

Development and performance analysis of an embedded active solar flat plate collector water heater for clinical applications

¹Duvuna, G. A., and ²Ali, M.

¹Department of Mechanical Engineering, Federal Polytechnic Mubi, Adamawa State, Nigeria

²Department of Computer Engineering, Federal Polytechnic Mubi, Adamawa State, Nigeria

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Abstract:

The Abubakar Tafawa Balewa University (ATBU) clinic situated in Yelwa campus, Bauchi required water supply at varying temperatures for clinical applications. An active solar water heating system that would supply hot water at temperatures of 54°C, 43°C, 60°C and volumes of water 150 litres, 113 litres and 88 litres for laundry, post-natal and sterilization applications respectively was developed and tested. The system characteristics and components sizes were obtained from design calculations and the parametric study coded in MATLAB. The month of August was used as the design month bearing in mind that the month had the least solar radiation in Bauchi. The collector areas of 2.30m², 1.15m² and 2.1m² for laundry, post-natal and sterilization applications respectively were embedded in each other and tilted at an angle of 10.23°, the latitude of Bauchi. The system was then tested for a period of three months (i.e. August to October). The highest temperatures attained in August were 46.5°C, 36.2°C and 53.6°C for Laundry, Post-natal and Sterilization applications respectively. In all the other months, the desired water temperatures were achieved within an average time interval of 13 to 15 hours of the day. To meet up in the month of August, an auxiliary energy may be provided. This system can be adopted in hard to reach areas where the solar intensity is appreciable and national grid for electricity does not pass through.

Corresponding author

Duvuna, G. A.

ayubagideon2@gmail.com

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1. Introduction

Solar energy, which is energy from sun, is nature's best gift to humanity and the world's most abundant renewable and "cheapest" source of energy. According to Sukhatme, S.P [1], the estimated power from the sun intercepted by the earth is approximately 1.8×10^{11} MW daily, which are many thousands of times larger than the world energy consumption rate of all commercial energy resources. Thus, in principle, solar energy could supply all the present and future energy needs of the world on a continuing basis if effective harnessing devices are deployed. The principles, fundamentals, and operations of solar energy technologies are in two broad categories: namely; solar photovoltaic technologies and solar thermal technology [2].

Nigeria lies within a high sunshine belt and within the country; solar radiation is fairly well distributed. According to a report by Energy Commission of Nigeria [3], the annual average total solar radiation in Nigeria varies from about 12.6MJ/m²-day (3.5 Wh/m²-day) in the coastal latitude to about 25.2MJ/m²-day (7.0KWh/m²-day) in the Northern latitude. This gives an average annual solar energy intensity of 1934.5KWh/m²- year, thus over a whole year an average of 6,372,613PJ/year (1770 thousand TWh/year) of solar energy falls on the entire land of

Nigeria. This is about 120 thousand times the total annual average electrical energy generation by the Power Holding Company of Nigeria [3]. According to Gerg and Prakash [4], Duvuna, *et al.* [13], Duvuna, *et al.* [14] and Zwalnan, *et al.* [15], Developing countries like Nigeria need to adopt solar water heating for 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 rural health centres and cottage industries could readily be met by solar water heaters.

According to Block [5], sterilization is a technique for destroying microorganisms or inanimate objects using heat, water, chemicals or gases or the process of destroying all microorganisms and their pathogenic products. High and moderate temperature is used for surgical instruments sterilization. For lower or moderate water temperatures, water temperature of 55°C – 60°C (i.e. 130°F – 140°F) has often been used for disinfecting due to the extended time or prolonged duration of exposure. High temperatures of 80°C and above for 5 – 10 minutes will destroy all active bacteria, yeast and fungi.

According to Elsegundo [6] and Stewart [7], laundry means articles of clothing, linens etc. that have been or are to be washed. A business establishment where clothes,

linens etc. are laundered, or a room, area or apartment building reserved for doing washing in clinics/maternity or family. Hot water is best to remove germs and heavy soil. However, hot water can shrink, fade, and damage some fabrics. Hot water of temperature 45°C – 54°C or slightly above, is the best choice for white clothes, very dirty or greasy clothes, diapers for clinics/maternity and sturdy fabrics that retain their dyes.

