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Design and Modelling of a Solar Water Heating System

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ABSTRACT

The demand for energy in Nigeria is usually met by burning fossil fuels such as charcoal, petroleum, natural gas, kerosene, etc. or by the use of electricity. These conventional energy sources are exhaustible, unstable and not environmentally friendly. Electricity generation in Nigeria is not sufficient enough to meet the demand for energy. This has often been blamed on lack of technical know-how, excess profiteering by marketers and large population size of the citizens. The seemingly alternative to these is burning of firewood. This however has its negative effects as exploitation of firewood will cause deforestation leading to desert formation in the country. Solar energy therefore appears to be the only veritable and viable alternative source of energy to heat water. It is inexhaustible, has no effect on the environment, and can be converted to many other forms of energy. Converting it to thermal energy in order to heat water is done with a solar water heating system. This work explores the use of solar energy to fulfil the hot water requirements in Nigeria and creates a model for the water heating system. Through modelling, the efficiency of the system and major factors affecting the system are determined. This project seeks to model a thermo-syphon system, which relates the effect of efficiency and also a gross area of the solar collector on the volumetric flow, from experimental results in Akure, Nigeria. Thermo-syphon systems, being the most suitable for the climate of Nigeria, were evaluated and analysed. The result of the analysis shows that if the efficiency of the system is increased, the area is increased resulting in an increase in the volumetric flow, which can be used to evaluate the amount of water being heated per time.

Keywords: Solar Energy; Solar Water Heating (SWH) System; Modelling, Volumetric Flow.

1. INTRODUCTION

The importance of energy in our modern environment cannot be overemphasized, as energy plays a vital role in the well-being of any society and human life. The effective use and supply of energy has an essential role in the economic development as well as the growth of the society. Energy sources are generally classified into two forms: non-renewable and renewable sources [1, 2]. Non-renewable energy is energy that comes from the ground and is not replaced in a relatively short amount of time after being exhausted, while renewable energy is energy that automatically replenishes itself from on-going natural processes [3]. For example, fossil fuels (such as coal, petroleum, and natural gas) and certain aquifers are all non-renewable energy sources, whereas sunshine, wind, flowing water, biological processes, and so on, are forms of renewable energy sources.

Solar energy is energy derived from the sun rays. The sun is the centre of the solar system with a surface temperature of about 5762°C, radiates about 1.353KW/m3 of solar power on the outside of the earth's atmosphere [4]. Presently, the use of conventional energy sources which are non-renewable like fossil fuels is increasing due to increase in demand as a result of population growth. Burning these fossil fuels accounts for the generation of carbon dioxide emissions in the atmosphere, which is the major cause of global warming and climate change [5]. Carbon dioxide emission from fossil fuels can therefore be mitigated by using more renewable energy, to supplement and in the future replace the use of fossil fuels.

Solar energy is often seen as the fuel for the future as it is environmentally friendly and inexhaustible. Solar energy is used in two major ways such as the generation of electricity and heat. Solar energy is renewable, zero-carbon energy source and can be used to displace non-renewable or carbon-emitting fuels [6]. In situations where it becomes difficult to upgrade a conventional domestic hot water (DHW) system or where the part load efficiency of a boiler is very poor, solar system becomes much useful, and as such can be used to mitigate carbon dioxide [6]. This type of renewable energy, if deployed rapidly, may lead to significant energy security, climate change mitigation, and economic benefits.

One of the major ways to harness solar is for water heating. Hot water also finds application in every sector. In Nigeria for instance, where fossil fuels are natural endowments, yet very expensive and not readily available, energy supply is therefore not contemporaneous with the demand for it, thus making it unreliable. Supplementing solar energy for producing hot water will not only make it a cheaper source but also more reliable. For instance, when the demand arises to quickly heat a small amount of water for drinking or to sanitizing equipment, going to make a fire from wood or using a stove is often cumbersome. In this situation, solar energy becomes simpler, strong and much compact solution [6, 7].

Modelling is the process of producing a representation of the construction and working of some system of interest [8]. Modelling serves to produce a similar but simpler version of the system it represents. The major purpose of modelling is to be able to predict the effect of changes to the system without having to spend money and time on trial and error construction. Modelling of the system helps to approximate the performance characteristics of collectors [8], solar fraction, and comparison between collector types. This makes modelling a very essential tool for the approximation and also prediction purposes.

