Modeling and Simulation of a Thermosiphon Solar Water Heater in Makurdi using Transient System Simulation

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ABSTRACT

The modeling and simulation of a thermosyphon solar water heater at Makurdi (7.74ºN) Nigeria was conducted for a period of three months (November, 2013- January, 2014). The research was aimed at simulating the performance of a solar water heater by using various parameters for greater efficiency. The solar water heater was developed and its performance was simulated at University of Agriculture Makurdi. The solar radiation on a horizontal surface was measured using a solarimeter. The water mass flow rates were measured using a Flow meter. The relative humidity data were measured using the Hygrometer. The inlet, outlet and ambient temperatures were measured using a Digital thermometer. For the simulation of the entire system the following measured parameters were used, as global solar radiation on collector plate, collector ambient temperature, heat exchanger and storage tank ambient temperature, flow rate of the collector and storage loop, the cold tap water temperature and the hot water usage. For the validation of the model and for the identification of parameters as heat loss coefficients in situ measurements were performed. Based on the developed models parameter sensitivity analysis and transient influences can be examining for the element and the entire system as well. The results obtained were simulated using Transient simulation software16 (TRNSYS). The results obtained showed that the daily average solar radiation for the period varied from 405 W/m^2 to1008 W/m^2. In the month of November, 2013 the daily average solar radiation on a horizontal surface varied from 451 W/m^2 to 936 W/m^2. In December, 2013 the values varied from 511 W/m^2 to923 W/m^2. For January, 2014 the values varied from to 405 W/m^2 to1008 w/m^2. The daily average mass flow rates varied from 0.2088Kg/hr to 0.9144Kg/hr whereas the relative humidity (November 2013 to January 2014) varied from 66.91% to 89.25%.Simulated results revealed that the performance of the solar water heater depends very much on the incident solar radiation. This works was carried out to help overcome the challenges of designing solar water heaters with very low efficiency by certifying the suitability of designs by making choice of optimal parameters.

Keywords: Transient, Simulation, Modelling, Collector, Thermosyphon, Solar Water Heater, Insolation

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1.0
INTRODUCTION

Mankind has enjoyed the heat from the sun during all his existence. It is, however, periodic and in most places a fickle source of energy; so much that our most significant single technical accomplishment has been the development of auxiliary energy source. The most convenient fossil fuels – oil and gas – are now in short supply, and within a few decades even the remaining oil-rich areas will be exhausted. The present rate of consumption is so enormous that no discoveries conceivable can change this conclusion – they could only push the date a few more decades into the future. Energy efficiency improvements beyond the substantial energy conservation can further reduce the energy demand and narrow the prospective gaps between energy demand and supply. Energy is considered a prime agent in the generation of wealth and a significant factor in economic development. The importance of energy in economic development is recognized universally, and historical data verified that there is a strong relationship between the availability of energy and economic activity (Soteris, 2004). Although in the early seventies, after the oil crises, the concern was on the cost of energy, however during the past two decades, the risk and reality of environmental degradation have become more apparent. Renewable energy resources appear to be one of the most efficient and effective solutions.

Renewable energy utilization is synonymous with solar energy utilization, as the Sun is the source of all renewable energy. The transition to a solar energy economy has begun all over the world and the renewable energy sector has moved progressively to the center stage of the energy mix and energy policy of the developed and developing nations of the world. Direct solar energy means the radiation intercepted by collectors and indirect solar energy includes wind, ocean and biomass energy (2009). Solar water systems can heat the water from ambient temperature to over 90°C. Using solar collector to heat the water can very easily attain required temperatures. In this study, a domestic solar water heater will be developed and its performance simulated using Transient system simulation software (TRNSYS)16. The protype solar water heater would be used to measure the thermo physical properties of the system to predict its performance. The proposed model will consider the distributed parameters of the collector. In the model the boundary conditions will be taken to be time dependent (sun radiation and ambient conditions). All the thermo-physical properties of the fluid and absorber would computed in online mode (time-dependents).

