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# SIMULATION OF A SENSIBLE HEAT THERMAL ENERGY STORAGE SYSTEM USING MATLAB'S BLOCK-ORIENTED APPROACH

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## ABSTRACT

***This paper presents the dynamic simulation of the mathematical model of a solar water heating (SWH) system consisting of a solar collector and a thermal storage tank developed using MATLAB's block-oriented technique according to the law of energy conservation. The governing heat balance equations are given along with the assumptions applied in the model. As a case study, this paper analysed the SWH system performance under the climatic condition of Abeokuta for the design month of December. Global Horizontal Irradiation data for Nigeria were used to determine the average daily solar radiation intensity for the month. The results shows that a collector tilt angle of 7degrees can receive more energy with a thermal efficiency of 0.8. The results demonstrate that at the highest solar radiation intensity, the system's maximum temperature output was 61.98 °C. From the result obtained, it can be concluded that a SWH system of collector area 1.5 $m^2$ has the ability to heat 150 liters of water to a temperature of 60℃ in the month with the highest average sunshine hours in Alabata, Abeokuta. The simulation results can support the selection of appropriate components and predict the operation of the solar water heating system to be built.***

***Keywords*: Solar collector, Storage tank, Modelling, Simulation, Simulink**

## INTRODUCTION

With rising electricity prices and environmental concerns, new technologies are being built to extract energy from every available source and store the surplus energy produced for later use. One such solution is provided by Thermal Energy Storage (TES) systems with their ability to store thermal energy in order for it to be applied for later use, either at the harvesting source or elsewhere (Dincer, 2002; Dincer and Rosen, 2007). TES is a promising environmentally friendly technology that seeks to improve the utilization of energy to achieve maximum effective utilization of solar energyenergy, as well as economically bridge the gap between energy supply and the end-user demand.

The purpose of this study is to shift energy demand for heating domestically to off-peak periods to reduce monthly electric utility bills. This can be achieved with a fully-mixed sensible heat thermal energy storage system as it utilizes the heat capacity and the change in temperature of the storage material during charging or discharging processes. The set up in this study is a passive system which does not require the use of forced convection produced by pump (Fang et al., 2010) .

Water is one of the most prevalent mediums for sensible heat TES, and the TES water tank has been tested by researchers to predict its ability to reduce energy demands and cost as well as improve reliability of solar heating (Angrisani et al., 2014; DeForest et al., 2014; Han et al.,2009; pavlov et al., 2011). TES tank is assumed to be a heat recovery system and its output in terms of storage water temperature and temperature distribution is considered.

Solar water heating systems are available in different forms and can be used in different applications. Domestic hot water usually uses small systems applications while larger systems are used in industrial applications (Akuffo et al., 1998). On a larger scale, it is applicable for the production of electricity (Wu et al., 2001). Designs appropriate for hot climates can be both easier and cheaper and can be deemed an acceptable technology for such areas (Kalogirou 2009).

Recently, two complementary approaches are available for studying a water storage system. One is a quasi-static approach which is based on a steady-state analysis; another is a dynamic approach by means of dynamic simulation software such as MATLAB. The latter is widely used since it is dependent on time and allows for the calculation of the fluid's mass flow rate.

For instance, Busaz, et al. (1998) developed a numerical model for the dynamic simulation of a hot water storage tanks using MATLAB software. Three different cases were studied; a divided hot water storage tank, a storage tank with heat exchanger and a fully-mixed one.

For system analysis, the dynamic mathematical models are established according to the law of energy conservation. For the simulation of the entire system, the parameters to be used include; global solar radiation on collector plate, collector ambient temperature,the flow rate of the collector and storage loop, supplied cold water temperature and extracted hot water. All these are evaluated within the MATLAB-Simulink software as a function of various design parameters such as location, dimensions, and meteorological data of the region.

Zwalnan (2015) designed, simulated, constructed and tested a thermosyphon solar water heater. The monthly average daily solar radiation and weather data obtained from the typical meteorological year solar data of Zaria were used to determine the design month as the month (August) with the least monthly average daily solar energy ratio. The results of this research led to the conclusion that a thermosyphon solar system with collector area of 2.24m$^2$ operated under the weather condition of Zaria, would be capable of supplying a daily domestic water of 0.1m$^3$ at temperature ranging from 59$^o$C for the worst month (August) to 81$^o$C.

