Experimental Analysis of a 200 Litre Underground Thermal Storage Reservoir for Solar Water Heater System

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Abstract
The paper seeks to explore the concept of underground thermal storage tank system for the purpose of increasing the thermal storage duration of solar water heating system (SWHS) to meet daily hot water demand. A laboratory pre-testing of the temperature retention capacity of thermal storage tank without any form of lagging shows an average temperature loss of 3^0C per hour and an average temperature loss of 1^0C per hour, when it was lagged (with only polystyrene) before deployment to the site. The experimental setup of the system comprises an overhead cold water storage tank, circulation pump, two collectors (a flat plate collector and an evacuated collector), a 200 litres underground thermal storage tank and a temperature data logger with temperature probes. A five months (May, 2021 to September, 2021) experimental investigation of the underground thermal storage tank installed at the Good Pasture Clinic and Maternity, Kano shows that it took five months for the temperature of water of about 42^0C to fall to about 28^0C. The first two months recorded a temperature drop in the water of about 3^0C, while the third month recorded about 7^0C drop in water temperature. A sort of thermal equilibrium was reached with temperature of water fluctuating around 29^0C and 28^0C in the fourth and fifth months of the experiment. From the empirical results presented, underground thermal storage tank can increase the thermal retention capability of solar hot water system for use during nocturnal and overcast periods.

Key Words: Renewable, Solar, Intermittent, Underground, Seasonal and Temperature.

Introduction
The ever-increasing world energy demand coupled with the environmental degradation from the use of conventional fossil fuels is twin challenges currently facing the world (Ternenge, *et al.,* 2021). The volatility and uncertainty in global oil prices, as well as environmental challenges emanating from its exploration and usage has created an environmental, as well as an energy crisis situation across the globe. This crises situation has compelled a global campaign for a significant change from over reliance on fossil fuel to other alternatives, especially green energy. Renewable energy is, no doubt, a viable solution to Nigeria's energy crises. Solar energy, being one of the viable and readily available renewable alternatives, can provide sufficient energy to heat up fluid to a desired temperature for both domestic and industrial applications with cost reduction in energy and its associated consumption (Oguche, *et al., 2020).*

The process of solar water heating and thermal storage systems involves some technicalities, such as, sizing, material selection, insulation, techniques and thermal transport among other considerations. Solar water heating, therefore, as advanced by Arekete (2013), is a means of tapping energy from the sun, with the sole aim of raising the temperature of water from local water supply, in order to achieve a desirable higher temperature. The irregular feature of solar radiations is a significant drawback; hence, effective thermal storage system for optimal supply of hot water will help meet hot water demand. In order to play a key role in the future energy system infrastructure, thermal energy storage technologies would have to be developed, as this would help in enhancing the availability of energy in line with its demand (Koornneef, *et al.*, 2019).

Worthy of note is the notion that, there has been a steady growth in the global market for the generation of clean energy, for which storage technologies have become viable means and solution in dealing with the sporadic nature of renewable resources (Menéndeza, *et al.*, 2019). Various forms of thermal storage systems have been developed and experimented upon in the past. The underground thermal storage system as a form of thermal storage system is a virgin research area, especially in sub-Saharan Africa, as compared to European climes or cold climate where it is gaining more acceptability and has been deployed for seasonal thermal storage for space heating and other thermal applications. The use of sensible heat storage materials for underground thermal energy storage (UTES) demonstrates high prospect for solar thermal energy storage for thermal application (Oguche *et al 2020).*

Literature Review

The concept of the underground thermal storage system like other thermal storage system is simply to store heat collected from a heat source into an insulated built ground facility to be used in a later time. Several research efforts on improving solar thermal storage system have been carried out over the years with new innovations ongoing. A study conducted by Pavlov and Olsen (2011) indicates that, the concept of central solar heating plants with seasonal storage of solar energy requires further research activities, so as to make it economically competitive with conventional energy sources. Similarly, Hailu *et al.*, (2017) carried out an experimental investigation into seasonal solar thermal energy sand bed storage in a region with extended freezing periods. The difference between the maximum measured and simulated temperatures was found to be 15%, while the difference between the average measured and simulated temperatures was 4.7%.

In their study, Zhou, et al. (2020) describes the technical classification and operating principles of underground seasonal thermal energy storage. They review the state-of-art of underground seasonal thermal energy storage across the globe; hence their prediction of the development trends of the technology. In another instance, Li et al., (2020) in their study on space heating management for solar heating system with underground pit storage, built a pilot solar heating system integrated with a 3000m^3 underground pit seasonal storage.

In another light, the finding from the study by Akhmetov et al., (2016) reveals that, one of the technologies that allows the storage of thermal energy in a large-scale is underground thermal energy, which is based on phase change materials known as latent heat storage. Similarly, a critical review on large scale hot water tank and pit has been performed by Dahash *et al.*, (2019). They anchored their study on advances in seasonal thermal energy storage for solar district heating applications. Thus, the study reviews the different seasonal thermal energy storage technologies that are feasible for district heating applications.

