

Modelling and simulation of an active solar flat plate collector water heater

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Abstract:

The research predicts the weekly performance of an active solar water heating system in the months of June to October under the weather condition of Mubi, Nigeria latitude 10. 26° and altitude 582 m using TRNSYS 16 software. The simulated system consists of an embedded flat plate solar collector (having surface area of 2.10 m² tilted at 10.26° from horizontal). 100 litres thermally insulated vertical storage tank, 20-Watt solar panel and 4.8-Watt solar direct current (DC) pumps (discharging at 240 litres/hr at a maximum head of 3 m). The daily and monthly average weather data from the system were simulated. TRNSYS components (TYPE 109) which represent each physical components of the real system were selected from the components library in the simulation studio. These components were then linked in such a manner that represents how the system works. The parameters describing each component (TYPE 109) of the system was modified according to the system characteristics. The results of the simulation revealed that, the system was capable of meeting the desired daily hot water requirement of 68°C, 67.5°C 53°C, 62.1°C, and 65.2°C for the months of June to October respectively at averagely 15 hours of the day. This indicated that the active solar flat plate water heater with area of 2.10 m² adopted tilted at an angle of 10.26 ° to the horizontal would be capable of producing daily domestic hot water of 100 litres for most part of the months except the month of August where the tank temperature dropped to 53.5 °C, auxiliary energy might be provided in this month. This indicates that the system would be required to supplement the hot water requirements for industries, hospitals and community – based organization.

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1. Introduction

In recent years a number of international, national and local institutions, Non-Governmental Organizations (NGOs) and private companies are now deploying renewable energy systems to rural communities in the developing world where health care in rural areas is a national priority [1, 2, 3]. Expanded programme on immunization of the World Health Organization (WHO/EPI) has played a leading role in evaluating the possibility of using various types of energy sources for the vaccines cold chain, electricity and hot water demand. Rapidly it became obvious that solar energy was a technology that would play a critical role in ensuring good quality electricity, safe vaccines and hot water demand in remote health centres [4].

In developing countries like Nigeria, there is even more urgent need for the adoption of solar water heating. This is not only because many of these countries do not have the natural reserves of conventional fuel but as a result of the fact that the bulk proportion of the population of these countries live in the rural areas where conventional electricity grids have not been extended. In

such circumstances, the hot water requirements for example in rural health centres and cottage industries could readily be met only by solar water heaters [5, 6]. At the moment water heating in Nigeria is done using the conventional electric supply, gas, and fuel wood, these however, have not left the nation without their attended adverse health, economic and environmental impacts. Generally, solar water heating systems have not been widely adopted in the country as is the case in some other developed and developing nations. Variable factors, such as; purchasing power, technology of installation and fabrications, awareness, culture, governmental policy and politics has been identified for the slow pace of solar energy utilization in Nigeria.

Flat plate collector is one of the most important components of solar water heater. Flat-plate collectors are the simplest and most commonly used collectors for converting the sun's radiation into useful heat. They are designed for applications requiring energy delivery at moderate temperature (less than 100°C) as in water space heating [7]. They have the advantages of using both beam and diffuse solar radiation, not requiring sun tracking and have little maintenance [8, 9]. One of the most spectacular

developments in solar water heaters is the way in which Scandinavian countries have manage to produce some of the most efficient solar collector systems in the world. Even though they receive little sunlight, their large solar water heating plants are in some cases substitutes for conventional energy sources in other cases they are supplemented [10, 11]. The environmental impact of the production of energy from fossil fuels is the emission of carbon dioxide (CO₂), carbon monoxide (CO), sulphur oxide (SO₂) and other harmful gases and products. The most important implications are related to change in global climate, acid rains and increased land and water requirements. A well-known CO₂ is of primary concern as a major component of greenhouse and human health effect [12].