2.0 REVIEW OF LITERATURE

Review of Relevant Works

A TRNSYS model was developed by Ayompe *et al.* (2011) for the performance evaluation and other parameter calculations like outlet temperature in case of forced flow for flat plate and evacuated tube collector. The model was validated with the experimental data for systems installed in Dublin, Ireland. Results obtained showed that the model predicted the collector outlet fluid temperature with percentage mean absolute error (PMAE) of 16.9 % and 18.4 % for the flat plate collector and evacuated tube collector systems respectively. Heat collected and delivered to the load was also predicted with percentage mean absolute error of 14.1 % and 6.9 % for the flat plate collector system and 16.9 % and 7.6 % for the evacuated tube collector system respectively. The TRNSYS model underestimated the collector outlet fluid temperature by -9.6 % and overestimated the heat collected and heat delivered to load by 7.6 % and 6.9 % for the flat plate collector system. The TRNSYS model overestimated all three parameters by 13.7 %, 12.4 % and 7.6 % for the evacuated tube collector system.

Kalogirou (2006) developed six Artificial Neural Network (ANN) models for the prediction of standard performance collector equations coefficients, wind and no-wind conditions, the incident angle modifier coefficients at longitudinal and transverse directions, the collector time constant, the collector stagnation temperature and the collector capacity were considered. The study based on a steady-state operation conditions.

Fan *et al.* (2007) investigated experimentally and theoretically the flow and temperature distribution in a solar collector panel with an absorber consisting of horizontally inclined fins. Numerically, the flow and heat transfer in the collector panel were studied by the means of CFD calculations. Experimentally, the flow distribution through the absorber evaluated by means of temperature measurements on the backside of the absorber tubes. Their results showed a good agreement between the Computational Fluid Dynamics (CFD) result and the experimental data at high flow rates. However for small flow rates, large differences appeared between the computed and measured temperatures. This disagreement was most likely due to the oversimplification of the solar collector model.

Beckman *et al*. (1976) used the results of many simulations with TRNSYS programme to develop the f-chart method which was in the form of generalized performance charts which correlated the performance of a particular type of system with its design parameters and the weather. However, this method was applicable only for systems with separate preheat and auxiliary tanks, and systems having a preheat tank loss coefficient of 0.42 W/m^2 °C. Overall, the f-chart method is an accurate tool for sizing domestic water heating systems with well insulated storage tanks, but it is not valid for comparing the performance of systems with differing amounts of storage tank insulation. The method is also not applicable to many process water heating systems where cold water enters the system above 20 °C and/or the desired set temperature is greater than 70 °C.

Ong. (1976) investigated the effect of the height between the collector and the storage tank of a thermosyphon solar water heater, both analytically and experimentally. The analytical results showed that the mean system efficiency and the mean storage tank temperature increased with increased tank height and also with increased solar radiation. The experimental results indicated that by increasing the height of the tank, the water mass flow rate was increased and resulted to lower collector temperatures and hence higher collector efficiencies. He did not, however, recommend an optimum height.

Anderson *et al.,* (2010) examined the performance of different colored solar collector. Based on the transmittance-absorptance product of different colored collectors the theoretical performances of these collectors were determined using the Hottel Whillier-Bliss 1-D steady-state model presented by Duffie and Beckmann (2006). Their result showed that coloured solar collector absorbers can make noticeable contributions to heating loads, but the thermal efficiency was lower than highly developed selective coating absorbers.

A detailed information on thermosyphon system behaviour was provided by Shitzer *et al,*. (1979). They studied the water temperature distribution along the collector tubes, measured the water flow rates in the system which was found to generally follow the pattern of variation of the solar insolation, and tested the validity of an analytical model developed for the estimation of the water flow rate. Results showed relatively linear temperature distribution along the collectors and in the storage tank when no water consumption was allowed. Water flow rate was found to follow the pattern of variation of the solar radiation and reached a maximum of 950cm^3/min.

Fanney and Liu (1980) measured the performance of one thermosyphon solar water heater and five forced circulation systems over a year and compared the predictions of several simulations. They found that the thermosyphon system gave slightly better performance than the closest equivalent pumped system.

Parker. (1981) studied the performance characteristics of a thermosyphon solar water heating system, installed in a house, under dynamic conditions of normal operation. This investigation showed that there was a substantial heat loss from the long runs of pipe connecting the storage tank to the collectors and there was also evidence of a small amount of back circulation at night despite the 2 metres difference in height between the tank and the panels.