Koornneef *et al.*, (2019) have implemented a study on heat store. The focus is on high temperature underground thermal energy storage using six new demonstration pilots and eight case studies of existing systems with distinct configurations of heat sources, heat storage and heat utilization. The study aimed at lowering cost, reducing risks and improving the performance of high temperature ($\sim 25^0C\ to \sim 90^0C$) underground thermal energy storage technologies to optimize heat network demand side management. A study on underground solar energy storage via energy piles have been carried out by Ma, and Wang, (2020). In the study, thermal performance of an energy pile-solar collector coupled system for underground solar energy was examined, using numerical modelling. According to the authors, findings obtained from the study recommended that a lower flow rate should be adopted for the energy pile-solar collector coupled system to save the operational cost of the circulation pump.

Significance of the Underground Storage Tank

Solar energy is one of the viable renewable energy sources that can be deployed for a range of applications. It is a cleaner and environmentally friendly energy source; however, due to the irregular and changeable nature of solar energy, it is difficult to supply solar thermal energy without having an effective thermal storage system (Akhmetov, *et al*., 2016). The underground thermal storage tank is suitably posed to providing viable and durable thermal energy storage for solar hot water systems, which can be deployed to augment the huge hot water demand in hospitals, hospitality industries and manufacturing industries. Asides seasonal storage applications, the underground thermal energy storage (UTES) tank can be deployed in climes within or around the sun-belt to tackle the increasing high volume demands of daily hot water for domestic, commercial and industrial sectors, as well as air district heating (Oguche *et al 2020).* There are also combinations in which the storage is used for both short-term and seasonal storage (Nordell, 2012).

Sensible Heat Storage Fundamentals

Thermal storage can be regarded as a "heat battery", due to its potential to store heat energy to be released later (Stevens *et al.*, 2013). According Stevens *et al.*, (2013), all thermal storage systems have these three functions, namely: Charge, Storage and Discharge.

The volume of heat that a material can accommodate is largely dependent on the amount of material present, as well as its specific or exact heat. The specific heat capacity (c_p) is the amount of heat needed to raise one kilogram of a substance by 1°C (Stevens *et al.*, 2013). The amount of sensible heat (Q) stored in a mass is given by the equation 1 below:

$$Q = mc_p\Delta T \tag{1}$$

Where:

m = Mass of substance

(c_p =Specific heat of substance

ΔT= Temperature change

According to Kumar and Shukla, (2018), sensible heat storage (SHS), thermal energy is stored by raising the temperature of a solid or liquid. The amount of heat stored depends on the specific heat of the medium, the change in temperature and the amount of storage material as shown by equation below (Kumar and Shukla, 2018):

$$Q = \int_{T_i}^{T_f} mC_p dT = mC_{ap}\left(T_f - T_i\right) \tag{2}$$

Tiwari (2002) further expressed sensible heat storage in terms of density and volume of the material as:

$$Q = V\int_{T_i}^{T_f} \rho C_p dT \tag{3}$$

Hesaraki, *et al.*, (2015) has also expressed equation (3) as the highest total storage capacity of a storage medium and it is calculated thus:

$$Q_{max} = V \times \rho \times C_p(\theta_{max} - \theta_{min}) \tag{4}$$

Where:
$Q_{\mathbf{max}}$ = maximum total storage capacity
V = the volume of the thermal energy storage (m^3)
ρ = the medium density (kgm^{-3})
C_p = the specific heat of the storage medium ($Jkg^{-1}K^{-1}$)
θ_{max}= the temperature of fully charged storage
θ_{min}= the temperature of fully discharged storage
Low temperature seasonal thermal energy storage

Water appears to be the best SHS liquid available because it is inexpensive and has a high specific heat. However, above 100^0C, oils, molten salts and liquid metals etc. are used. For air heating applications, rock bed type storage materials are used (Kumar and Shukla, 2018).

Methodology

Experimental Setup

The experimental setup of the system was built and located at the facility of Good Pasture Clinic and Maternity, located at No. 6 Citta Avenue, No-Mans-Land Kano, Nigeria. Experiments on the system were conducted under Kano's meteorological conditions. The solar water heater system as shown in figures 1 and 2 comprises of the following components:

a. Cold water feed tank
b. Two collectors (flat plate and evacuated tube) connected in series
c. Underground thermal storage tank
d. Circulation pump
e. Temperature data logger with temperature probe

The cold-water feed tank mounted on elevated tank stand, supplies cold water to the solar water heating source (comprising of a flat plate collector and evacuated tube collector connected in series) via gravity. The hot water is then distributed to end users as well as conveyed to the underground thermal storage tank when not in use for storage for later usage.

A pump connected to the underground thermal storage tank was used in circulating hot water stored to end users as well as recirculate back to the heating sources when necessary. Figure 3 shows a sectional view of the underground thermal storage tank made from stainless steel with polystyrene, wood and concrete as its lagging material casing. Temperature probes connected to an MSSI temperature data logger was used for temperature monitoring of the system as shown in figure 1.