New installation declined when the availability of natural gas provided a means of heating domestic water at lower cost. Oil shock rekindled worldwide interest in solar energy technologies. The most widely known and understood method of converting solar energy into heat is by the use of flat plate collector for heating water, air or other fluid. Many different types of collectors have been built and tested by independent investigators in the last seventy years; tests were carried out in specific location with wide variations in test procedures and in the availability of solar radiation. The main objectives of these tests have been to convert as much solar radiation as possible into heat, at the highest attainable temperature [13]. The major British research in this field was carried out by Heywood [14], commencing with experimental work in 1947 on the characteristics of flat plate collectors. His earliest experiments were carried out on small square collectors, 0.093m² in area using water as the heat transfer fluid. The somewhat simplified theoretical treatment which he established at that time is still used as the basis for some of the current design work on domestic flat plate collectors. After 1950's water heater designs using flat plate collectors were greatly improved in Israel, Australia and Japan by incorporating better thermal contact between the black metal plate and the tubing through which water circulates as well as by the development of black surfaces that provided greater net energy recovery from the sun. Commercial firms in Israel began manufacturing and marketing solar water heaters for local and foreign use, sales have been in the range of 10,000 – 15000 units per year. At present about 20% of the households in Israel have solar water heaters [15, 16]. In Australia, solar water heaters were further improved by development studies in the 1950s and by early 1960s several manufacturers went into production, the Commonwealth Scientific and Industrial Research Organization (CSIRO), subsequently published a guide to the principles of the designed construction and installation of solar water heaters [17].

As mentioned earlier, the need for hot water in education, healthcare, domestic and other sectors of the Nigerian economy are high and are met through the use of electricity, kerosene, and wood as the major energy sources. Electricity generation in the country is dependent on stations powered by natural gas and water driven turbines. Irregular supply of natural gas, the fluctuation of water levels in hydropower sites and obsolete equipment in

electric utility network are factors which contribute to the epileptic supply of electricity in the country [18]. Thus, electricity is not readily available particularly in the rural communities which have a share of about 70% of the country's population [19]. As such the rural dwellers therefore resort to fuel-wood for water heating and other energy requirements [20]. Higher cost associated with production is yet another factor that hampers successful utilization of these systems that is why the increasing attention given to this area of studies is quite justifiable. The need to embrace a cost-effective and sustainable alternative to our depleting conventional energy sources has become imperative and should not be taken for granted. Preliminary research work must be undertaken to prove this beyond any reasonable doubt. This study therefore proposed a novel solar water heating configuration that uses three in-line fluid passages for hot water demand.

2. Materials and Methods

Material and equipment use in the study include an embedded flat plate solar collector (having surface area of 2.10 m² tilted at 10.26° from horizontal). 100 litres thermally insulated vertical storage tank of, 20-Watt solar panel and 4.8-Watt brushless solar DC pumps discharging at 240 litres/hr at a maximum head of 3 m. The following methodology were adopted for the modelling and simulation of the system.

2.1 Determination of the Design Month

The design month is defined as the month with the least value of the energy ratio (ER). The energy ratio (ER) is the ratio of monthly average daily solar radiation on the collector surface to the monthly daily solar system load expressed in equation 1:

$$E_R = \frac{H_T}{Q_s/D_{load}} \quad (1)$$

Where; H_T is the monthly average daily solar radiation on the tilted collector surface (kJ/m²) and Q_s/D_{load} is the monthly average daily load (kJ/day)

2.2 Methodology for collector sizing

The sensible heat consideration in system design was calculated as the heat required for increasing the temperature to meet the desired load temperature. For instance, if the rate of hot water demand is \dot{m}_L , in kg/hr then the heat Q_s required per day to increase the mains water temperature (T_{mains}) to the desired Load Temperature (T_L) is expressed in equation 2 [21].

$$Q_s = \int_1^{24} \dot{m}_L C_p (T_L - T_{mains}) dt \quad (2)$$

Losses from the storage tanks may be significant and should be considered part of the total system load. The rate of tank losses (Q_{stL}) is estimated using the tank loss coefficient-area product (UA)_{st} (mostly specified in the manufactures datasheet and the temperature difference between the tank water temperature T_{st} and the ambient temperature T_a surrounding the tank. Similarly, the total loss per day is calculated using equation 3 [22].

$$Q_{stL} = \int_1^{24} (UA)_{st} (T_{st} - T_a) dt \quad (3)$$

For good performance, the solar collector must be sized to meet both the sensible heat requirement and the tank loss which is expressed by equation 4;

$$Q_L = Q_s + Q_{stL} \quad (4)$$

The heat needed to raise the temperature of water required at a flow rate (\dot{m}) in kg/hr of the supply mains temperature (T_{mains}) was calculated using equations 5 to 7 respectively.