Arinze et al. (1988) explored techniques for improving the output of flat-plate collectors by allowing the collection to track the sun. Complete tracking and semi-tracking strategies have been studied for five northern areas, including Kaduna, Kano, Zaria, Jos and Sokoto, and their findings have shown that higher energy gains by flat-plate collectors may be obtained through operating in specific sun-tracking modes.

Sambo et al. (1990) designed, constructed and tested four solar water heating systems at the Sokoto Energy Research Center. The systems were set up in a thermosyphonic arrangement. The absorbers of the collectors were made as: flat plate dark painted aluminium sheet, flat plate dark separated galvanized mild steel sheets, quasi flat plate zinc covered mild galvanized aluminum sheet andquasi flat plate zinc covered mild galvanized sheet.The output assessment of these collectors showed that the dark painted flat plate galvanized sheet provided the highest water outlet temperature, while the dark painted aluminum flat plate generated the highest efficiency values.

(Bolaji, 2006) designed, constructed and conducted an experimental analysis of the mass flow rate of the collector of a passive solar water heating system. The system was tested at Ado-Ekiti, Nigeria on latitude 7.5$^o$N. The result reveals that the operation of the system relies, in fact, on both the flow rate through the collector and the solar radiation. Daily system analysis reveals that the collector's output is strong particularly late in the morning when the collector absorbs the largest amount of solar radiation. During the test, the outcomes indicated that the system displayed the ideal flow rate of $0.1\, kgsm^{-2}$ at highest efficiencyof a collector of 68.5%. Likewise, the average daily efficiency of the system was 57.7% and the maximum water temperature acquired was 83.5$^o$C while the greatest ambient temperature got was 34.5$^o$.

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## SYSTEM CONFIGURATION

The solar system in Figure 1comprises of a solar collector and the storage tank unit.The flat plate collector produces heat from the energy of the sun absorbed by the absorber plate.The heat is transferred from the collector to the storage tank by heat transfer fluid (water). The storage tank contains water that accumulates heat obtained from the collector. The cold water enters the storage tank at the bottom and the extracted hot water from the top.

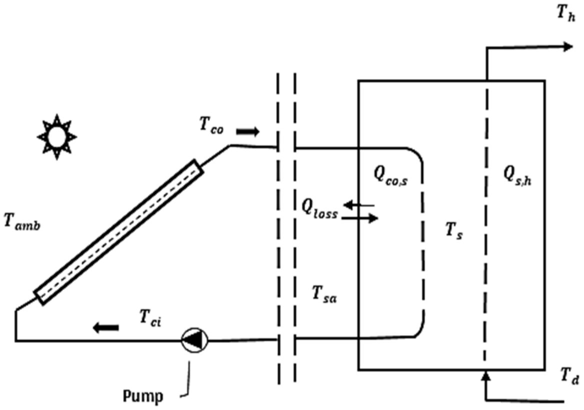

Figure 1: Schematic diagram of aSWH system.

The heat interaction between the system’s sub-models are set up such that $Q_{co,s}$ indicates the heat transfer between the collector and the storage tank and $Q_{s,h}$ ;the heat drawn by the load. $T_{co}$ and $T_s$ give the temperature of the collector and storage tank.

## MATHEMATICAL MODEL

The block-orientedmodelling approach of the solar domestic hot water system wasemployed.The entire model is made up of the sub-system models namely, solar collector and storage tank.

**Solar collector model**

A mathematical model for the solar energy collector plate was set up as shown in fig. 2. In order to simplify the model, the following assumptions are made:

(i) the fluid in the collector completely is mixed.
(ii) the temperature of the collector absorber plate is approximately equal to thatof the fluid running through it.
(iii) thermal property parameter of the fluid medium is independent of temperature.

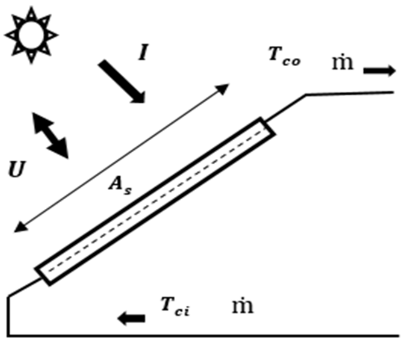

Figure 2: Schematic diagram of a solar collector.

