Modeling and simulation of an active solar water heating system for Maiduguri, Borno State, Nigeria

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Abstract. The recent interests in renewable energy throughout the world has created a need for research in the area of solar technology, specially solar water heating system. A numerical experimental investigation was conducted to develop a model of an active solar water heating system to produce domestic hot water at 90°C using Typical meteorogical year (TMY 2) solar weather condition data of Maiduguri. The numerical experiment was used for simulation and TRNSYS 16 software was also used to determine the hourly thermal performance of the model. The main component of the TRNSYS deck file constructed for this purpose is Type 109, accompanied by other components require for the model. TMY 2 weather data of Maiduguri was processed to obtain the monthly average daily hot water for Maiduguri, and the recommended average day of each months were also used. The weather condition of the month of August was considered for the design. The result of simulation shows that an active solar system collector area of 2.04m² with inlet flow rate of 120kg/hour for hot water application, tilted at an angle of 12° to the horizontal would be capable of producing daily domestic hot water of 0.1m³ volume to the desired temperature of 90°C. The validation computed by using statistical tool of Nash-Sutcliffe Coefficient Efficiency (NSE) and Root Mean Square Error (RMSE) reveal the system ambient temperature and storage tank temperature of 1.60°C, 0.82 and 3.60°C, 0.96 respectively. For the experiment conducted, the model has capacity of predicting the performance of system with 82% and 96% degree of accuracy for that the experiment conducted. The early hours of each months as compared by the collectors showed that the serpentine solar collector has higher thermal performance than the riser-header flat plate collector but after 15:00 hours, Riser-header solar collector performance is better. This means that that riser-header solar collector has higher performance better than serpentine solar collector.

1. Introduction
The sun which radiates heat and light produces solar energy and it is in exhaustible storehouse of the earth; the supply will never run short [1]. The earth receives a fraction of power emitted (solar radiation) by sun of about 174 x 10kW of inward solar radiation of the upper layer of atmosphere. It has proven that approximately 0.3 (30%) is reflected back to terrestrial while the rest is absorbed by atmosphere mists, lands then oceans [2], [3] reported that it is an important, clean, cheap and abundantly available renewable energy and further, solar energy is known as an ancient clean source and it is the fundamental ingredient of almost all conventional fuel and renewable energy on earth.
In the reported of [2] solar energy system has been use to generate both electricity and hot water for domestic across the world whereas many people and corporate bodies did not aware of the benefits of this environmental friendly of solar technologies while those who aware are discourage because of its high cost accessories. According to [4] Nigeria blessed with abundant energy resources in both renewable and non-renewable source and further, stated that is one of the top countries in the world that has high solar energy potential because her potential fall between 3.5 to 7.0 kWh/m²/day [5]. According to [6] Northern states of Nigeria have 5.67 to 6.12 kWh/m²/day of direct normal radiation which is higher than the recommended value demanded for concentrating solar power technologies. There are various researches on the solar water heating system performance and their result has been published by several papers.

A study by [7] reported that solar water heating system is a new technology to harness free existing solar thermal energy at a particular location in the world. Further stated that it must be designed to meet energy required and its size must also depend on weather condition of that location. [8] stated that usage of solar energy for thermal application varies from one zone to another throughout the world and further, accounted on that, energy evaluation, solar collector’s configuration and designed system equipped for solar water heating system must be different from one climate region to another. [9] studied the active solar water heating systems with flat plate and heat pipe evacuated tube collectors and used TRNSYS simulation software to validate their results in Dublin(Ireland). Their results shown that, their model predicted outlet fluid temperature of collector with percentage mean absolute error (PMAE) of 16.9% for flat plate collector (FPC) and 18.4% for evacuated tube collector (ETC) and concluded that the model is underestimated in FPC and overestimated in ETC. Thermal execution of solar water in a balcony was conducted by [10] in Lianyungang city (China). Their system using the flat plate collector which is titled at 70° to test and analysis solar heat gain of the system and the heat loss coefficient of the storage tank under the city weather condition. They found out that global radiation inclination, heat gain, and average daily efficiency affected solar water heating system.