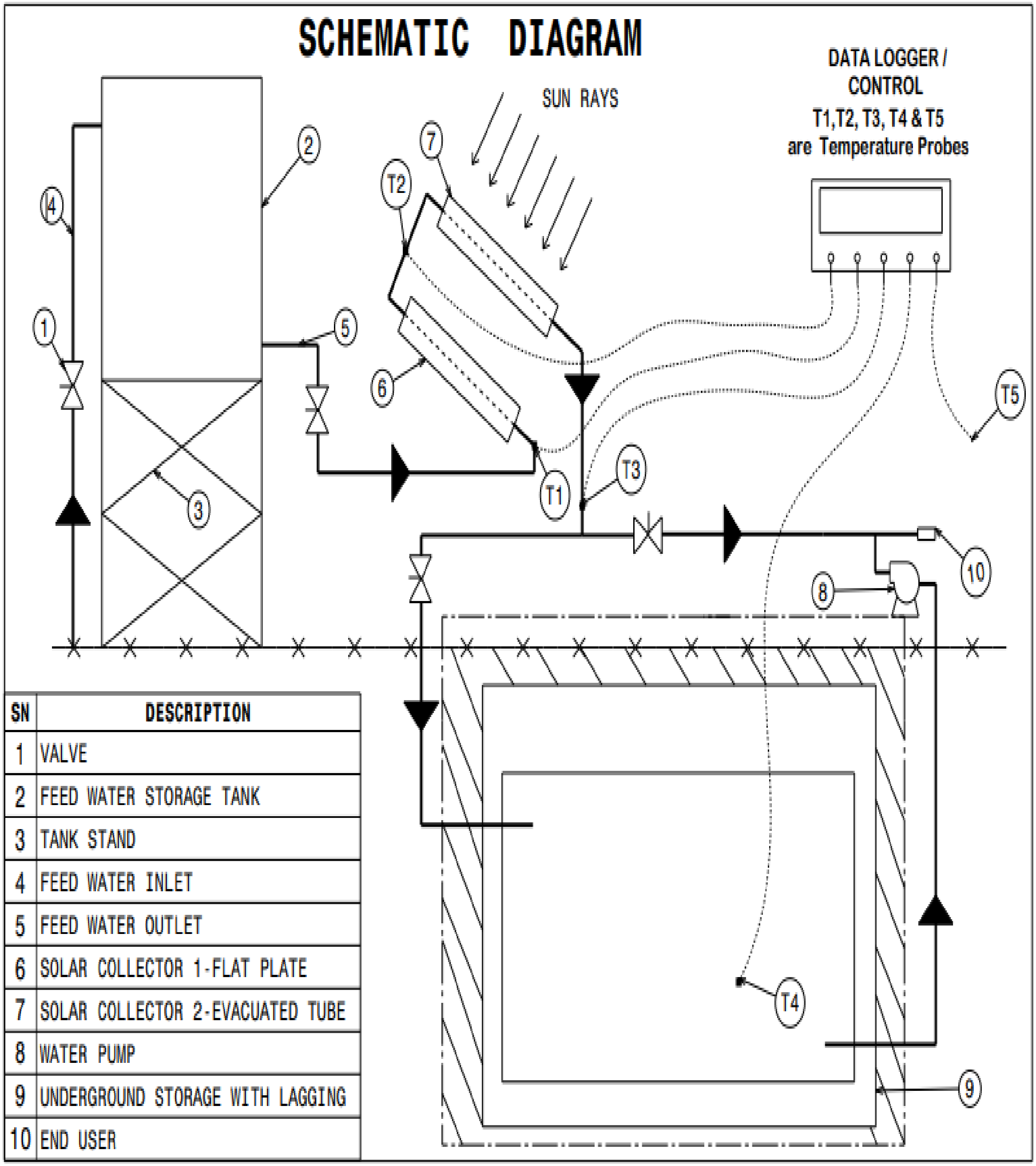

Figure 1: Schematic diagram of the experimental setup (Oguche *et al.,* 2022)