$$Q_l = \int_1^{24} \dot{m} C_p (T_l - T_{main}) dt + Q_{stL} \quad (5)$$

$$Q_p = \int_1^{24} \dot{m} C_p (T_p - T_{main}) dt + Q_{stp} \quad (6)$$

$$Q_s = \int_1^{24} \dot{m} C_p (T_s - T_{main}) dt + Q_{sts} \quad (7)$$

Where; C_p is the specific heat capacity of water in kJ/kg.K, Q_l , Q_p , and Q_s are the average daily thermal energy demand obtained by integrating the hourly hot water demands. T_l , T_p and T_s are the desired hot water temperature. The second term in equations 5 to 7 represents the tank losses of the hot water storage tank.

Furthermore, from each application's daily thermal energy requirement values, the collector area requirement is approximated for each application based on equations 8 to 10. A_l , A_p and A_s are the desired collector areas

$$A_l = \frac{Q_l}{LF \times \int_1^{24} I_T dt} \quad (8)$$

$$A_p = \frac{Q_p}{LF \times \int_1^{24} I_T dt} \quad (9)$$

$$A_s = \frac{Q_s}{LF \times \int_1^{24} I_T dt} \quad (10)$$

Where; LF (= 0.56) is the hourly utilisability factor of the hourly available irradiance (I_T) obtained from the study location's solar radiation analysis based on formulations, as suggested by Duffie and Beckman, [23]. The size of collector area was estimated based on equations 8 to 10 which determines the length of water passages' tubing.

2.3 System Performance measurement and analysis

The monthly average hourly performance of the system for the recommended average days for the months was numerically simulated based on typical meteorological year (TMY) weather data for the said location. In solar systems design, the weather conditions strongly influence the size of the system. However, the weather condition of any place is highly random and unpredictable. Therefore, proper sizing of the solar system is a complicated and tricky task [24]. The numerical simulation using TRNSYS is an approach used to evaluate the solar system's long term (annual) performance based on the preliminary design parameters [25]. With this approach, it is possible to visualise the hourly and even daily performance throughout the year. Therefore, it will be possible to adjust design parameters until a reliable performance is reached. To predict the thermal characteristic in a steady-state of the

flat plate collector, the Hottel-Whillier-Bliss (HWB) mathematical models and energy balance equations expressed in equation 11 models the collector component. The rate of useful energy gain of the solar collection (\dot{Q}_u) at a given moment is the positive difference between the energy absorbed by the plate and the energy lost by the collector to the environment as described by equation 11 [25].

$$\dot{Q}_u = F_R [S - U_L (T_i - T_a)]^+ \quad (11)$$

Where F_R , S , U_L , T_i and T_a are the energy absorbed by the absorber plate, the collector overall heat loss coefficient, circulating fluid collector inlet temperature and the temperature of the surrounding where the collector is placed respectively. The plus superscript indicates that only positive values of the square bracket terms were used. The Hottel-Whillier equation defines the efficiency of a solar collector (η_{coll}) under a steady radiant energy per unit area (I_T) falling on the collector surface with fluid flowing at a steady fluid flow rate, and constant wind speed and ambient temperature, as expressed in equation 12 [26].

$$\eta_{coll} = \frac{Q_u}{I_T A_c} \quad (12)$$

The collector efficiency is also calculated as the ratio of the total useful energy from the collector to the total solar radiation ($I_T A_c$) received on the collector surface using equation 13.

$$\eta_{coll} = \frac{Q_{u1} + Q_{u2} + Q_{u3}}{I_T A_c} \quad (13)$$

Where: Q_{u1} , Q_{u2} and Q_{u3} are the useful energy of the proposed collector from outlet 1, 2 and 3 respectively and A_c is the total collector area.