Braun *et al*. (1983) used the results of hundreds of TRNSYS simulations of a solar hot water system to develop a design method for solar water heating systems, which was in fact an improvement of the f-chart method. They assumed a fully mixed storage tank and a daily hot water consumption pattern similar to that developed by Rand Corporation Survey (Mutch 1974). The resulting procedures overcome the main limitations of the f-chart method concerning the water set temperature, water mains temperature and the preheat tank loss coefficient. The results obtained with the improved method agree with detailed TRNSYS simulation results within 2 percent on an annual basis and 3 per cent for monthly comparisons.

So many researches have been conducted in the area of solar water heater in terms of optimization and performance but the problem of improving efficiency has always been the problem because most of the designs were not simulated to certify their suitability before construction. This then leads to making solar water heater with very low efficiency and performance. This work describes an analytical method of modelling and predicting the daily performance of thermosyphon solar hot water system using Transient System Simulation Software16 (TRNSYS). The program developed for this purpose is however general and can be used to predict the performance of solar system using a variety of data inputs as different options for any given location.

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3.0 EXPERIMENTATION

INSTRUMENTATION

The Instruments were used to measure various parameters during the experimentation from the developed prototype solar water heater.

Table 1: MATERIALS AND EQUIPMENT USED FOR THE RESEARCH

Serial	Instrument	Model	Manufacturer	Unit
1.	Liquid Flow Meter	FL-200series (ISO4064B compliant)	OMEGA(USA	cc/min
2.	Digital Thermometer	ST-9269	MEXTECH(India)	℃/℉
3.	Solar Meter	DS-05A	DAYSTAR (New Mexico,USA)	w/m^2
4.	Hygrometer	G-342	OMSONS(india)	%
5.	GlobalPositioning System	RINO-120	GARMIN(USA)	degrees
5.	TRNSYS Software	TRNSYS 16	SOLAR ENERGY LAB USA	

Table 2: MATERIALS USED FOR THE SOLAR WATER HEATER

Serial	Component	Material	Purpose
1.	Glazing	Glass	low reflectance, (ρ), low absorptance, (α), and high transmittance, (τ)
2.	Absorber plate	Aluminium	high reflectance
3.	Absorber Pipes(header and risers)	Copper	Copper being the best among the materials for absorber plate due to its high thermal conductivity.
4.	Collector tank and insulation	Saw dust and Poly urethane foam	It is relatively cheap and available in the local market.
5.	Collector casing	Afara wood	Poor conductor of heat, low cost, Availability and very light as well as it serves as insulation
6.	Connecting Pipes	PVC	strength and availability in the market
7.	Hot water storage Tank	galvanized iron sheets	
8.	Collector and storage stand	”mild steel angle iron	strength and availability in the market

3.1 System Design

3.1.1 Design Analysis

In the design analysis of the system, the following assumptions were made:

1. The collector operates in steady state.

2. Temperature gradient through the cover thickness is negligible.
3. There is one-dimensional heat flow through the back and side insulation and through the cover system.
4. The temperature gradient around and through the tubes is negligible.
5. The temperature gradient through the absorber plate is negligible.
6. The radiation model employed to calculate heat transfer in the system assumes that the radiation remains constant through the hours and days.
7. Fluid flow distribution is one dimensional.
8. Temperature distributions in the collector tubes and the storage tank are linear.
9. Flow inside the tubes is laminar and uniformly distributed.

3.1.2 Assumed parameters

(i) Volume of water to be heated, v = $50m^3$
(ii) Average heating time, t = 8 hours
(iii) Average insolation, I = $950\ w/m^2$
(iv) Ambient temperature, T_a = 25 °C
(v) Water inlet temperature, T_i = 25 °C
(vi) Transmittance of the cover material, = 0.9

(vii) Absorptivity of the absorber plate (coated with black paint), = 0.95

(viii) Angle of inclination of solar collector = 17 degrees

3.1.3 Experimentation

The natural circulation solar water heater was tested for 3 months in November, December 2018 and January 2019 at hourly intervals between 9.00 a.m and 4.00 p.m each day. The flat plate collector was orientated in such a way that it received maximum solar radiation during the desired season of use. According to (Adegoke and Bolaji 2000), the best stationary orientation is due south in the northern hemisphere. In this position the inclination of the collector to the horizontal plane for the best all year round performance is approximately 10^0 more than the local geographical latitude. The absorbing plate and the absorbing surface of the pipes absorb solar radiation and the absorbed heat is then transmitted to the water in the pipes. Under the mode of natural convection the water flow through the pipes by the thermosyphonic effect and enters the storage tank.