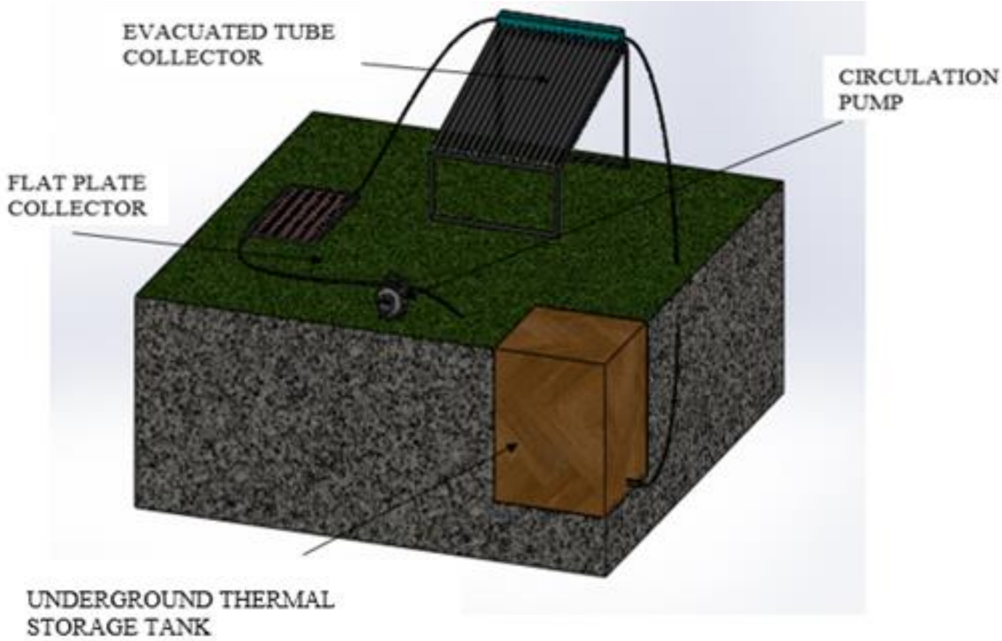

Figure 2: System Assembly

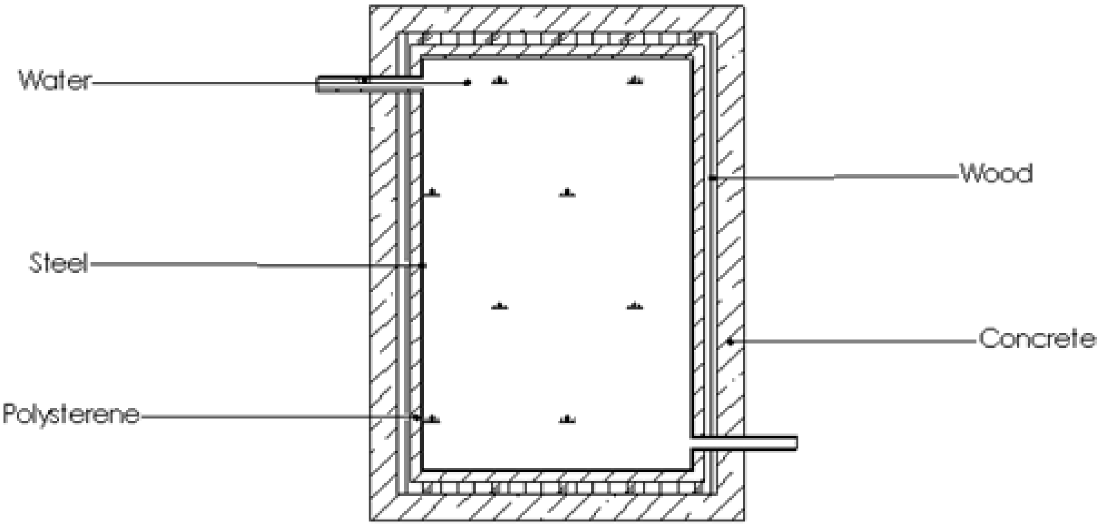

Figure 3: Sectional view of underground thermal storage tank

Results and Discussions

Tables 1 and 2 presents data observed during the pre-testing experiment of the 200 Litres thermal storage tank at the thermodynamic laboratory of Bayero University, Kano between 14th and 28th of March, 2021. The experiment involves testing the temperature retention performance of the storage tank without any sort of lagging in place and then with lagging respectively, before deploying to site to be buried in an underground concrete casing. Figures 4 to 8 presents a weekly average temperature performance of the empirical underground thermal storage tank (UTST) for five months (May, 2021 to September, 2021) while figure 9 gives a five months summary of the monthly average temperature performance of the (UTST).

Table 1: Performance Testing of the Storage Tank without Lagging (Thermodynamic Lab 14/03/2021)

S/N	Time (Hr)	Hot Water Temp. in Tank (Without Lagging) (^{0}C)	Ambient Temp (^{0}C)
1	12.00	55.7	33.7
2	13.00	52.3	33.7
3	14.00	50.8	32.9
4	15.00	49.3	31.4
5	16.00	45.6	30.1
6	17.00	43.7	29.6
7	18.00	43.1	29.4

Table 2: Performance Testing of the Thermal Storage Tank with Lagging (Thermodynamic Lab. - 27/03/2021)

S/N	Time (Hr)	Hot Water Temp. in tank (with Partial lagging) (^{0}C)	Ambient Temp. (^{0}C)
1	12.00	64.4	29.9
2	12.30	64.1	29.9
3	13.00	63.9	29.8
4	13.30	63.8	30.1
5	14.00	63.2	30.0
6	14.30	62.5	30.1
7	15.00	62.0	30.1
8	15.30	61.6	30.0
9	16.00	61.4	30.0
10	16.30	61.1	30.0
11	17.00	60.7	29.9
12	17.30	60.2	29.7
13	18.00	59.8	29.7