Investigated on solar potential and feasibility of solar water heating system for single residential in Inland Norway by using two types of collectors; tubular and glazed flat plates of the same size, their results shown that tubular collector supplied 62% of annual hot water demanded while glazed flat collector supply 48% demand annually [11]. Energy and energy analysis of forced circulation solar water heating system was presented in order to obtain alternative efficient solar energy utilization by introduced integrated heat pipes. Flat plate collector as a mean of heat extractions device. The authors used MATLAB to perform the numerical experiment using coldest month temperature of the year (9.56°C) in Fez (Morocco) to access overall performance efficiency under worst weather condition. They concluded that the simulation results had better agreement with experimental values [12]. The experiment on comparative study for thermal performance of straight and serpentine tube solar water heater in 3 months (March, April and May) was carried out using K types thermocouple at appropriate location by [13], they found out that May has the highest atmospheric temperature with 49°C of system and concluded that serpentine tube designer need to improve on the efficiency of Serpentine time in order to obtain better optimization.

Energy usage in building to generate domestic hot water for a single-family apartement remained unchanged reported by [14]. Their main objective was to introduce a high-resolution measuring technique for domestic heat water demand and its usage. Their result shown that the period of draw hot water varies significantly in tapping areas (shower and kitchen). [15] conducted thermal evaluation of solar water desalination using evacuated tubes collectors. The system consisted water storage of 60litres capacity, ten evacuated tubes collectors which design and fabricated at department of unconventional energy source and electrical engineering, Akola, India. Their finding revealed that evaporative heat transfer coefficient of the system was better than radioactive and convective heat transfer coefficient. [16] reviewed the stage of solar energy application by focus on the solar water heating system. In their report they mentioned two types of solar water heating system: passive and active and basic components for solar water system such as solar collectors, storage tank and heat
transfer fluid (water/air). They concluded that among all collectors’ parabolic dish reflector (PDR) revealed the overall performance in terms of optical optimization.

Authors of [3] explained that TRNSYS is a transient system simulation tool used to solve algebraic equation. It is also having library with components types to models energy system and feasible enough for user to add components. Several studies had been used TRNSYS to evaluate the effect of different design parameters and operating conditions on the performance of thermosiphon/active solar water heating system [17]. TRNSYS is an energetic simulation program for energy system which is well recognized globally for the simulation of solar water heating system in the most field worldwide such as teaching, research and applied engineering [18]. The TRNSYS simulation software has been used to analyzed dynamic behavior of the system [3]. [19] reviewed on domestic hot water in buildings and mentioned some of modeling tools used to generate domestic heat water system and stated that TRNSYS is one of them.

Optimal designed of a forced circulation solar water heating system for cold climate in Montreal, Canada [20]. The weather and meteorological data was obtained from typical meteorological year (TMY 2) data bank of TRNSYS and the model was built in TRNSYS environment. They found that their model can provide 83-98% of the hot water demand (may to September) and 30-68% of the demand would be for October to February. Simulation and economic analysis for solar heating was conducted for several residences (parquet Goya) in Zaragoza, Spain using TRNSYS software to develop model with seasonal storage tank in different climate areas. The climate data for the Zaragoza were obtained from energy plus. Their result was compared with experimental available in Europe and showed that models have good agreement with exist one available [21]. [22] did the comparative analysis of retrofitting domestic hot water for a single-family house in Swedish. The authors used TRNSYS Software to determine the performance of four different systems configuration have highest annual performance which made the retrofitted system archived 50.5% of annual solar fraction. [18] worked a simple procedure to size active solar heating by setup the experiment in Badajouz in SW Spain (European Union) and also obtained the climate data from CLIMWAT database. The experimental result was validated with four worldwide accepted software (ISOFOTON, CENSOLAR, F-CHART and TRNSYS) and concluded that their results are similar in all the cases therefore; the program can be applied in any part in the world. [23] presented integrated solar water heating system used in industrial process heat in three different climate conditions (Jemixco, Morelos, and Mexico) was carried out and validated with experimental data. The experiment set-up contained evacuated tube collectors (18), thermal storage tank (700litres), auxiliary heating backup (10kW) and plate heat exchanger coupled chiller (25kW). They use TRNSYS types to develop model and validated their result through statistical measure of means deviation. Their conclusion revealed that the numerical result is in a good agreement with experimental data (predicted wall) for different working and weather conditions.[24] conducted modeling and Assessment of solar process heat systems in India using TRNYSY Software to simulate and monitor the system by comparing the result on the basis of energy yield and efficiencies with a mean deviation index. [25] presented performance of solar water heater in Akure (Nigeria) by designing and constructed thermosiphon and tested for 6 days in the same town. The author obtained 73°C hot water temperature at 2.00pm and concluded that solar water heating system is feasible throughout Nigeria and most part of tropical Africa because their solar weather conditions is similar. This paper evaluates the thermal of the two different solar collector systems: Serpentine Flat Plate (SFP) and Riser Flat Plate (RFP) for domestic solar water heating system under Maiduguri, Borno State, Nigeria and TRNSYS 16 software is used for simulation of model and other components of models.