According to Enkil, *et al.* [8] Natal and post natal refers to events occurring during and after birth, usually understood as within the first week to the month after birth. Most thermometers indicate an ideal temperature of 37°C – 38°C, which is around body temperature for the babies. 38°C - 43°C can be ideal for adult. Shariah and Shialabi [9], studied optimisation parameters for Domestic Solar Water Heater (DSWH) in Jordan using TRNSYS simulation programme. Result obtained indicated that, solar fraction of the system can be improved by 10 - 25% when each parameter is chosen properly. Delfin, *et al.* [10], carried out a simulation study of a DSWH with different collector efficiencies and different volume storage tanks using MATLAB. Results obtained showed that, the system with greater storage tank volume yield lower system solar fraction values. Rhushi and Byregowda [11], studied and simulated with a computer programme in C-language the performance of a solar water heater using a flat plate collector.

The Program calculates instantaneous beam and diffuse radiations for the given location of the collector, number of days for the given date in a year and angle of incidence of beam radiation on the collector. Total solar flux incident on the collector, transmissivity – absorptivity product for beam and diffuse radiations were also calculated. In addition, incident flux absorbed by the absorber plate, collector heat removal factor, overall loss coefficient, water outlet temperature and the instantaneous efficiency were calculated. The main thrust of this work is to develop an active solar flat plate collector water heater for clinical applications.

2. Materials and method

2.1 Design considerations

A solar domestic hot water system was designed based on the following considerations:

- A design month which was determined from the mean daily heat load (W) and the mean daily solar irradiance (W/m²) from the months of the year.
- The amount of water required, to determine the system load.
- The range of operating temperatures for selection of materials, and
- The cost of materials.

2.2 Design using f-Chart method

The performance of service hot water systems with storage is estimated with f-Chart method. The purpose of the method is to calculate f, the fraction of the hot water load that is provided by solar heating system (solar fraction). The method enables the calculation of monthly energy delivered by hot water systems with storage.

2.3 Solar resources and weather data

Solar radiation and meteorological data which are very important driving functions for all solar system design often seem to be highly random and irregular. However, long-term statistical analysis indicates that, these variables are predictable to some degree of accuracy. Therefore, the dynamic nature of solar data can be smoothed out by formulating a representative data which can characterize the mean – value behavior of any location over a long period [12]. Based on this method, Typical Meteorological Year (TMY) weather data for the location (Bauchi) latitude 10.23° 738' N and longitude 9.47° 614' E was used as input functions to design and simulate the annual performance of the active solar water heating system. Typical Meteorological Year weather data is defined as a year which sums up all the climatic information characterizing a period as long as the mean life of the system.

2.4 System Design Approach and Calculation

Satisfactory performance and reliability of a solar water heating system requires adequate sizing of its components as well as accurate prediction of the system performance (i.e. delivered useful energy and outlet water temperature, solar fraction, and thermal efficiency, etc.). Therefore, proper sizing of system components and the determination of system characteristics through calculation of system design parameters is very important to achieving satisfactory performance. To calculate these design parameters and evaluate the sensitivity and effect of design parameters on the performance of an active solar water heating system, the following design method was adopted.

2.5 Determination of the Design Month

The design month is defined as the month with the least value of the energy ratio (E_R). The energy ratio (E_R) is the ratio of monthly average daily solar radiation on the collector surface to the monthly daily solar system load. The demand on the system for the design month is usually the highest and therefore the calculation of the design parameters and subsequent components sizing was done based on the design month average daily solar radiation and weather data of Bauchi. To determine the design month, the monthly average daily weather data and solar radiations on the surface of the collector for all the months obtained from the weather data processor (type 109 component) of TRNSYS 16 software was used as input into programme codes written in MATLAB to calculate the energy ratio (E_R). Month of August was found to have least value of energy ratio (E_R) and is considered the design month.

2.6 Determination of design parameters

System design parameters and characteristics were calculated from the programme codes developed in MATLAB programming language. The monthly average daily solar radiation and weather data of Bauchi, obtained from the weather data of TRNSYS 16 were used as input for the calculations.

2.7 Design parameters optimization

The system design parameters optimization procedure was performed to study the effect and sensitivity of the solar flat plate collector design parameters on the solar fraction (f) of the system in order to determine the proper system characteristics that will give satisfactory performance. Solar radiation, meteorological data and monthly average daily system characteristics for the design month were used as input data into the programme codes written in MATLAB programming language.