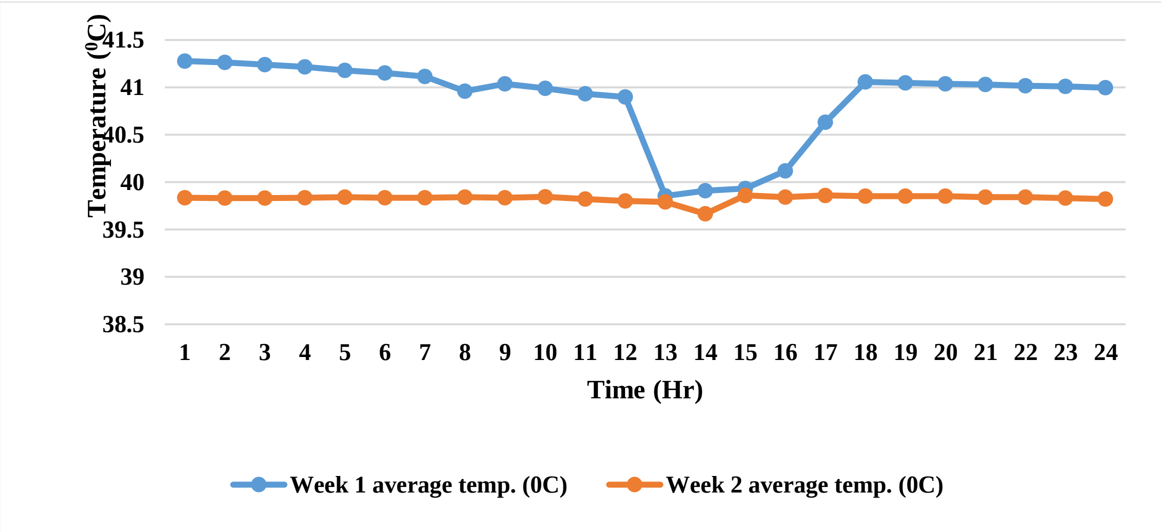

Figure 4: Weekly Average Temperature Performance of the Empirical Underground Thermal Storage Tank for the Month of May 2021

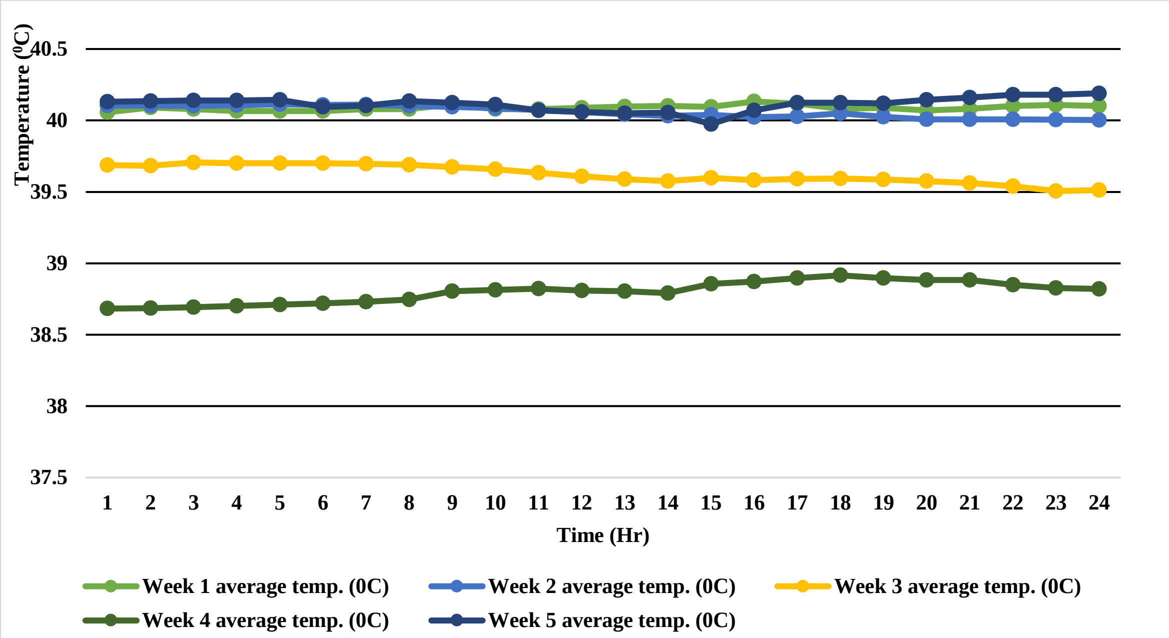

Figure 5: Weekly Average Temperature Performance of the Empirical Underground Thermal Storage Tank for the Month of June 2021