A flat-plate solar collector is shown in Fig. 2, where the temperature of the fluid entering the collector is $T_{ci}$, the temperature of fluid leaving the collector $T_{co}$, the aperture surface of the collector $A_s$, the irradiance in the plane of the collector *I*, the mass flow rate of fluid ṁ, and the heat loss coefficient of the collector is *U*. The model describes $T_{co}$ as a function of $T_{ci}$, ṁ, *I*, and *U*.

The energy balance equation of the collector is given in equation 1 as:

$$\frac{dT_{co}}{dt} = \frac{A_s \eta_o}{C} I - \frac{U_L A_s}{C} (T_{av} - T_{amb}) + \frac{\dot{m}}{V} (T_{ci} - T_{co}) \tag{1}$$

where $\eta_o$ is the optical efficiency of the collector, C = $\rho c V$ is the overall heat capacity of fluid in the collector, $\rho$ is the density of the fluid in the collector, $c$ is the specific heat of the fluid in the collector loop, $V$ is the volume of the collector and $T_{av}$ is the average fluid temperature in the collector. The average fluid temperature in the collector is calculated in equation 2 as:

$$T_{av} = \frac{T_{ci} - T_{co}}{2} \tag{2}$$

***Storage tank model***

A mathematical model was set up for the hot water storage tank which adopts water as the heat storage medium. This is shown in Fig.3.In order to simplify the model, the following assumptions are made in this paper:

(i) thewater in the storage tank is fully mixed, sothe temperature distribution is even.
(ii)the heat capacity of the storage tank material is not taken into account.
(iii) the supplied cold water temperature $T_d$ is constant.

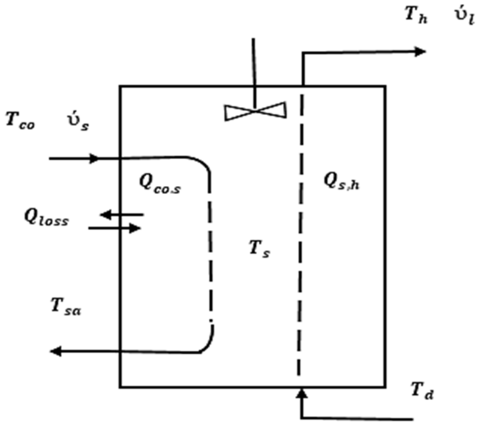

Figure 3: Schematic diagram of a storage tank.

The model is built up as a fully-mixed storage tank where the heat is transferred from the collector to the tank by a heat transfer fluid (Busaz et al, 1998). $T_s$ isthe water temperature of the storage tank, $T_{sa}$ is the ambient air temperature of the storage tank, $T_{co}$ is the temperature of the solar liquid which comes from the collector, $V_s$ is the volume of the storage tank, $T_d$ is the temperature of the supplied cold water, $\acute{\upsilon}_s$ is the volumetric flow rate of the collector, and $\acute{\upsilon}_l$ is the volumetric flow rate of the extracted hot water.

The energy balance equation of a thermally-mixed storage tank unit is given in equation 3 as:

$$\frac{dT_s}{dt} = \frac{\acute{\upsilon}_s}{V_s}(T_{co} - T_s) + \frac{\acute{\upsilon}_l}{V_s}(T_d - T_s) - \frac{A_t k_s}{\rho_s c_s V_s}(T_{sa} - T_s) \tag{3}$$

where$k_s$ and $A_t$ are the heat loss coefficient and the boundary surface of the storage tank respectively and $\rho_s, c_s,$ *and* $V_s$ are the density, heat capacity and volume of the fluid in the tank respectively.

**Simulation Model Based On Matlab/Simulink**

The dynamic simulation of each part of the solar water heating system is established based on the derived mathematical models using the MATLAB/Simulink platform. This are shown in figures 4 and 5. The input variables of the overall system model are the solar irradiance intensity on the absorber plate $I$, the collector ambient temperature $T_{amb}$, the volumetric flow rate of the collector fluid $F_C$, the ambient air temperature of the storage tank $T_{sa}$, the temperature of the solar liquid which comes from the collector $T_{co}$, the temperature of the supplied cold water $T_d$, the volumetric flow rate of the collector $\acute{\upsilon}_s$, and the volumetric flow rate of the extracted hot water $\acute{\upsilon}_l$.

