. Muthuraman et al. (2021) compared the performance of a conventional parallel pipe, curved pipe and spiral type collector in the Kovilpatti region of Tamil Nadu, India and found out that the spiral type provided the highest efficiency of 73% compared to the curved and parallel pipe efficiency of 58% and 62% respectively.

One of the main challenges of designing a solar water heating system is the determination of the performance of the system for at least one year since solar radiation received from the sun varies from day to day and month to month. So most researchers are limited to testing their solar water heaters for a small period of time and use these test as basis for the performance. To be satisfied with any solar system it must be tested for at least a year. Thus, there is the need to have a realistic model that can predict the annual performance of the solar system considering all days of the year.

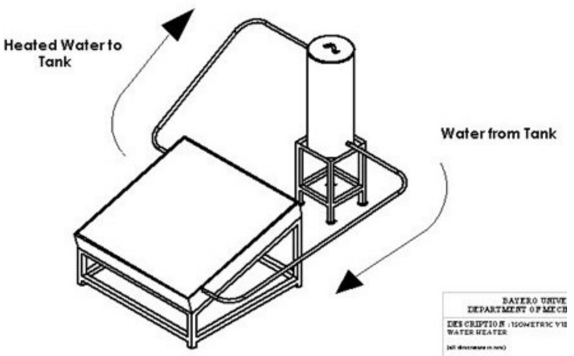
In view of this, in this paper the real performance of a constructed spiral type solar water heating system was evaluated in Kano, Nigeria (12.0022° N, 8.5920° E) for a period of three months and a correlation that can be used for the prediction of the annual performance of the system was developed.

2. METHODOLOGY

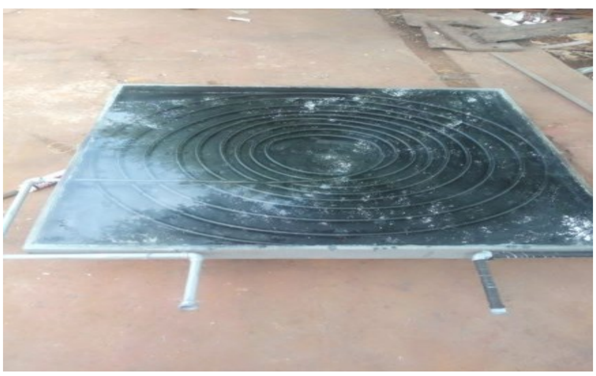
2.1 The Experimental System

2.1.1 System Description

The system consists of a flat plate solar collector, tilted from the horizontal, a thermally insulated horizontal storage tank and interconnecting pipes connecting the solar collector and the storage tank. The flat plate collector casing was made of dry wood to minimize heat loss. The flat plate collector has spiral copper tube with inlet for cooled water and outlet for hot water as shown in figure 1.



(a)



(b)

Figure 1: (a) Assembled Spiral type Solar Water Heater (b) The collector configuration.

The casing was covered at the top with a 4mm thick glass sealed with a rubber gasket. The absorber plate was painted with black fine matte paint to achieve high absorption coefficient. The hot water storage tank which was constructed using a galvanized iron sheet and properly lagged with fibre glass to minimize heat loss to the surroundings. The hot water storage tank was linked to a source of water from the mains water supply. Control valve to control the inflow of water into the storage tank from the main supply were incorporated along the length of the pipe linking the mains water supply to the storage tank. The hot water to meet the domestic load is collected through the hot water outlet.

2.1.2 The Spiral Collector Configuration

Plate 1 shows the picture of the constructed spiral solar collector. The system was designed to supply a total of 110 litres of hot water per day at a temperature of 70^{o}C. The following are the dimensions of the collector:

Collector area: 1.62 m^2; Copper tube diameter: 15.6 mm; Copper tube length: 10.9 m

Plate 1: Picture of the Spiral Solar Collector

2.2 Experimental Materials/Equipment

The materials/equipment used in conducting experiment to test the performance of the solar water heater system are:

- Thermocouple sensors to determine temperatures at the inlet and outlet of the collector
- Solar Power Meter (Solarimeter): To measure solar radiation.