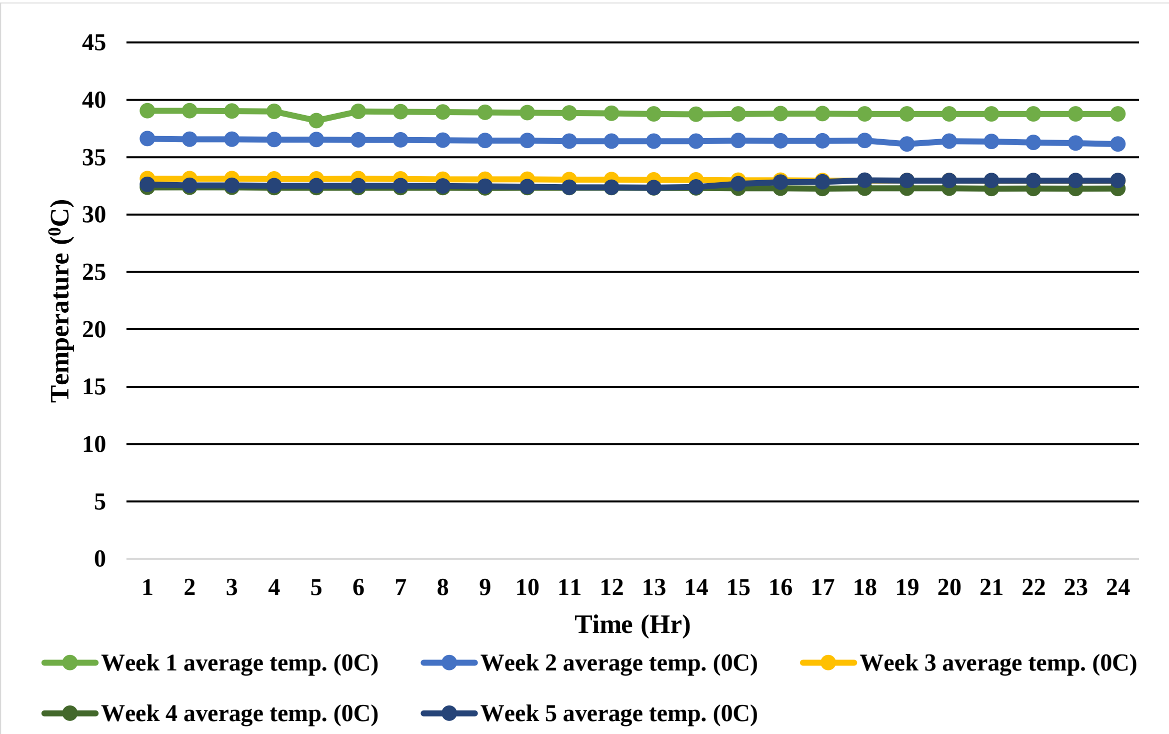

Figure 6: Weekly Average Temperature Performance of the Empirical Underground Thermal Storage Tank for the Month of July 2021

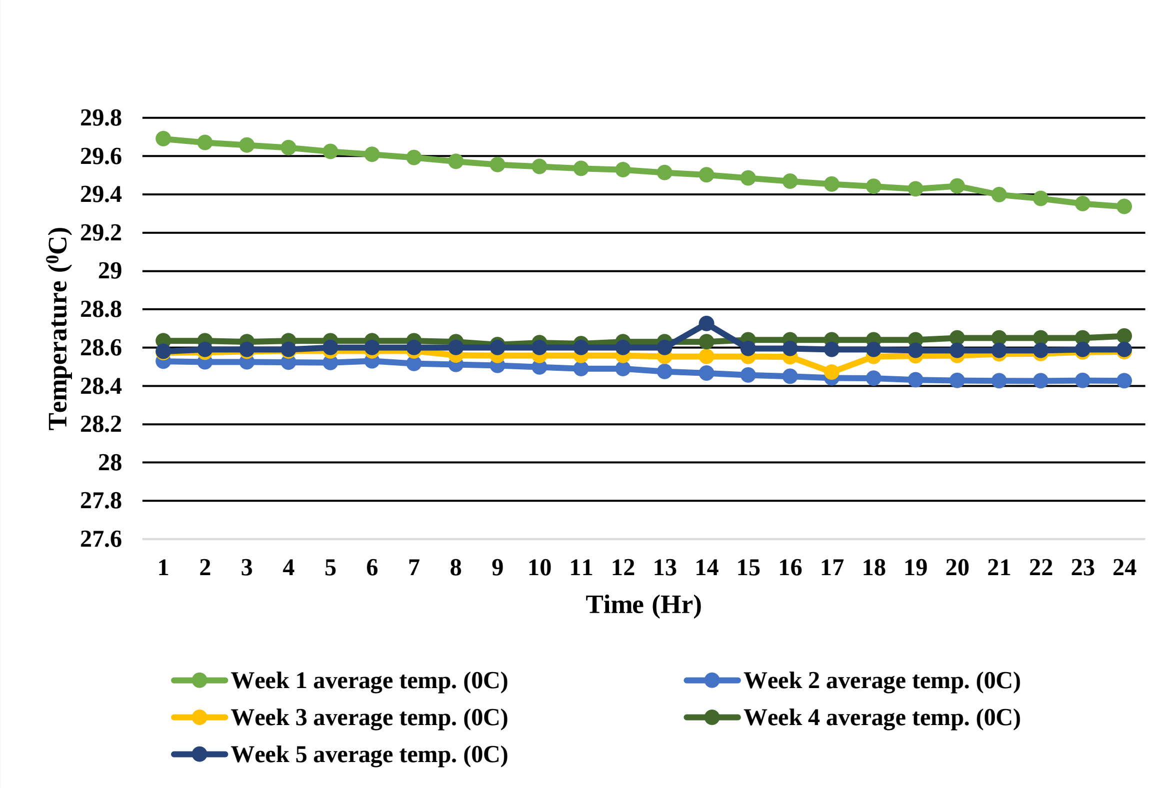

Figure 7: Weekly Average Temperature Performance of the Empirical Underground Thermal Storage Tank for the Month of August 2021