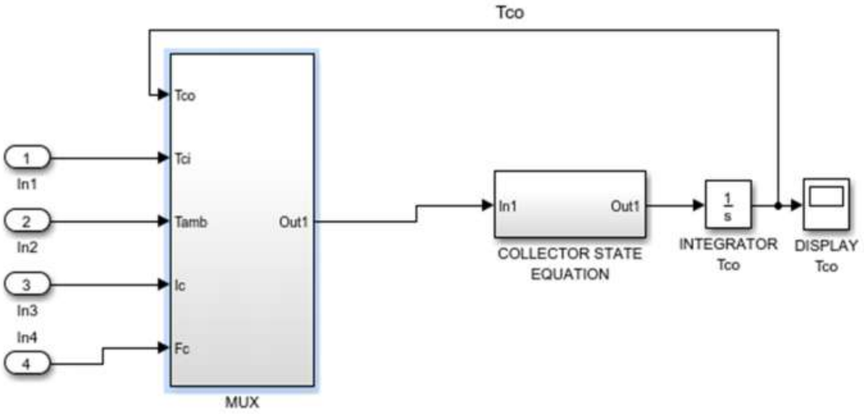

Figure 4: A simulation model of the solar collector.

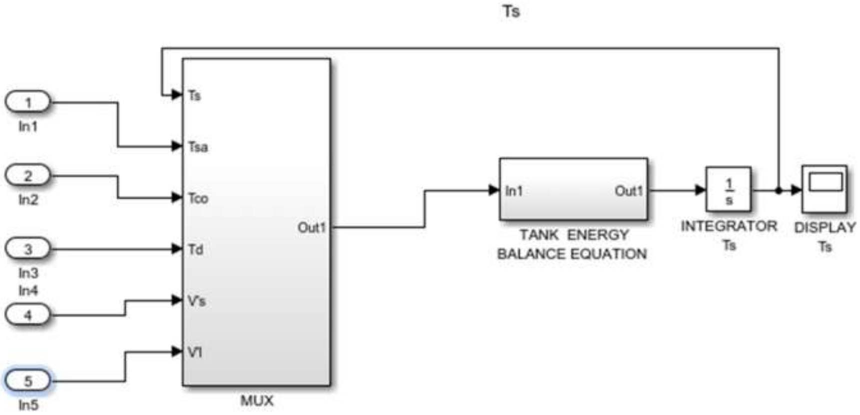

Figure 5: A simulation model of the storage tank.

**Simulation parameters**

The final system characteristics and design parameters adopted for the system performance simulation using MATLAB Simulink are shown in Table1.

Table 1. Parameters of the solar water heating system.

| **Items** | **Condition** |
|---|---|
| Location | Alabata |
| Latitude | 7.2°N |
| Testing period | December 2019 |
| The volume of water to be heated (V) | $0.1 m^3$ |
| Ambient temperature $(T_{amb})$ | 25°C |
| Collectorinlet temperature $(T_{ci})$ | 20°C |
| tank cold water temperature $(T_d)$ | 20°C |
| Collector outlet temperature $(T_{co})$ | 70°C |
| Top, edge and bottom loss | Negligible |
| Orientation | Due South |
| Collector inclination angle(β) | 7 ° |
| Collector type | Glazed collector |
| Collector optical efficiency $(\eta_o)$ | 0.8 |
| Collector heat loss coefficient $(U_L)$ | $7 W m^{-2} K^{-1}$ |
| Collector volumetric flow rate $(F_c)$ | $0.00015 m^3 s^{-1}$ |
| Tank Height (h) | 1m |
| Tank Diameter (d) | 0.44m |
| Tank heat loss coefficient $(U_L)$ | $250 W m^{-2} K^{-1}$ |
| The density of water (ρ) | $1 kgm^{-3}$ |
| Specific heat capacity of water (c) | $4200 J kg^{-1} K^{-1}$ |

The assumptions adopted for this study stemmed from the need to provide heat energy for residential heating systems. Hence, they are not suitable for larger systems used in industrial application.