These programme codes were used to study the effects of varying some selected system characteristics (e.g. collector area, tube spacing, length of the collector tube, mass flow rate, air gap between the absorber plate and the first glazing, tube internal diameter etc.) on the chosen design objective function (i.e. solar fraction of the system). After the parameters optimization, these were chosen as the final system component sizes as presented in Tables 1 to 3

Table 1: Flat plate collector system design parameters

Parameter	Value	Unit
Glazing (Glass)		
Refractive index of glass	1.5	-
Number of glazing	1	-
Latitude of Bauchi	10.23	degree (°)
Thickness of glazing	5	Mm
reflective index of glazing	0.2	-
Emittance of glazing	0.88	-
Absorbance of glazing	0.28	-
Thermal conductivity of glazing	1.05	kW/m.K
Absorber plate (Aluminium)		
Emittance	0.95	-
Absorbance	0.9	-
Thickness of absorber plate	0.001	M
Thermal conductivity of plate	220	kW/m.K
Specific heat capacity of absorber plate	900	J/kg.K
Tube spacing	0.1	m
Adopted areas of the collector		
For laundry	2.3	m ²
For post natal	1.15	m ²
For sterilization	2.1	m ²

Table 2: Connecting pipe and pump design parameters

Parameter	Value	Unit
Connecting pipes:		
Pipe inner diameter	0.01	M
Pipe outer diameter	0.02	M
Length of pipe	12.5	M
Thermal conductivity of pipe (copper)	401	kW/m.K
Insulating material (sawdust)		
thermal conductivity of saw dust	0.08	kW/m.K
Thickness of insulating material	0.07	M
Pump (D.C. Solar water pump)		
Rated power	4.8	W
Discharge rate	150/0.042	km/hr - kg/s

2.8 Material Selection

Table 4 show the materials selected and used for the construction of the system. The system was constructed at

the centre for industrial studies (CIS) workshop of Abubakar Tafawa Balewa University (ATBU) Bauchi based on the optimum system dimensions of Tables 1 to 4

Table 3: Fluid (water) and tank design parameters

Parameter	Value	Unit
Fluid (water)		
Dynamic viscosity	9.7720x10 ⁻⁴	kg/m.s
Kinematic viscosity	9.7937 x10 ⁻⁷	-
Specific heat capacity	4.0764 x10 ³	J/kg. K
Thermal conductivity	0.60475	W/m.K
Thermal diffusivity	1.4868x10 ⁻⁷	m ² /s
Thermal expansion coefficient	3.4112 x10 ⁻³	1/K
Prandtl number	6.587	-
Tank 1 (laundry)		
Tank diameter	0.4	m
Tank height	1.2	m
Tank volume	0.15	m ³
Tank mass density	150/0.042	kg/hr - kg/s
Tank stratification	6 nodes	-
Desired temperature	54	degree(°C)
Tank 2 (post natal)		
Tank diameter	0.35	m
Tank height	1.2	m
Tank volume	0.113	m ³
Tank mass density	150/0.042	kg/hr - kg/s
Tank stratification	6 nodes	-
Desired temperature	43	degree (°C)
Tank 3 (sterilization)		
Tank diameter	0.31	m
Tank height	1.2	m
Tank volume	0.088	m ³
Tank mass density	150/0.042	kg/hr - kg/s
Tank stratification	6 nodes	-
Desired temperature	60	degree (°C)

2.9 Measuring Equipment Used

Solarimeter/solar power meter with accuracy of $\pm 5\text{W/m}^2$ to $\pm 10\text{W/m}^2$ of the measured value was used to measure the solar radiation, Kane-May 330 digital thermometer was used to measure the temperature of the working fluid (inlet and outlet) water temperature as well as ambient temperature; humidity meter with temperature accuracy $\pm 0.5^\circ\text{C}$. R.H. accuracy of $\pm 2\%$ was used to measure relative humidity and the anemometer to measure the wind speed.

2.10 Description of the Experimental Set-Up

The constructed active solar flat plate collector water heating system whose characteristics and configurations were presented in Tables 1 to 4 was installed at the Medical Centre of Abubakar Tafawa Balewa University Bauchi, Yelwa Campus and was used to carry out the performance test.