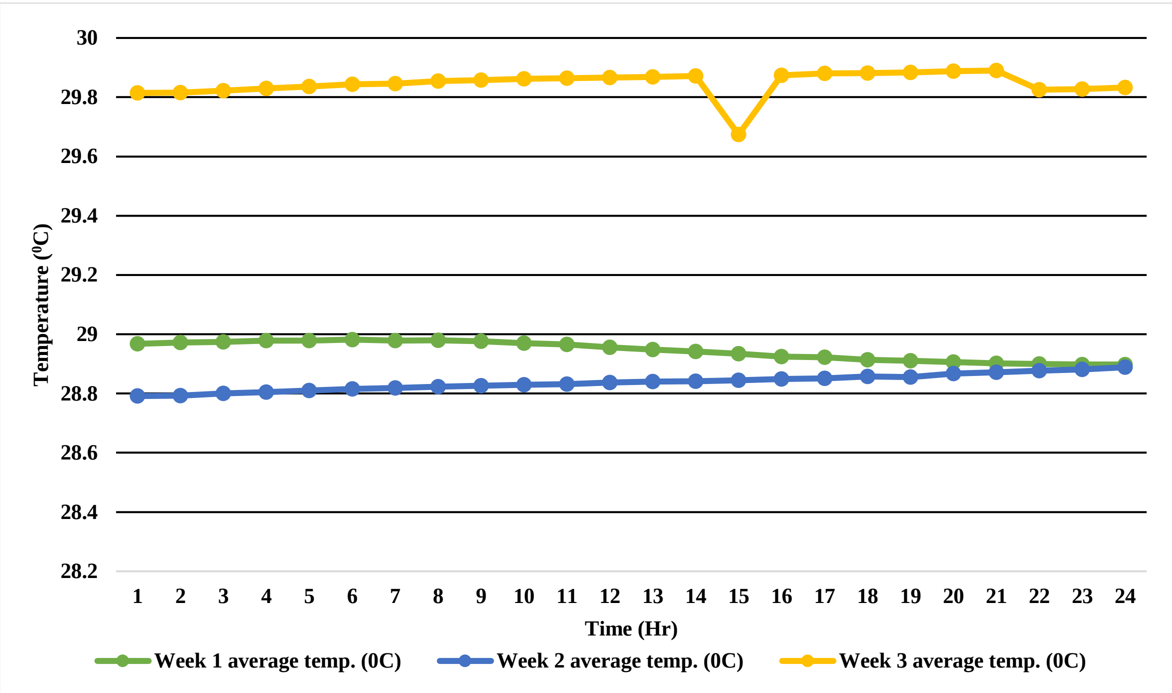

Figure 8: Weekly Average Temperature Performance of the Empirical Underground Thermal Storage Tank for the Month of September 2021