## System Design and Sizing

### Mean solar radiation intensity for December

The average solar insolation for Alabata, the global horizontal irradiation, as well as the average daily hours of sunshine for the month of December, are obtained for Abeokuta. The necessary data are provided in Figures 6 and 7 respectively.

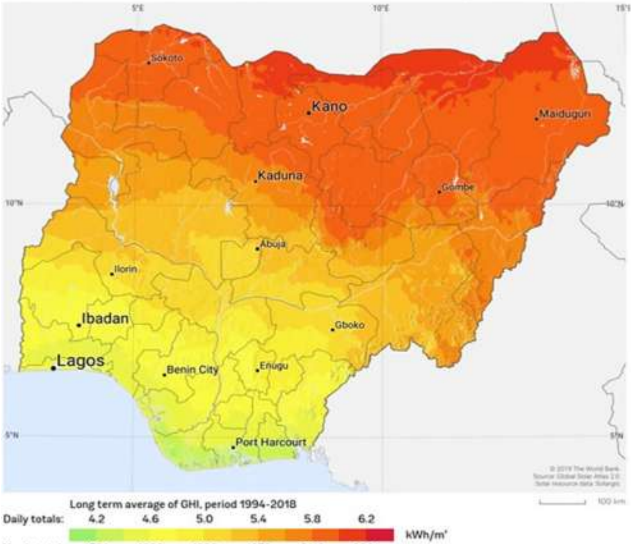

Figure 6: Global horizontal irradiation in Nigeria (Solargis, 2019)

From figure 6, daily global irradiation in Abeokuta is 4.8kWh/m$^2$/day.

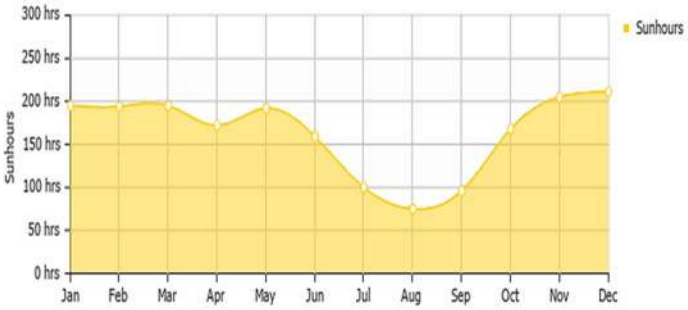

Figure 7: Average monthly sun-hours in Abeokuta. (Weather and climate, 2019).

Figure 7 shows that the monthly sun-hours for the month of December is approximately 210 hours = 210h/31days = 6.8h/day.

Mean solar radiation intensity = $\frac{Daily\ global\ irradiation}{Average\ daily\ sun-hours}$

Mean solar radiation intensity in W/m$^2$ = $\frac{4.8 \times 10^3\ Wh/m^2/\ day}{6.8h/day}$ = 705W/$m^2$

**Sizing of the collector based on hot water demand**

Hot water demand determines the sizing of the collector area. The heat requirement $Q_f$ is given in equation 4 by:

$$Q_f = \dot{m}c\,(T_{co} - T_{ci}) \qquad (4)$$

Since Mass = Density × Total Volume = ρV

Substitute for mass in equation 4 yields:

$$Q_f = \rho V c\,(T_{co} - T_{ci}) \qquad (5)$$

Therefore, for 100 liter of water, the heat requirement is

$$Q_f = 1\times100\times4200(70\text{-}20)$$

$$=21000000 \text{ Joules}$$

The collector area is given in equation 6 by:

$$A_C = \frac{Q_f}{\eta_o t I} \qquad (6)$$

Where *t*is the heating time and *I* solar radiation.

$$A_C = \frac{210000000}{0.8\times7\ 05\times6.8\times36\ 00} = 1.5\ m^2$$

The solar collector ofarea $1.5m^2$ is required to heat the water of capacity 100 litre per day from 20°C to 70°C for approximately 7 hours.

**Sizing of Storage Tank**

**The volume of the hot water tank**

The volume of the hot water tank was determined based on the collector area. The hot water tank capacity should be 1.5 to 1.6 of theoperating hot water load (Danshehu, 1997), and (Bande, 2011). Therefore,

Tank Volume = 100 litres ×1.5 = 150 litres.