To evaluate the overall system performance, the solar fraction SF is a better performance indicator than the collector efficiency and heat removal factor. It assesses the entire system's overall efficiency rather than a component. Beausoleil-Morrison, *et al.* [27] expressed solar fraction (SF) as the fraction of the actual hot water demand met by the solar system to the total system load as in equation 14.

$$SF = \frac{\text{Actual load met by solar system}}{\text{Total system load}} = 1 - \frac{Q_{Aux}}{Q_L} \quad (14)$$

Where, Q_{Aux} is the energy supplemented by another system component to provide for the shortfall needed to meet design load completely. This energy could include supplementary thermal energy by electric or gas boiler. The average daily auxiliary energy is found from the positive value of equation 15. When equation 15 results in negative value during the simulation, the negative values are taken as the system's excess thermal energy.

$$Q_{aux} = \left[\int_1^{24} \dot{m}_L C_p (T_L - T_{mains}) dt - \int_1^{24} \dot{m}_L C_p (T_d - T_{mains}) dt \right]^+ \quad (15)$$

T_d and T_{mains} are the hot water temperatures delivered by the system and the mains water temperature. Another performance indicator that does not consider whether the collector's energy matches demand is system efficiency. Using this evaluator gives an idea of how well

the system converts the total incident energy to hot water without concern for its usefulness. The system efficiency is defined as the ratio of the heat that changes the mains water temperature (T_{mains}) to the temperature at which water is delivered (T_{LDT}) by the system load to the total energy received on the collector surface ($H_T A_c$) as expressed in equation 16 [28].

$$\eta_s = \frac{\dot{m}_L C_p (T_{LDT} - T_{mains})}{H_T A_c} \quad (16)$$

3. Results and Discussion.

Figures 1 to 5 show the weekly average daily system simulated performance of the system for the months of June to October, 2022. The weekly/monthly average hourly performance of the system for the recommended average days for the months was numerically simulated using equations 1 to 16 based on typical meteorological year (TMY) weather data for the said location as presented in the Figures (i.e., Figures 1 to 5)

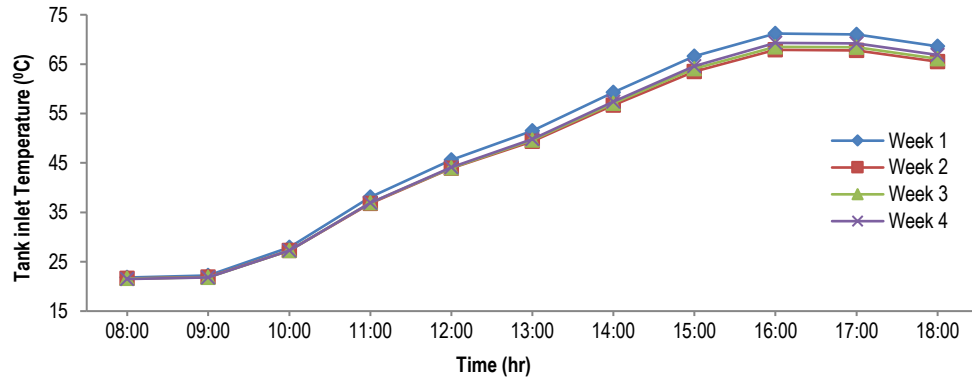


Figure 1: Weekly average daily simulated system performance for June, 2022

Figure 1 shows weekly average daily simulated system performance in weeks 1, 2, 3, and 4 in June, 2022. The Figure shows an increase in the performance of the system. The system performed better in week 1 followed by the rest of the weeks. The performances of the system in the four weeks were closed. The system performances

in all the weeks attain the peak temperatures at about 16 to 17 hours of the day as can be seen in Figure 1. This implies that, the solar system is capable of meeting the desired hot water temperature or energy need in the four weeks of the month.