After the system was installed, the cylindrical water storage tanks were filled with water (i.e. the working fluid). On each day within the test period, experiment was started and completed by measuring the initial and end day inlet and outlet water temperatures in the storage tanks and solar collector at one hour interval. The active solar water heater was tested every day from 16th August to October, (i.e. for three months) between 08:00hrs and 18:00hrs. The

amount of solar radiation, relative humidity, wind speed, ambient temperature, and inlet and outlet temperatures for the three applications were measured and recorded.

3. Results and discussion

The performance results obtained are shown in Figures 1 to 3. Figure 1 show the monthly average daily system performance for laundry application. Figure 2 shows monthly average daily system performance for post natal application while Figure 3 shows the monthly average daily system performance for sterilization application.

Figure 1 shows the hourly variation of the tank inlet water temperatures for the months of August, September and October. In the months of September and October the system was able to attain the desired temperature of 54°C for laundry application between the hours of 13 to 15 hours of the day. In the month of August the maximum temperature attained by the system was 46.5°C. This poor performance of the system can be attributed to the clearness index of the month. To meet up with the hot water needed for laundry application in the month of August, auxiliary source of energy may be provided.

Table 4: Materials used for the construction/development of the system

Component	Material used	Quantity	Dimension
Glazing	Glass(LITG)	2	1000mm x1000mm: 1000mm x 2000mm
Absorber plate	Aluminium	1	3000mm x 1000mm x1mm
Flow tube	Copper pipe	7 rolls	12mm ext. dia by 10mm Int. Dia.
Storage tank	Plastic	3	2mm thick, vol. 15m ³ , 0.0113m ³ , 0.088m ³
Support	Angle iron	7	50mm x 50mm x 5mm
Casing	Wood	1	2 pieces of 3000mm x150mm x 30mm & 2 pieces of 1000mm x 150mm x30mm
Insulating	Sawdust/Form		7mm thick/50mm thick
Material	& Metal Sheet		2mm thick wrapped around the drum

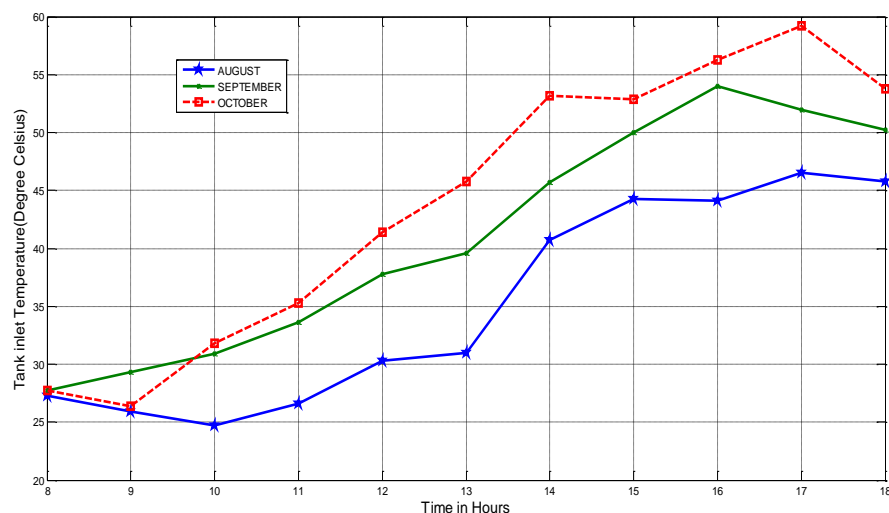


Figure 1: Monthly average daily system performance for the months of August, September, and October, for laundry application