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- Thermocouple wires: To measure temperatures at specific points

2.3 Data Collection Procedure

The collector was mounted on its stand and placed on the surface of the earth facing the south at a tilt of 15°, while the storage tank which was already mounted on its stand, was also placed very close to the collector, at least 30cm away so as to reduce heat loss through the collector outlet pipe as shown in plate 2. Ambient temperature was measured using mercury in glass thermometer. The inlet temperature, outlet temperature, copper tube temperature, glass temperature, plate temperature, and hot water storage tank temperature were all measured using digital thermocouple thermometer in degree Celsius scale. The amount of solar radiation falling on to the surface of the solar collector was measured using solar meter (solarimeter) in Watts per meter square. The Data was taken on hourly basis during the operation. The test was conducted for eighty (80) days and it commenced at 9:00am and ended at 17:00pm, daily. This gives a data of 640 points.

Plate 2: Experimental set-up of the Solar Water Heater

2.4 Performance Determination

The raw data collected in section 2.3 was analyzed to determine the performance of the system. The difference in the tank water temperatures between successive hours, the mass of water in the tank and the specific heat capacity of water were used to determine the amount of heat that has been collected during each hour using the following equation:

$$Q_{collected} = mc_p(T_b - T_a) \qquad (1)$$

Where;

$$m = mass\ of water = \rho v = (1000)(111 \times 10^{-3})kg$$

$$c_p = 4.182\, kJ/kgK$$

$$T_a = tank\ temperature\ at\ hour\ n = 32.8\text{°C} = 305.8\text{K}$$

$$T_b = tank\ temperature\ at\ hour\ n+1 = 34.6\text{°C} = 307.6K$$

$$Q_{collected} = 111 \times 4.182 \times (307.6 - 305.8)$$

$$\therefore Q = 827.6kJ$$

Energy input is the solar radiation intercepted by the collector area and is calculated using (Duffie and Beckman, 1991).:

$$Q_{sol} = I_{Av} \times A_c \times 3.6 \text{ kJ} \qquad (2)$$

Where

I_{Av} is the average hourly solar radiation measured at the location.

To get values per unit area that can be used, the energy input and the energy collected, these values were divided by the area of the collector to get the performance per unit area

Thus:

$$q_{collected} = \frac{Q_{collected}}{A_c} \qquad (3)$$

Where A_c is the area of the collector

$$q_{sol} = \frac{Q_{sol}}{A_c} \qquad (4)$$

The system efficiency can thus be determined hourly as:

$$\eta = \frac{q_{collected}}{q_{sol}}$$

2.5 Regression model

Using the eighty days hourly data collected and the subsequent determination of the hourly energy output of the system ($q_{collected}$), A linear regression model was developed by plotting the Energy Output of the system against the solar radiation values for each hour. The values were presented per unit area of collector. Similarly, the model for the system efficiency was also determined using the same approach. The model predicted values were compared with actual data collected to ascertain the accuracy and validate the regression model.

2.6 Annual System Performance

Solar radiation data was collected for a complete year from Nigerian Metrological Agency (NiMET), Kano State. This solar radiation data was used to predict the performance of the system using the model developed in the previous section for all the months of the year. The annual performance of the spiral-type solar collector system was then ascertained.

3. RESULT AND DISCUSSION

4.1 Performance of the system from experimental data

Figure 2 presents the plot of the energy collected calculated using equation 3 against the solar radiation received which was measured using a Solarimeter on site for the 80 days period of data collection. It will be observed that the energy collected increases as the amount of solar radiation increases. The relationship between the energy collected and the solar radiation has a linear trend with an R^2 value of 0.9 meaning that the linear relationship is very strong and thus using a linear correlation between the energy collected and the solar energy received is a valid proposition.