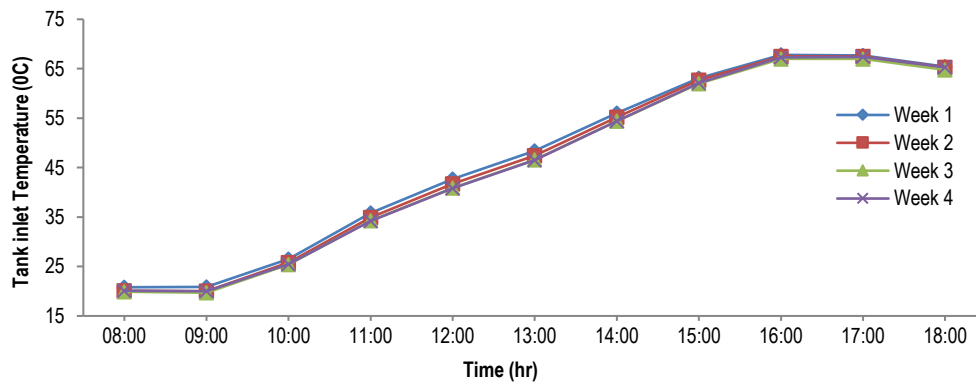


Figure 2: Weekly average daily simulated system performance for July, 2022

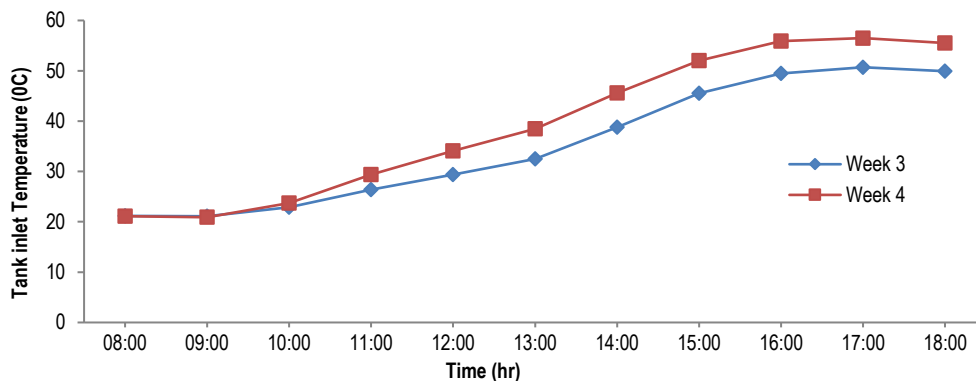


Figure 3: Weekly average daily simulated system performance for August, 2022

Figure 2 demonstrates weekly average daily simulated system performance in weeks 1, 2, 3, and 4 in July, 2022. The performances in the four weeks show a much-closed performance or behaviour and attained a peak temperature at about 16 to 17 hours of the day with a temperature of 71.8 °C for week 1, weeks 2 and 4 at

70.5 °C and week 3 at 69.9 °C as can be seen in the Figure. This implies that, the solar system is capable of meeting the energy need in the four weeks of this month as can also be seen in Figure 2. Also, the slight variation in those weeks of the month is attributed to the differences in solar and weather experienced in those weeks.