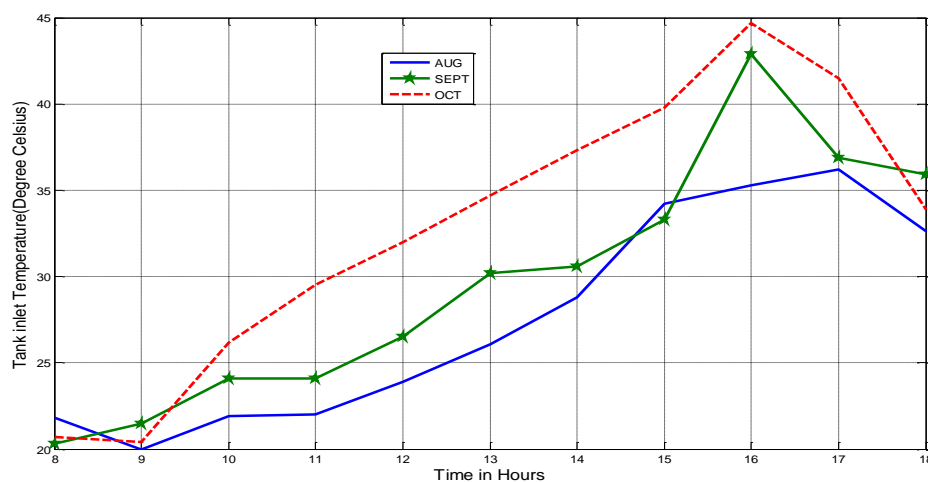


Figure 2: Monthly average daily system performance for the months of August, September, and October for post-natal application

Figure 2 shows the hourly variation of the tank inlet water temperatures for the months of August, September and October. In the months of September and October the system was able to attain the desired temperature of 43°C for post-natal application between the hours of 13 to 14 hours of the day. However, in the month of August, the

maximum temperature attained by the system was 36.2°C. This poor performance of the system can also be attributed to the clearness index of the month. To meet up with the hot water need for post-natal application, auxiliary source of energy may be provided.

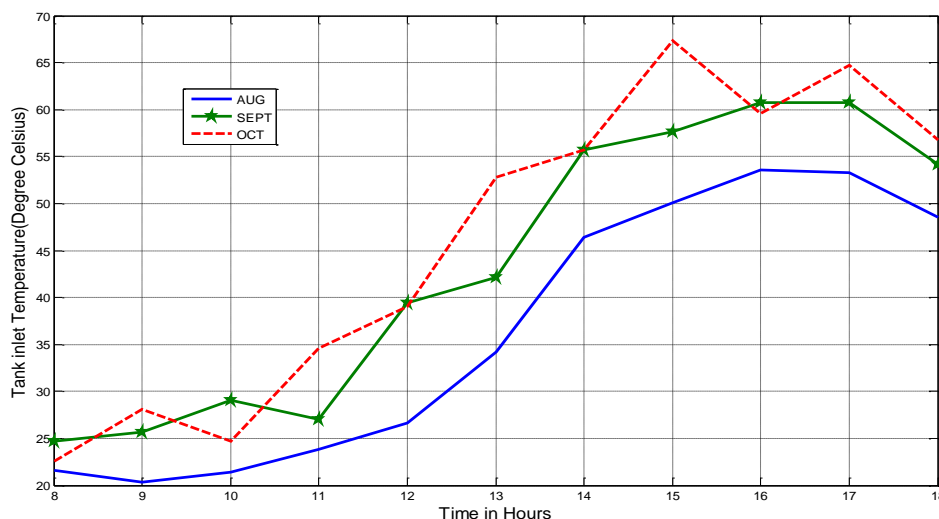


Figure 3: Monthly average daily system performance for the months of August, September, and October, for sterilization application.

Figure 3 shows the hourly variation of the tank inlet water temperatures for the months of August, September and October. The system performed according to the design criteria in the months of September and October; the sterilisation temperature of 60°C for sterilization application attained between the hours of 13 and 14 hours of the day. Again, in the month of August the system was not able to attain the desired temperature for the application. This poor performance of the system can also be attributed to the clearness index of the month. For the desired hot water temperature need therefore an auxiliary energy source may be provided.

4. Conclusion

An active solar water heating system that would supply hot water at various temperatures of 54°C, 43°C, 60°C and volumes of water of 150 litres, 113 litres and 88 litres for laundry, post-natal and sterilization applications respectively has been developed and subjected to performance test. The analyses of the system based on monthly average daily performance revealed that, the month of August recorded least performance, though this was used as the designed month. The highest temperatures attained were 46.5°C, 36.2°C and 53.6°C for Laundry, Post-natal and Sterilization applications respectively. The poor performance of the system can be attributed to the clearness index of the month and the consideration of the solar fraction (f) factor less than one. The peculiar climatic conditions which were slightly different from those considered at the design stage may also be a factor. Despite these, the system provided daily domestic hot water as designed for the three applications.

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