This paper is organized as follows: the introductory part of the paper provided in Section 1.0 deals with the general perspective and objective of the work. Section 2.0 discusses the theoretical background and a review of relevant works on solar water heating system. Section 3.0 gives a detailed explanation of the system design and implementation, which includes design specification, methodology, and modelling of solar water heating system. The result of the modelling and its discussions are presented in Section 4.0. Finally, Section 5.0 presents the conclusion, recommendations and future work to be done.

2. REVIEW OF RELEVANT WORKS ON SOLAR WATER HEATING SYSTEM

The thermo-syphon SWH system designed by William J. Bailey is the basis on which other systems have been designed. Much research has been carried out on SWH systems and most of this research contains model that helps forecast the characteristics of the SWH systems. In [9], Michaelides used the models of TRNSYS (Transient Systems) program to compare the various types of SWH and solar space heating systems. This was used to identify and optimize the design of the most suitable system for Cyprus. He proposed that:

- Collector efficiency is a function of collector size.
- Tilt angle also affects the efficiency of the collector.
- Solar water heating is a cost effective application compared to electric water heating.

In [5, 10], a solar domestic water heating system was modelled and simulated using MATLAB programming language. Its findings revealed that systems with greater storage volume yield higher solar fraction. However, when the storage volume is larger, the solar fraction is less sensitive to a variation of the operating parameters. In [10], the f-chart modelling was used to optimize solar water heating sizing based on assumed collector parameters applicable in India. Using the f-chart, it showed the acceptable discount rate and the matching of load profile with the solar water heating system output. In [11], the performance of heat pipe solar collectors were investigated both theoretically and experimentally under different heat pipe condenser types and compared with conventional natural circulation solar collector. Numerical and experimental results were found with good agreement. In both cases, heat pipe solar collectors outperformed as compared with conventional natural circulation solar collector after the start up.

3. SYSTEM DESIGN AND IMPLEMENTATION

3.1 Design Methodology: This section gives an overview of the design procedures for a solar water heating system. It is further outlined in the following formats:

3.1.1 Typical Working Principle of Solar Water Heating System: Solar water heating system uses renewable energy from the sun to heat up water which is earth friendly. Solar water heating system is made up of the solar collector, storage tank, heat transfer fluid, system controls, depending on the type of system and backup heater where necessary.

The solar collector is installed to face the sun so as to absorb energy in the form of heat. This heat is transferred to the potable water in the storage tank, which is to be heated. This is possible either by thermo-siphon flow, where no pumping is required as hot water naturally rises into the tank or by heat transfer fluid between the tank and the solar collector. In some cases, there is pump circulation, in which the pump moves the potable water. Solar energy is available on demand for an average of 12 hours per day [11, 12]. Solar energy is therefore not available all day and also not in the same all year round. Therefore, backup heaters are necessary to maintain constant flow of hot water and sufficient insulation of the system.

3.1.2 Selection of Appropriate System: Integrated collector storage or batch systems are relatively the easiest and cheapest to build and are very similar to the earliest form of SWH systems. As a type of passive direct system, it has no basic protection against overheating and freezing. This type of system is suitable for moderate climates where temperatures do not get to zero degrees centigrade [6, 12, 13]. Convection heat storage systems or Thermo-siphon systems which are another passive direct type of system separates the collector from the storage tank. This makes this system more efficient than the ICS system as heat loss during the night cycle is reduced [13]. This type of systems is also suitable for moderate climates, but with sufficient freeze and overheat protection it will function in any climate.

Drain-back systems are suitable for very cold climates as it is an active indirect system type [14]. The system drains the HTF into a drain-back reservoir anytime the pump is switched off. This system requires a pump to circulate the HTF and needs electricity to power the pump unlike ICS or CHS systems. This type of system gives more flexibility in placement of the storage tank as the particular positioning of the tank is inconsequential.

3.1.2.1 Freeze Protection: When water freezes, it expands. Freezing occurs when temperatures drop below zero degrees centigrade, which causes the HTF or portable water in direct systems to expand. This expansion destroys the collectors and also the connecting pipes [14]. Frozen water in pipes is likely to rupture them, and this is a major cause of breakdown of solar heating systems [13, 14]. Freeze protection measures prevent damage that can affect the system due to the expansion of HTF in the system pipes and the collectors. This occurs in climates whose temperatures reach freezing temperatures. Some of the ways to prevent freezing include:

- ✓ Use of a freeze tolerance. Direct systems employ the use of freeze tolerance where low pressure polymer water channels made of silicone rubber simply expands on freezing accommodating the expansion caused by freezing [12, 15].
- ✓ Provide drain-back pipe design. Drain-back systems drain the HTF when the pump is switched off into the drain-back reservoir preventing it from freezing [10, 16].
- ✓ Use an anti-freeze solution in the outdoor collector and piping. One of such solutions is a water glycol mixture like ethylene and propylene glycol which are freeze resistant and can resist temperatures up to -20^{o}C. These antifreeze solutions have a disadvantage of causing corrosion at high temperatures [10, 15, 16].
- ✓ When there is no freeze tolerance applied for direct system manual draining will be required to prevent freezing [16].