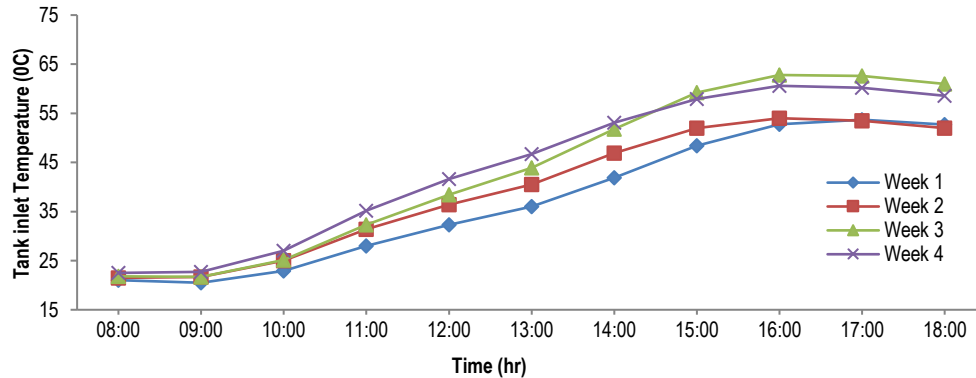


Figure 4: Weekly average daily simulated system performance for September, 2022

Figure 3 depicts weekly average daily simulated system performance for weeks 3 and 4 in August, 2022. The Figure revealed that, the system performance in week 4 was better than the system performance in week 3. The temperature builds up increases steadily from morning hours of 8:00 am until it reached a temperature of 54.9 °C at about 16 hours of the day and declined to late hours of the day (18 hours). The system performance in week 3 also reached a maximum temperature of 48.1 °C at about 16 hours of the day. It can be seen also from Figure 3 that, both the performance in weeks 3 and 4, was low. This indicated a drop in performance of the system. The poor performance of the system in those weeks was attributed to the poor amount of solar radiation received on the surface of the collector in this month. Highest values of solar radiation, relative humidity, ambient temperature, and wind velocity recorded in this month were 769.8 W/m², 84.1 %, 29.5 °C and 2.9 m/s at about 14 hours, 8 hours, 13 hours, and 10 hours of the day respectively. The solar and weather data recorded in the weeks/month were lower than the values recorded in the rest of the months. To meet up with the hot water or energy need in this month (August) auxiliary energy must be provided.

Figure 4 presents weekly average daily simulated system performance in weeks 1, 2, 3, and 4 in September, 2022. The Figure revealed that, the system performed

better in week 4, followed by the performance in week 3, then week 2 and week 1. The temperatures build up increases steadily from morning hours of 8:00am to 16 hours of the day and decreases to late hours (18 hours) of the day. Weeks 1 and 2 the system performance was low with highest temperature attain as 53.7 °C and 54.2 °C for weeks 1 and 2 respectively at about 15 to 16 hours of the day. The variations in performance of the system in those weeks were attributed to the difference in average solar radiation received, ambient temperature, wind velocity, and relative humidity. Highest values of solar radiation, relative humidity, ambient temperature, and wind velocity recorded in this month were 860 W/m², 84.6 %, 30.5 °C and 2.4 m/s at about 13 hours, 8 hours, 13 hours, and 9, 10 hours of the day respectively. This shows that, the solar and weather data in this month were a bit higher than the values obtained in the month of August. 860 W/m² in this month, and in August was 769.8 W/m², ambient temperature of 30.5 °C in this month, and in August 29.5 °C. This shows an improvement in the solar and weather data in this month, which lead to the improvement in system performance in this month (September) than in the month of August. To meet up with hot water need in weeks 1 and 2 of this month an auxiliary energy will be provided.

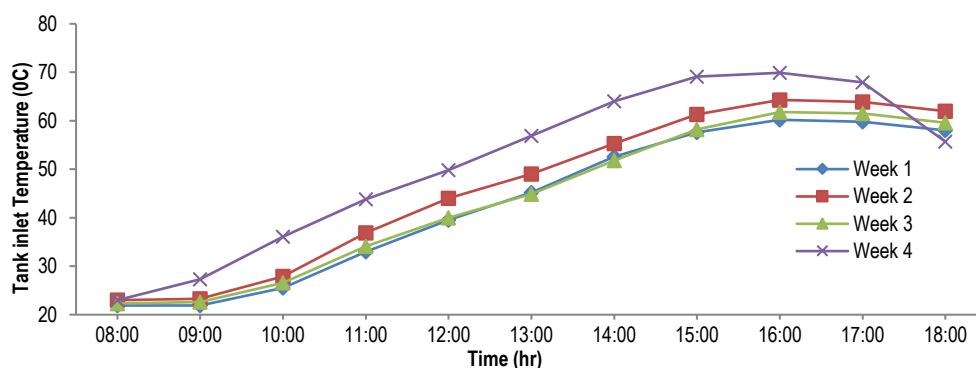


Figure 5: Weekly average daily simulated system performance for October, 2022

Figure 5 shows weekly average daily simulated system performance in weeks 1, 2, 3, and 4 in October, 2022. From the Figure, the system performed better in week 4, then performance in week 2, followed by performance in weeks 1 and 3. The Figure also showed an increase in performance of the system, which attain peak temperatures at about 13 to 16 hours of the day, as can be seen in the Figure. Also, the slight variations in the performance of the system in those weeks of the month was attributed to the differences or variations of solar radiation received, ambient temperature, wind velocity, and relative humidity. Highest values of solar radiation, relative humidity, ambient temperature, and wind velocity were 940.6 W/m², 70.2 %, 35.5 °C and 2.9 m/s at about 12 hours, 8 hours, 13 hours, and 9 hours of the day respectively. This shows an improvement in solar and weather data in this month. The values of solar radiation, ambient temperature of 940.6 W/m², and 35.5 °C respectively were higher than those obtained in August and September, which leads to the improvement in system performance in this month, since the performance of the system also depends on solar and weather data. This month is also approaching dry season.