3.1.4 Working Principle

The working principle of the solar water heater is shown in Figure 1 .When solar radiation from the sun is absorbed by the blackened absorber plate, it is converted to heat. The heat is transferred to the flow tubes by conduction. The water in the flow tubes is in turn heated by convection process between the tubes and the water molecules. The heated water becomes warmer and less dense than the water in the storage tank. This density difference results in buoyancy force, often referred to as the thermosyphon head (Agbo and Unachukwu, 2006), which creates a continuous convective circulation of water from the bottom of the tank to the bottom of the collector, up through the collector flow tubes, and back into the top of tank. The steady circulation of water in the collector loop results in the rise of water temperature in the tank. Mixing between the water at upper and lower parts of the tank, results in a uniform water temperature in the tank at sunset. At sunset the water supply line is locked to stop water circulation in the loop. This is to prevent further fall in temperature of the water in the tank since the absorber plate temperature is now the same as the ambient temperature and will increase heat loss if circulation is not discontinued at such period.

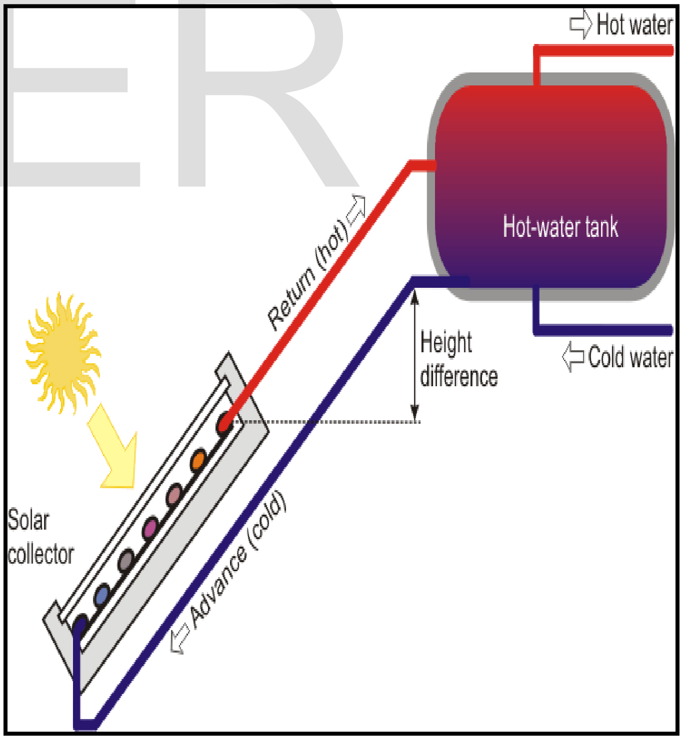

Fig 1: Working Principle of the Thermosyphon Solar Water Heater(Google images)

3.1.5 Simulation approach

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Before starting the project in the Simulation Studio, the simulated system was thoroughly studied to decide what factors will be of interest and the components that will be used in the simulation. The solar water heating system consists of solar collectors, a storage tank, and pipes. Weather data for Makurdi was read and processed and output some results (both to the online plotter and to a printed file).

The following components were used:

- **Type 109 Weather data reader and processor**: This component reads weather data and processes it to calculate the solar radiation properties on any surface.
- **Type 1 Solar collector**: adapted to flat-plate collectors with quadratic efficiency parameters.
- **Type 24 Integrator**: This was used to integrate energy rates
- **Type 25 Printer:** This was used to print out the simulated results after integration and plotting
- **Type 65 Online plotter**: This was used to plot the graphs of the parameters.

3.1.6 Creating a New Component

The simulation began with generating new components using the Simulation Studio to create the component Performa as follows:

- Launch the Simulation Studio and open File/New
- Select "New Component"
- In the component "General" tab, type in the component's object and its Type number.Type number was assigned which was different from zero. The selected number was in the [201-300] range in order to avoid conflicts with existing libraries.Figures 16 and 17 show two simulation studio interfaces.