2. Materials and methods

2.1. Study Area

The study area covers semi-arid in Nigeria with continental climate that has long hours of sunshine’s duration which utilized to generate solar energy for energy consumption [26, 27]. Maiduguri is a city
in Nigeria which is located between Latitude (11°51’ - 11°55’) N and Longitude (13°02’ - 13°16’) E. It has an area of 61,435km² with an average elevation of 345m above sea level [28]. According to [29] the semi-arid had climate with three types of seasons: cool-dry season, hot season and rainy season which are experience in October to March, April to June and July to September respectively. In the study of [30], the arid region of northern Nigeria received not less than 9 hours of sunlight on a daily basis and therefore experience high solar radiation intensity which makes Maiduguri to receives 6.176kW/m²/day of global irradiation.

2.2. Component Collection

The solar water heating systems mainly comprise of hot water storage tank, pumps, load profile, flat plate collectors (serpentine and riser-header) and others. TRNSYS-16 was used to model the system. TRNSYS is a transient systems simulation program which can be used to model thermal energy systems with detailed mathematical and behavioral analyses. The TRNSYS system modeled was shown in figure 2. The system main components had two flat plate collectors, two pumps, two storage tanks, load profile and printers.

![Figure 1. TRNSYS system model of serpentine and riser-header flat plate collectors.](image)

This system is considered under the real weather conditions of Maiduguri. The model components are selected from TRNSYS library and linked to each other. The input to the model is TMY 2 weather data of Maiduguri was generated by type 109. The TMY 2 files included solar radiation and meteorological information for an area. In addition, in design of a water heating system, the most important parameter to be considered over a certain period of time (hourly, daily or monthly). Type 14h is the load profile shows this item which other input of model depend on. The outputs of model are online plotter in Type 65a for read the results. Other components modeling is discussed in the following subsections.

2.2.1 Solar collector. Type 564 and Type 565 are selected for riser/header and serpentine flat plate collector respectively from solar TRNSYS library list. There components are able to model the thermal performance of solar collector. A larger number of collectors are required to generate hot water heating demand in both commercial and industrial systems. Therefore, two collectors are considered in series form. Some technical parameter was collected from catalogue and access data as the input into the collectors.
2.2.2 Storage tank. Solar energy is an energy that depends on time. Therefore, solar collected is usually carried circulating fluid directly to the thermal energy storage tank which it possible to be used at night or cloudy days [31]. The stratified storage tank, Type 4 is selected from TRNSYS component libraries in this study.

2.2.3 Pump. The use of the pump is to circulate the working fluid into the solar collectors. Type 3 is considered from hydronic list for system pump (single speed) modeling. The pump operation is according to the temperature to heat source in storage tank outlet and outlet temperature of the collectors. The pumps also circulates the working fluid at a rate of 60kg/hr, the actual flow rate was output by the component and was determined by the control signal and the maximum flow rate set in the parameters of the display menu. The outputs comprised: the outlet fluid temperature, outlet flow rate and power consumption [17].

2.2.4 Time dependent forcing function. The Type 14 water draw forcing function was used in the model to specify the draw profile that was applied to the system. This component generated a time dependent forcing function that was created by a set of discrete data points specifying the value of the function at various times throughout an period. These data points were specified by the user in the parameters of Type14 and the cycle that was created repeated throughout the entire simulation period.

2.2.5 Online graphical plotter. The online graphical plotter, Type 65 was used to show designated system variables while the simulation was developing [17]. It was a very useful tool because it provided instantaneous graphical results that permitted the user to determine if the system was performing as expected.

2.2.6 Printer. The Type 25 printer was another useful tool for analyzing the simulation results. This component was used to output selected system variables at every time step to an Excel file that could be opened for analysis after the simulation was completed. Type 25 was the main type used for extracting the detailed simulation results of the system.

2.3 System performance simulation

The annual performance of the system was predicted using model formulated by TRNSYS 16 software. To predict the annual system performance, the monthly average daily thermal performance of the system was simulated based on the recommended average day of each month from January to December as stipulated by [32]. To predicted each month thermal performance, simulation start and stop time was set using the control card of the simulation studio, as recommended average day of each month for simulation of the prediction of SWHS [32].

3. Results and discussion

3.1 Comparison between the thermal performance of serpentine and riser solar collector system

Figure 2 to figure 4 show the comparison between the monthly average daily storage tank temperatures of riser header and serpentine flat plate solar systems for the months of January, April and August.
Figure 2. Comparison of Monthly average daily storage tank temperature between Riser-header flat plate and Serpentine flat plate system for the month of January 2017.