### 3.5.3.2 The area of the hot water tank

The area of the cylindrical hot water tank canbe obtained using the formula in equation 7 as,

$$A_t = 2\pi r\,(r + h) \qquad (7)$$

$$A_t = 2\times\pi\times0.22(0.22+1) = 1.68\ m^2$$

## RESULTS

**Collector tilt angle ($\beta$)**

The tilt angle of the solar collector greatly influences the amount of solar radiation the solar collector receives from the sun, Figure 8 shows that the angle at which this collector receive the highest solar radiation is approximately 7.2° which is the latitude of Alabata as confirmed by (Soteris, 2009); the highest solar radiation is received at angle of the collector equal to the latitude of the location. Therefore, for this study, 7.2° was used as the optimum collector tilt angle which is the same with the latitude of the location (Alabata).

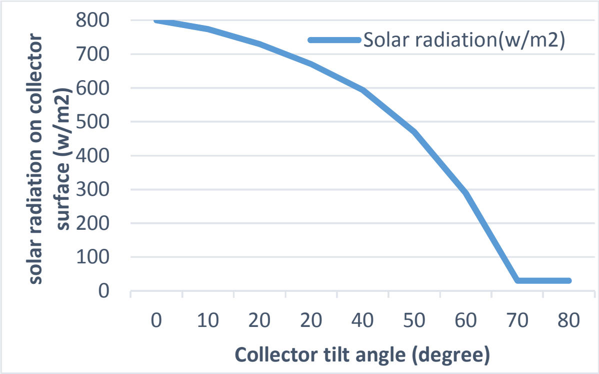

Figure 8: Solar radiation versuscollector tilt angle.

**Collector thermal efficiency ($\eta_o$)**

Figure 9 shows the variation of thermal efficiency of the solar collector with time for a typical day in the design month. Thehourly collector efficiency increases from 20% at 9.00am, reaches its highest value of 86% at 1 pm and decreases back to 37% at 5.00pm.It was observed that there is a strong relationship between daily insolation and thermal efficiency. Where there is high daily insolation, high thermal efficiency is obtained.

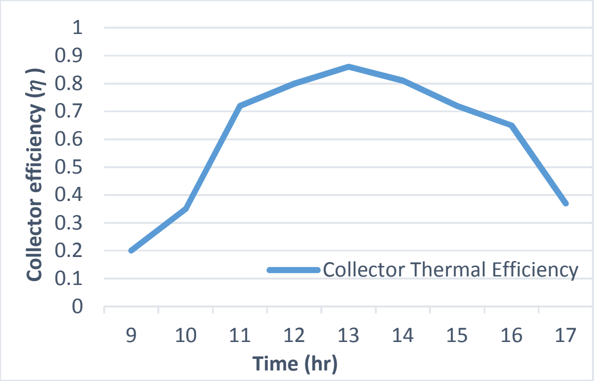

Figure 9: Collector thermal efficiency versus Time (hr)fot the month of December.

Simulated result for temperature against time for the collector output is shown in fig. 10. From the figure, the maximum energy gained is at 1 PM which is equivalent to 69.98°C, at this time, radiation is at its maximum level.The ambient temperature is comparatively high and the losses are therefore relatively minimal.

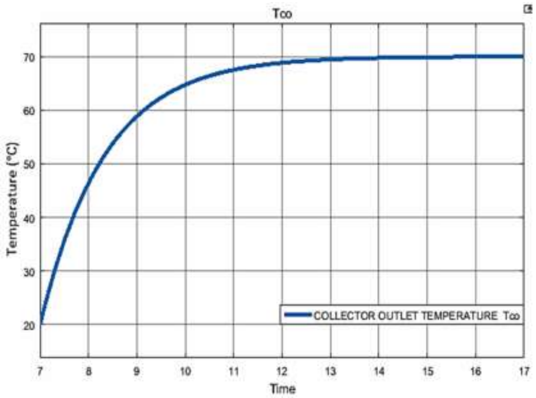

Figure 10: Simulated result for temperature versus time for collector output.

Figure 11 shows the hourly variation of hot water temperature in the solar collector andstorage tank with solar data for the month of December between 7am to 5pm.