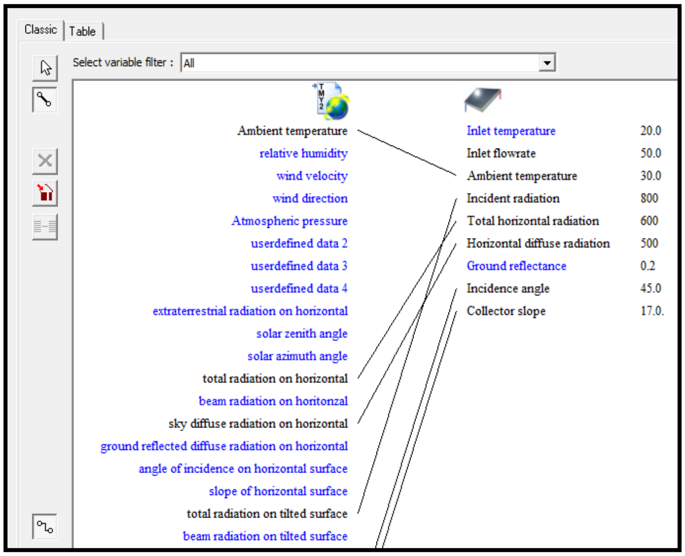
3.1.7 System connections

The following connections were made to complete the system in the simulation studio.

3.6.5.1 Type109 (weather data) to type1 (Solar collector)

The type 109 weather data reader was connected to the type 1 Solar collector linking the parameters below.

- Ambient temperature → Ambient temperature
- Total radiation on horizontal → Total horizontal radiation
- Sky diffuse radiation on horizontal → Horizontal diffuse radiation
- Total radiation on tilted surface → Incident radiation
- Angle of incidence for tilted surface → Incidence angle



Select variable filter : All

Inlet temperature	20.0
Inlet flowrate	50.0
Ambient temperature	30.0
Incident radiation	800
Total horizontal radiation	600
Horizontal diffuse radiation	500
Ground reflectance	0.2
Incidence angle	45.0
Collector slope	17.0.

Fig 2: Connecting Weather Data to Solar Collector (Simulation studio)

3.1.8 Connections to output devices

All the connections made above were then connected to output devices for computation of results obtained from the parameters linked. Figure 16 shows system components and connections.

2.6.6.1 Connections to type 24 (integrator)

• Type 1 (Solar collector), Useful energy gain → Input to be integrated-1

2.6.6.2 Connections to type 65 (online plotter)

• Type 3 (Pump), Outlet fluid temperature → Left axis variable-1
• Type 1 (Solar collector), Outlet temperature → Left axis variable-2
• Type 1 (Solar collector), Useful energy gain → Right axis variable-1
2.6.6.3 Connections to type 25 (printer)

• Type 24 (Integrator), Result of integration-1 → Input to be printed-1
• Type 24 (Integrator), Result of integration-2 → Input to be printed-2

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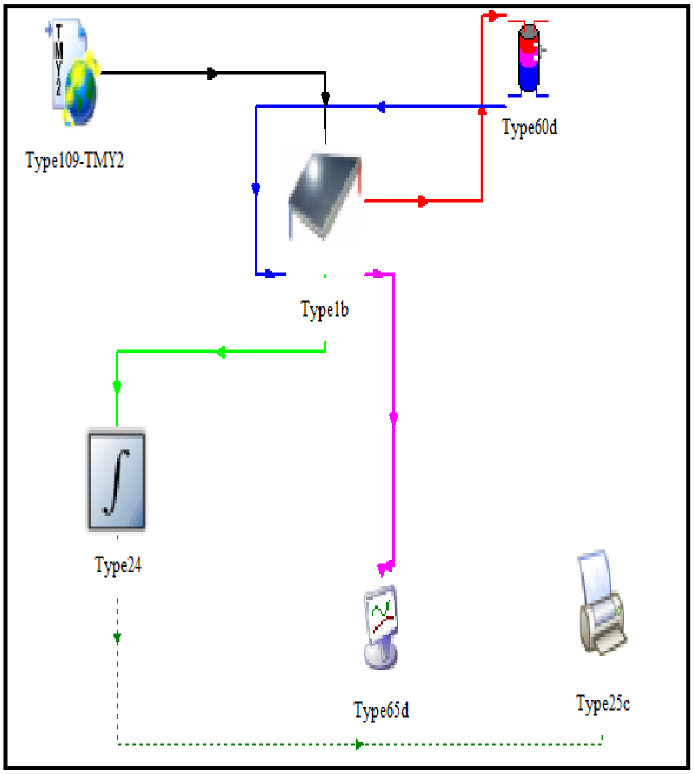