Figure 3. Comparison of Monthly average daily storage tank temperature between Riser-header flat plat and Serpentine flat plat system for the month of April 2017.

Figure 4. Comparison of Monthly average daily storage tank temperature between Riser-header flat plate and Serpentine flat plate system for the month of August 2017.
3.2 Validation of the model

3.2.1 Model validation with measured values. A model of solar water heating system produced in TRNSYS 16 had been validated with [33] measured values. In order to validate the model, the system behavior and performance analysis result of the model are compared with that of the measured data. Two statistical tools namely: The Roots Mean Square Error (RMSE) and the Nash-Sutcliffe coefficient of efficiency (NSE) shown in equation 1 and 2 are used to validate the model result and measured data.

The Root Mean Square Error (RMSE) = \( \left( \frac{\sum_{i=1}^{n}(T_{\text{sim}}-T_{\text{exp}})^2}{n} \right)^{\frac{1}{2}} \) (1)

Nash-Sutcliffe coefficient of efficiency (NSE) = \( 1 - \frac{\sum_{i=1}^{n}(T_{\text{sim}}-T_{\text{exp}})^2}{\sum_{i=1}^{n}(T_{\text{exp}}-T_{\text{exp}})^2} \) (2)

3.2.2 Validation result. The comparison of the behavior and the performance between the model result and experimental data had been carried out in the following:

3.2.3 System ambient temperature. The ambient temperature was used to evaluate the model experimental data. The result (Figure 5) shows RMSE value of 1.6°C and an NSE value of 0.82 between the model and the measured values. The value of RMSE means that the error between the measured ambient temperature and the model ambient temperature is 1.6°C. Where, Tecit and Tscit is experimental and simulation ambient temperature respectively.

![Figure 5. Validation of ambient temperature System.](image)

3.2.4 System storage tank temperature validation. To further, predict the developed model. The predicted storage tank temperature of the model and measured data is also compare (Figure 6). The results of RMSE and NSE values of 3.6°C and 0.96 respectively. The result also support [34] which indicates high predictive power of the model as a result of low RMSE value and NSE value trying to approach 1 with the positive value. Where, Tsst and Tesst is experimental and simulation storage tank temperature respectively.
4. Conclusion and recommendation

4.1 Conclusion

Active solar water heating system that capable the supply hot water at temperature of 90°C and volume of water of 0.1m³ for single family in Maiduguri has been successful modeled and simulated. TMY solar data of Maiduguri was processed to obtained the monthly average daily solar radiation of Maiduguri used the recommended average day of the months. The results of this research led to the following conclusions:

The prediction of solar thermal performance collectors showed that collectors water outlet temperature increases from morning (8:00 hours) and reaches its peak temperature between 15:00 hours to 16:00hours for the most part of the year. The figures also revealed that temperature of slightly above 90°C was achieved in most part of year. The temperature start dropping after reaching its maximum value of the day. However, the month of June, July and August showed the lower performance of the system but month of August was recorded as the worst performance. This signifies that it is the month with the highest rainfall within the rainy season.

The monthly average daily thermal performance of riser-header and serpentine flat plate solar collector system was compared, findings shows that during the easily hours of each months from 8:00hours to 13:00hours daily, the serpentine solar collector has higher thermal performance while compared with riser-header flat plate collector but at the long run, beyond 13:00hours the performance of the riser header solar collector is seen to be better. The figures reveal that the riser-header collector has higher performance than the serpentine solar collector.

4.2 Recommendation

Following areas are recommended for further investigation on the thermal modelling and simulation of SWH systems:

(i) In this paper, the weather data of Maiduguri was considered. One can take challenges to look at the behaviors of system at various locations across the north-east. It will not only boost the confidence in the thermal model developed but also help in understanding the complete picture of a retrofit option implementation in the North-East Nigeria.

(ii) The simulation of hot water demand profile was carried out on an hourly basis. However, an instantaneous demand profile should be next step of getting the better performance of the system. It will help in understanding the realistic behaviors (control) of the system.

(iii) In analysis, the two-storage water is considered for analysis purpose with 100liter (0.1m³) capacity of hot water storage tank. Storage tank with higher capacity such as 200 or 300 litres should be experimented.
Acknowledgments
Authors want to acknowledge financial support from Republic of Nigeria (TETFUND) and Federal Polytechnic Mubi. Adamawa State, Nigeria.

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