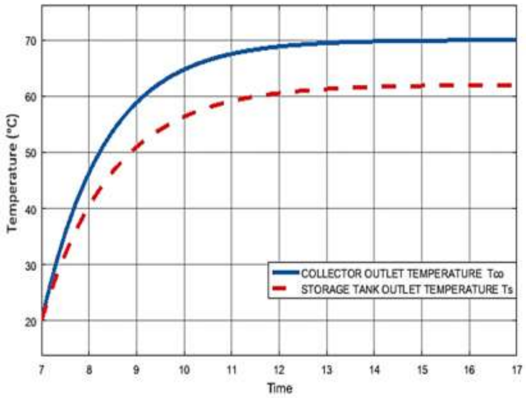

Figure 11: Comparison of the simulated result for temperature versus time for water outlet temperatures in the solar collector and tank.

From the result, it is inferred that the water temperature output in the tank is lower than the water temperature in the collector, since the hot water exiting the collector get mixed with the comparatively colder water contained in the storage tank. Maximum and minimum temperatures of collector hot water in tubes was found to be 69.98°C and 20°C at 1 pm and 7 am respectively.

## CONCLUSION

The dynamic simulation of the mathematical model of a SWH system composed of a solar collector and a thermal storage tank was established according to the law of energy conservation using MATLAB's Simulink block-oriented approach. The influence of inclination angle of the collector, the collector optical efficiency as well as the flow rate of theheat transfer medium have been investigated.

The heat storage mode via the MATLAB simulation showed that the maximum temperature of the solar collector was 69.98℃ compared to the tank output temperature which stood at 61.98 ℃ . System performance evaluation indicates a heat loss of 8℃ to the surrounding.

In this paper, according to the simulation results, it can be concluded that a SWH system ofcollector area 1.5 $m^2$ has the ability to heat 150 liters of water to a temperature of 61.98℃ on a moderately sunny day in Alabata, Abeokuta, Nigeria.

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## NOMENCLATURE

**Symbols**
$A_s$ = Surface area of collector ($m^2$)
$A_t$ = Boundary surface of tank ($m^2$)
C = Specific heat capacity of collector fluid (J $kg^{-1}$ $K^{-1}$)

C = Overall heat capacity of the fluid ( J $kg^{-1}$ $K^{-1}$)
$F_c$ = Volumetric flow rate of collector fluid (kg $s^{-1}$)
H = Tank height (m)
I = Collector irradiance (W $m^{-2}$)
$k_s$ = Heat loss coefficient of tank (W $m^{-2}$ $K^{-1}$)
$\dot{m}$ = Mass flow rate of fluid (kg $s^{-1}$)
$Q_{co}$ = Heat gained by absorber plate (W)
$Q_f$ = Heat absorbed by fluid (W)
$Q_s$ = Heat gained by storage tank (W)
$Q_h$ = Heat drawn by load (W)
$r$ = Tank radius (m)
$t$ = Heating time (s)
$T_{amb}$ = Ambient temperature (°C or K)
$T_{ci}$ = Collector inlet temperature (°C or K)
$T_{co}$ = Collector outlet temperature (°C or K)
$T_{sa}$ = Storage tank ambient temperature (°C or K)
$T_d$ = Supplied cold water temperature (°C or K)
$T_h$ = Extracted hot water temperature (°C or K)
$T_{av}$ = Average fluid temperature (°C or K)
$U$ = Collector heat loss coefficient (W $m^{-2}$ $K^{-1}$)
$V$ = Volume ($m^3$)
$\acute{\upsilon}_l$ = volumetric flow rate of extracted hot water (kg $s^{-1}$)
$\acute{\upsilon}_s$ = collector volumetric flow rate (kg $s^{-1}$)
$V_s$ = Storage tank volume ($m^3$)

**Greek**
$\eta_o$ = Optical efficiency (dimensionless)
Π = Tank circumference/diameter ratio
ρ = fluid Density (kg $m^{-3}$)
β = Collector Tilt Angle (degree)

**Acronyms**

MATLAB = Matrix Laboratory
SHTES = Sensible Heat Thermal Energy Storage
SWH = Solar Water Heating
TES = Thermal Energy Storage