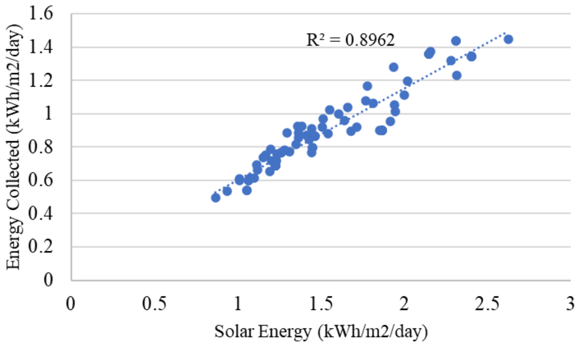

Figure 2: Relationship between energy collected and Solar Energy Received

Figure 3 presents the plot of the efficiency against the solar energy received. It will be observed that the efficiency varies between 50% to 70%. This is in line with what is obtainable in the literature for flat plate collectors. Also the efficiency does not increase or decrease as the Solar radiation increases (it is independent of the solar radiation). This is because the higher the solar radiation, the higher is going to be the energy collected and also the heat losses to the surrounding, since these heat losses depend on the temperature of the collector. From the figure it can be seen that the efficiency is somewhat independent on the solar energy received and thus it has a horizontal linear trend as the solar energy increases. This means a constant efficiency can be used for the prediction of the performance of a spiral type solar water heater at different solar radiation values.

Figure 4 presents the weekly Solar energy received, the energy collected and the collector efficiency for the 11 weeks (80 days) data collection period. The values are presented per unit area of the collector. The higher the solar radiation the higher the amount of energy collected with a maximum weekly energy collected of about 7.5 kWh/m^2 and a minimum of about 5.5 kWh/m^2.

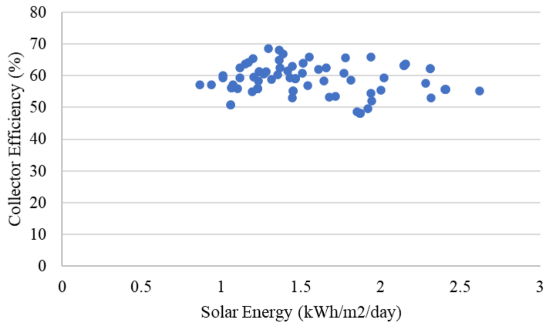

Figure 3: Relationship between solar energy and the collector efficiency

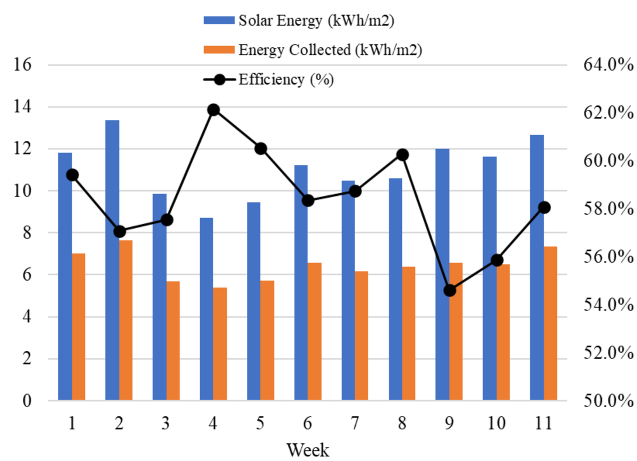

Figure 4: Weekly Performance of the Spiral Type Solar Collector

3.2 Regression Model

Figure 5 presents the hourly energy collected (calculated as shown in section 2.4) against the hourly solar energy received measured by using a solarimeter. Using the statistical tool in Microsoft excel, a linear regression trend line was developed as shown. The linear regression model with intercept of 0 representing the hourly relationship is:

$$q_{collected} = 0.5848(q_{sol})$$

This fitted model has an R^2 value of 0.9496, meaning that there is a very good correlation between the model and the data.

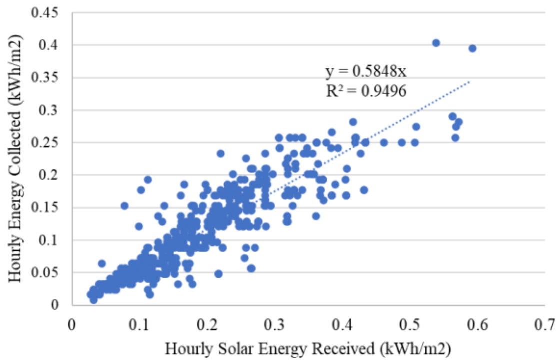

Figure 5: Plot of Hourly Energy Collected against the Solar Energy Received.