Fig 3: System Components and Connections (Simulation studio)

4.0 RESULTS AND DISCUSSIONS

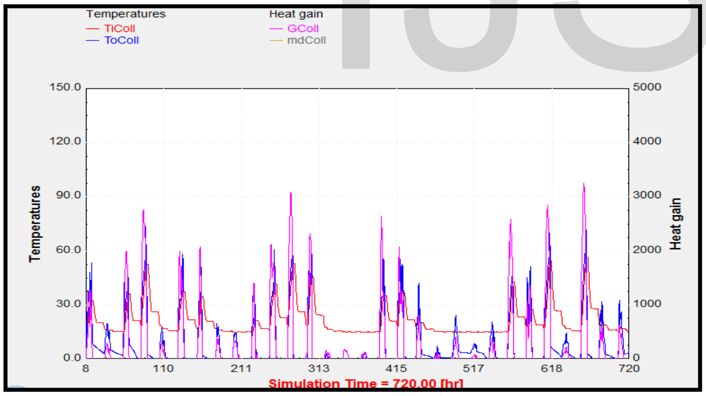

Fig 4: Outlet/Inlet Temperatures and Heat gain as functions of time for Novovember 20

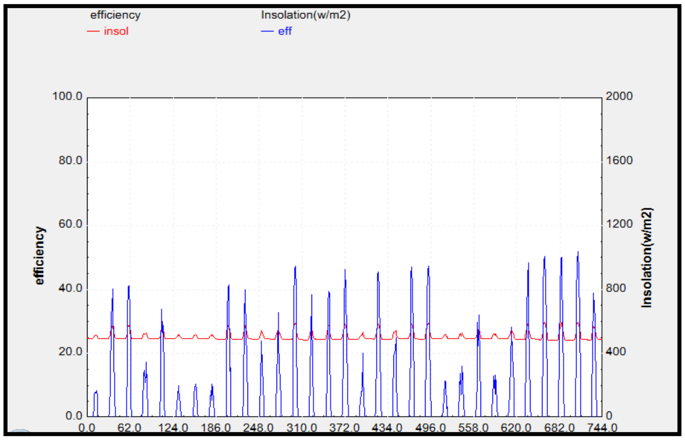

Fig 5: Graph of Efficiency and Solar Insolation as functions of time for December 2019

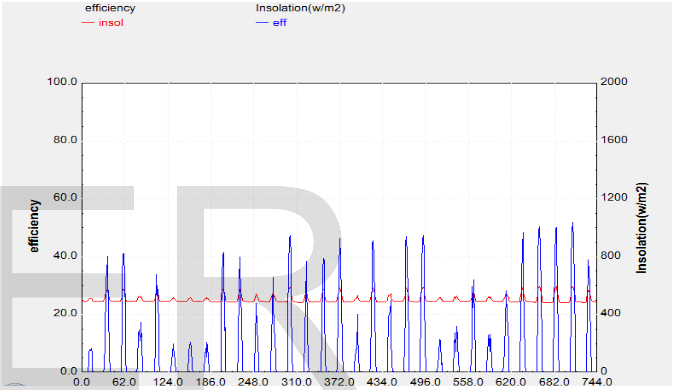

Fig 6: Graph of Collector Efficiency and Solar Insolation as a functions of time for January 2019