All those findings in the Figures 1 to 5 are in line with the works of Kumar and Bhupendra [29], Sharma and Joshi [30], Rajakrishnamoorthy *et al.* [31], Zwalnan [32] and Jayakanth *et al.* [33], obtained water temperature up to 72.3°C in hot season and 41.8°C in wet season in Rajasthan. Similar results for solar radiation, relative humidity, ambient temperature, and wind velocity were reported these studies. Rajakrishnamoorthy *et al.* [31], obtained water temperature of 79.7°C in hot season and low water temperature of 45.3°C in wet season. Kumar and Bhupendra [29] also obtained similar results. Raj *et al.* [34], Jouhri and Dhakar [35], Sezen *et al.* [36] and Soleymani *et al.* [37] simulated a solar flat plate collector for water heating for different applications and obtained similar results. Raj *et al.* [34] and Singh *et al.* [38] and Patel, *et al.* [39] obtained an average maximum temperature of 71.3°C in hot season and 41.8°C in wet season while the remaining studies reported similar results.

Danshehu *et al.* [40] and Agbo [41], reported an average water temperature of 81.5°C with 800 litres capacity in hot day in summer under the weather condition of Sokoto, Nigeria and the low temperatures in wet and dusty season. Nigeria Building and Road Research Institute (MBRRI), operated a temperature within the range of 40°C – 57.1°C on a clear day in Lagos, Nigeria. Studies of Agbo and Unachukwu [42] reported temperatures of 70.2 °C, 73 °C and 60.4 °C in clear and hot day season and low temperatures in a wet and dusty or cold season in Nsukka, Zaria and Ibadan, Nigeria respectively. Zwalnan [32] obtained minimum temperature of 61°C for most part of the year except the month of July where the water temperatures dropped to temperature below 34°C at the end of the day under the weather condition of Zaria, Nigeria. Anthony *et al.* [43], Mong *et al.* [44], Njoku *et al.* [45] and Mong *et al.* [46] carryout simulation and obtained temperatures of 60 to 75 °C, in a clear and hot day season and low temperatures in a wet and dusty or cold season in cities of several part of Nigeria. Zwalnan [32] obtained 34

°C in cooler season and 61 °C in the hotter season of Zaria Nigeria while Mong *et al.* [44] and Njoku *et al.* [45] evaluate the performance of flat-plate solar thermal collector for daily utilisability and obtained 60°C in Owerri, Nigeria. Heat absorber surface temperature of up to 108°C was obtained at a 35° tilt angle in the month of November in Kano metropolis by Waziri *et al.* [47]. Also, maximum temperature was 100°C, in April at the 12.1° tilt angle followed by 99.9°C and 99.8°C at – 2.9° and 0°, respectively were reported in Waziri *et al.* [48]. Even though the result of heat collection reported by Waziri, *et al.* [47] and Waziri, *et al.* [48] were not intended for water heating only but rather for various domestic and industrial applications in Kano metropolis.

4. Conclusions

An active solar water heating system was successfully designed, simulated, constructed and tested under the weather condition of Mubi, Nigeria latitude 10.26°, longitude 13.26° and altitude 582 m. The annual performance (storage tanks inlet and outlet temperatures) of the system was simulated under weather data of Mubi using TRNSYS 16 software. The results of the simulation revealed that, the system was capable of meeting the desired daily hot water requirement of 68°C, 67.5°C 53°C, 62.1°C, and 65.2°C for the months of June, July, August, September and October respectively at averagely 15 hours of the day. This indicated that the active solar flat plate water heater with area of 2.10 m² adopted tilted at an angle of 10.26° to the horizontal would be capable of producing daily domestic hot water of 100 litres for most part of the months except the month of August where the tank temperature dropped to 53.5°C, auxiliary energy might be provided in this month. This indicates that the system would be required to supplement the hot water requirements for industries, hospitals and community – based organization.

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