To validate and determine the accuracy of the regression model, Figure 6 presents the comparison of the weekly energy collected calculated using the model and the actual calculated energy collected. It will be seen that there is a good agreement between the model and actual results.

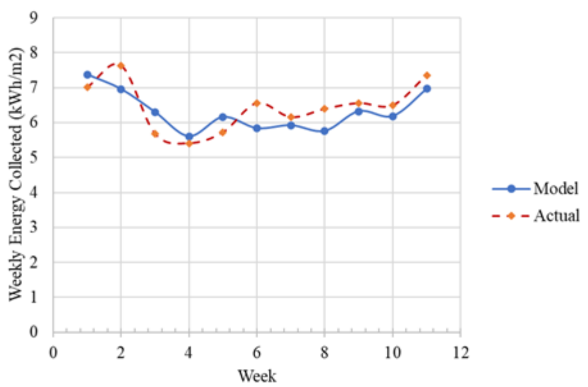

Figure 6: Comparison of Weekly Energy Collected computed using the Model and the actual experimental data

Table 1 presents the comparison of the weekly energy collected between the model and the actual experimental data with the weekly error and the error for the total eleven weeks. The maximum error in the model predicted weekly performance is 11% . But the difference between the total energy collected for the eleven weeks (80 days) between the model and the actual data is about 1.55 kWh/m2 which represent a difference of about 2.2%. This thus means that the model can be used for the prediction of the annual performance (cumulative performance) of the system with very high accuracy.

Table 1: Comparison of weekly Energy Collected between the model and actual data

Week	**Energy Collected ($Q_{collected}$), kWh/m^2**		**Error**	**% Error**
	Model	**Actual**		
1	7.38	7.01	0.37	5.3
2	6.96	7.63	-0.67	-8.8
3	6.30	5.68	0.62	11.0
4	5.61	5.41	0.20	3.7
5	6.16	5.72	0.44	7.7
6	5.84	6.56	-0.72	-10.9
7	5.92	6.15	-0.23	-3.8
8	5.76	6.39	-0.63	-9.9
9	6.32	6.55	-0.23	-3.5
10	6.19	6.49	-0.31	-4.7
11	6.96	7.36	-0.40	-5.4
Total	**69.40**	**70.95**	**-1.55**	**-2.2**

3.3 Annual Performance Prediction

Using the procedure described in section 2.6, Figure 7 presents the predicted annual performance of the spiral solar collector system per unit collector area for the twelve months of the year. The maximum energy collected is in the month of March with values of about 130 kWh/m^2. The total annual energy collected per unit area of the spiral type collector is 1.3MWh.

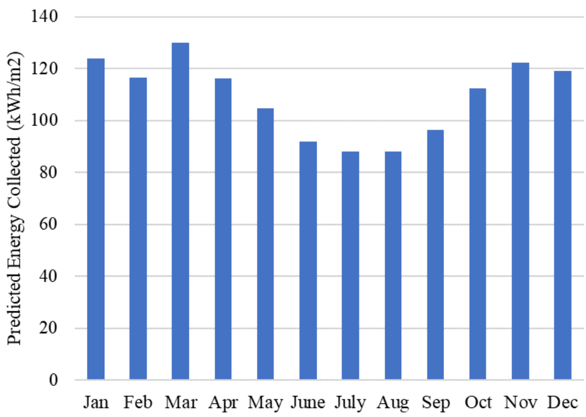

Figure 7–: Predicted Annual Performance of Spiral Type Solar Collector

5. CONCLUSION

An empirical model was developed using the performance data collected for a spiral type solar water heating system. This empirical model can be used to predict the annual performance of the solar water heating system using weather data obtained from metrological centres. The model was found to accurately predict the system performance with a maximum weekly error of 11% and a total error based on the 11 weeks of data collected of 1.55 kWh/m^2 corresponding to an error of 2.2%. It was also found out that the energy collected for a spiral type solar collector varies linearly with the solar radiation intercepted and the efficiency is independent on the solar radiation intercepted

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