Figure 4 shows simulated results of daily tank inlet, collector inlet, and tank average temperature of the system as predicted using TRNSYS 16 software for recommended average days of November (4,7,8,14,19 and 20 November, 2013) which recorded the highest and lowest temperatures. The curve shows a continuous rise in tank inlet temperature from an initial temperature of 21℃ at 9.00hours on 7th November and reaching a peak of 71.38℃ at 1200 hours on 8 November. This indicates that the system performance across the seasons has a very negligible variation. This is again followed by a drop in temperature from 16 hours to a temperature of 58℃ at hours. This observed drop in temperature is due to the lower amount of solar radiation received on the collector surface at this time of the day. On the other hand, the collector inlet temperature remains constant from the start of simulation 9.00 hours to 1300 hours. At about 1300 hours, the collector inlet temperature starts to rise. It could also be seen from the curve that at the end of the simulation time (1600hours), the tank average temperature remains greater than the collector inlet temperature. This reveals stratification of the storage tank temperature; the

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implication is a non uniform storage tank water temperature at the end of the day. That is, the temperature of water at the top layer of the storage tank is higher than the temperature of water at in the bottom layer of the storage tank at the end of the day. The curve shows that the higher the ambient temperature the higher the intensity of the radiation and the more the heat gain in the solar water heater collector and the higher the temperature at the outlet of the collector. A maximum solar radiation of 941 w/m^2 was obtained on 20 November 2018 at an ambient temperature of 37.13℃ , collector outlet temperature of 71.38℃ and a useful heat gain of 172.496 kJ/Kg on 8 November 2018.

Figure 5 is the curve of the collector efficiency and solar radiation as a function of time. Its shows that the efficiency increased with increased solar radiation. The efficiency is high especially around midday when the solar collector receives the highest energy but it is low in the morning and late afternoon due to low incident radiation during this period. This shows that the greater the energy received the more vigorous the circulation and the better the system. This is a clear indication of the dependence of the system performance on the total daily insolation. During the test, a system efficiency of 14.1% was obtained from the solar water heater and a maximum solar insolation of 906 w/m^2.

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5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

A thermosyphon solar water heating system to supply 50 liters at a minimum temperature of 50℃ has been successfully developed, tested and simulated in the Department of Mechanical Engineering, University of Agriculture (U.A.M) Makurdi, Nigeria (latitude 7.4° N).The Project approach was in three parts; firstly the development of the prototype Solar water heater based on solar data of Makurdi. This was processed to obtain the monthly average daily solar radiation of Makurdi for recommended average day of the months. The month of October with a moderate amount of average daily solar radiation was considered as the design month and solar radiation and weather data of this month was used as input data for system design. A parametric studies of the effect and sensitivity of some selected system components (i.e copper tube diameter, number of glass covers, absorber plate thickness, and centre to centre tube distance) on the design objective function (the heat removal factor) were studied in order to determine the appropriate components size for each component based on solar radiation for the design month.

Secondly, the prototype solar water heater was used to measure useful parameters such solar radiation on horizontal surface, water mass flow rates, relative humidity as well as the inlet, outlet and ambient temperatures was carried out. Thirdly, the daily performance (collector and storage tank temperature) of the system was simulated under weather data of Makurdi using TRNSYS 16 software. The Experimental results revealed that the performance of the solar water heater depends very much on the flow rate through the collector. The collector efficiency increases as the flow rate and the incident solar radiation increase. Therefore, the greater the energy received the more vigorous the water circulation and the better the system performance. During the test, results also showed that the system exhibited optimum flow rate of 0.9144kg/hr at maximum efficiency of 26.3% . Also, the maximum water temperature obtained was 71.38℃ at maximum ambient temperature of 40.0℃. Therefore, the performance of a thermosyphon solar heating system depends on many parameters which have to be exploited through simulation and experimental studies. These studies are necessary to obtain a detailed understanding of the system behaviour which leads to more efficient designs.

5.2 Recommendations

During the course of this project a lot of challenges were encountered some were solved immediately while others were difficult to make a break through. It is therefore recommended that:

- More work should be done on improving the efficiency of solar water heaters by incorporating automatic solar tracking sensors to enable the collector rotate freely along the Suns axis of radiation.
- Efficiencies of Concentrating collectors and Flat Plate collectors be investigated to ascertain the one with higher efficiency in Makurdi.
- Forced circulation and Natural Circulation be incorporated in one solar water heating system with a view to improving flow rate and system efficiency.
- The absorber plate of the solar collector in this study was placed below the copper tubes carrying the circulating water. It would be important here again to recommend that an investigation should be conducted to know if the absorber plate placed above the collector copper tube will give better performance of the system.

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