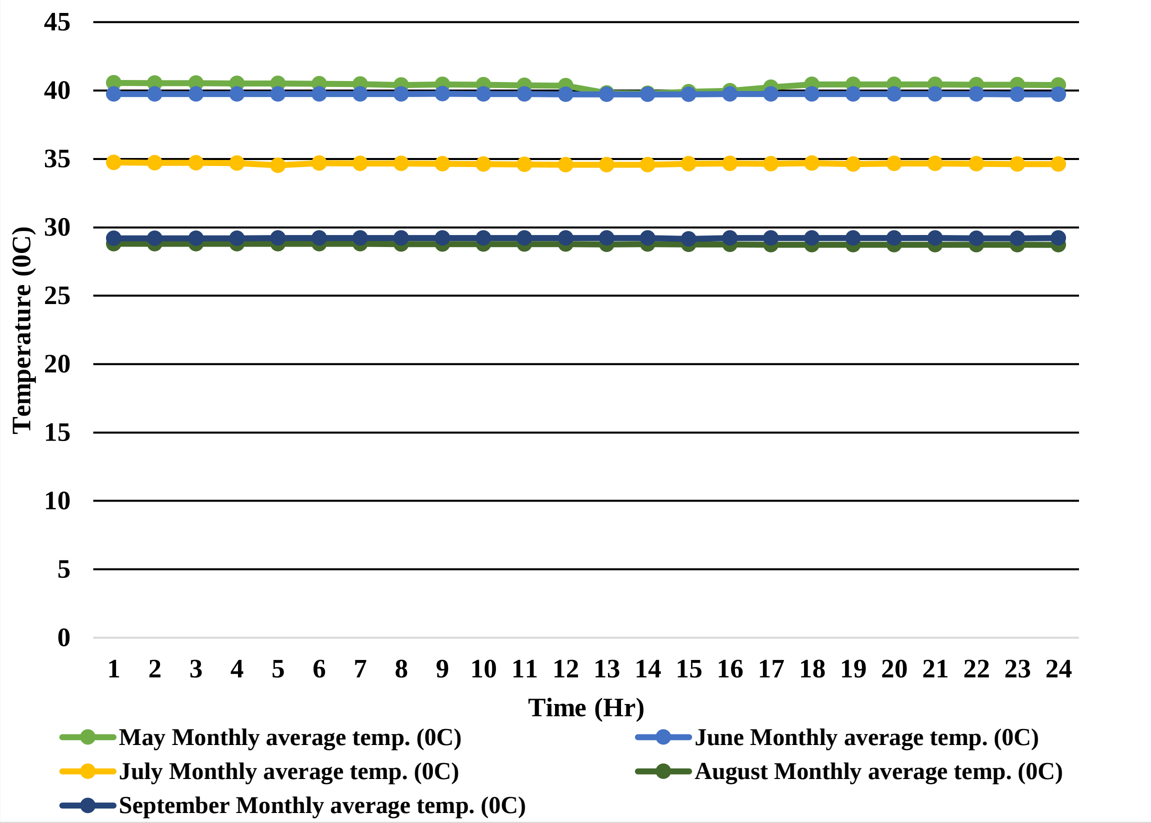

Figure 9: Monthly Average Hourly Temperature Performance of the Physical Underground Thermal Storage Tank for the Months of May, 202 to September 2021

For both experiments conducted at the laboratory as, water was heated using electric heater, while solar collector was used on site for the solar water heater. As observed in Table 1, the preliminary performance testing of the storage tank without lagging took about 6hours for the temperature of hot water to drop from 55^{0}C to 43^{0}C with an average temperature loss of 3^{0}C per hour. Similarly, when the same experiment was performed with lagging in place as shown in Table 2, it took about 6 hours for the initial temperature of hot water to drop from 64^{0}C to 59^{0}C with an average temperature loss of 1^{0}C per hour. After about 24Hours and 48hours check, the hot water temperature in the tank dropped to about 46^{0}C and 36^{0}C respectively. This implies the first 24hours witness a rapid loss in temperature (64^{0}C to 46^{0}C) as compared to the next 24hour (46^{0}C to 36^{0}C).

The rapid loss noticed in the first day may be due to convective heat loss attributable to the surrounding surfaces of the tank. The choice of stainless steel as material for the storage tank was influenced by its thermal properties and guaranteed safety for water storage against breeding of bacterial and algae. This makes it suitable for use in a hospital environment.

Conversely, the weekly average temperature performances of the empirical underground thermal storage tank for the period of may 2021 to September 2021 are presented in Figure 4, 5, 6, 7 and 8 respectively. Results from figure 9 give a summary of the monthly average hourly temperature performance of the empirical underground thermal storage tank.

It took about 5 months for the hot water temperature of about 42^{0}C to fall to about 28^{0}C. The month of May and June recorded a temperature drop of about 3^{0}C, while the month of July recorded a drop in hot water temperature of about 7^{0}C. A sort of thermal equilibrium was reached with temperature of water fluctuating around 29^{0}C and 28^{0}C in the months of August and September. The observed results have clearly demonstrated the underground thermal storage tank (UTST) as used in other climes for seasonal storage can be a suitable candidate for solar water thermal storage in northern Nigeria.

Conclusion

From the results presented and discussed, the underground thermal storage tank has proven to be a reliable and a viable thermal energy storage source for solar water heating system. The pretesting of the thermal storage tank shows an average temperature loss of 3^{0}C per hour when the tank was charged without lagging material in place and an average temperature loss of 1^{0}C per hour, when it was partially lagged (with only polystyrene). Performance analysis of the installed Underground Thermal Storage Tank (UTST) for the solar water heater was charged with initial temperature of about 42^{0}C in May, 2021. It took about five months for its temperature to fall to about 28^{0}C.An average temperature drop per month of about 3^{0}Cwas recorded for the first two months and 7^{0}C for the third month. A sort of thermal equilibrium observed for the last two months was observed with temperature fluctuating between 29^{0}C and 28^{0}C. The fluctuations in ambient temperature, cold water temperature has an inconsequential effect on the temperature of the tank. This shows as a testament, the suitability of the underground thermal storage tank as a candidate option for solar thermal storage that can be used to augment hot water demand during seasons of overcast.

Recommendations

From the foregoing presented results, discussions and conclusions, the following recommendations are appropriate:

i. The underground thermal storage tank should be located as close as possible to the solar collectors in order to reduce convective heat loss due to the long distance between heating source and storage.
ii. Temperature retention capability of ice cold water should also be experimented on the underground thermal storage tank model under Northern Nigeria weather condition. This will give a holistic thermal storage performance of the model and where to best deploy it.
iii. In order to cut down overhead cost for the system while maintaining high performance output, other materials for the construction of the thermal tank as well as for its lagging should be experimented upon.

Acknowledgements

The authors wish to recognise the support and contributions of the Chief Medical Director and staff of Good Pasture Clinic and Maternity, located at N0 6 Citta Avenue, No-Mans-Land, Kano-Nigeria, for their financial support, as well as for making their facility available for this experiment. Also, the technical support from technologist at the thermodynamic and the precision laboratory of the Department of Mechanical Engineering, Bayero University, Kano is appreciated. This is also to acknowledge profoundly, the contribution of the MD/CEO Mr. Alfred Iguh and technical staff of Alifig International Ltd, Abuja for providing the Data logger, the PT100 (3-Wire) Temperature Probes used for this study as well as the technical support they provided remotely. This kind gesture is truly appreciated.

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