3.1.2.2 Overheat Protection: This measure is used to protect the system from attaining excessive temperatures, which may occur if the hot water in the systems collector and storage are not used for long periods of time [17]. The state in which there is no net heat extraction from the collector is described as 'stagnation' [17]. If the collector is not designed for the 'stagnation' temperature, it can get to be over-heated and potentially unsafe.

In drain-back systems, the pump is switched off once the desired water temperature is reached and this will prevent the system from overheating, especially with the use of differential controller pumps. The Materials used in the system should be capable of withstanding the full range of temperatures to which they will be exposed [17]. This means that all the materials close to the solar collectors must be able to withstand the collector stagnation temperature and that the other materials in an indirect system should withstand temperatures up to 150 °C.

3.1.3 Selection of Solar Collectors: Solar collectors placed in view of the sun absorb and retain solar energy and convert it to heat, which heats up the water in the system. They can be regarded as the heart of the solar water heating system [18]. Choice of solar collector is dependent on the desired temperature output required of the system. This required temperature reflects the intended usage of the system. Unglazed collectors are suitable for low temperature applications like swimming pool heating. They are capable of absorbing heat from the surrounding even when the solar energy is no more available because the temperature of the water is lower than ambient temperature [18]. Flat plate collectors which are glazed, having more insulation, are suitable for moderate temperatures like domestic water heating [19]. When very high temperature is required evacuated tube collectors are more suitable. This can also be used for domestic water heating, and also finds application in electricity generation and absorption cooling [19].

3.1.4 Modelling of Solar Water Heating System: In this mathematical Modelling, we will be calculating the efficiency of the system, which will help in determining the size of the system as well as finding the relationship between the volume of water being heated and the solar collector area.

In solar collector efficiency, the surface area used is very important. There are three major forms of area, and they are: the gross area (which is calculated as the total width multiplied by the total height), aperture area (which is the total area of glazing exposed to sunlight for flat plate collectors), and absorber area (which is the total area of absorber material exposed to sunlight for flat plate collectors). For the purpose of this model the gross area will be considered in predicting the solar collector efficiency in a thermo-syphon system using flat plate collectors and then finding its effect on volumetric flow.

The radiant flux (R_f) striking the plate collector is

$$R_f = Ŧ_{cov} A_p G \tag{1}$$

Where, $Ŧ_{cov}$ = the transmittance of the transparent cover

Ap = exposed area of plate

G = the irradiance on the collector

Only a fraction, α_p, of the flux is actually absorbed. Since the plate is hotter than the environment, it loses heat at a rate $\frac{Tp-Ta}{Rl}$ Where R_l = resistance to heat loss from the plate to the outside environment

T_p = temperature of plate

T_a = temperature of environment

Where η_c = captured efficiency (<1), Hottel-Whiller equation is given as [20]

$$P_u = Ŧ_{cov} A_p \alpha_p G - [\frac{(Tp-Ta)}{Rl}] = \eta_c A_p G \tag{2}$$

Generally, only a fraction, η_{pf} of P_{net} is transferred to the fluid at the temperature *Tf.* For a well-designed collector, the temperature difference between the plate and the fluid is small and the transfer efficiency ηc is only slightly less than 1. Thus the useful output power from the collector is [20]

$$P_u = \eta_c P_{net} = \dot{m}c(T_2 - T_1) \tag{3}$$

If a mass ṁ flows through the collector per hour, T_1 = temperature of water entering the plate,

T_2 = temperature of water that is leaving the plate.

A collector of area Ap exposed to irradiance G measured in the plane of the collector gives a useful output.

$$P_u = A_p q_u = \eta_c A_p G \tag{4}$$

From (3) and (4), the thermal efficiency η_c becomes

$$\eta_c A_p G = \dot{m}c(T_2 - T_1) \tag{5}$$

Hence, $\eta_c = \frac{\dot{m}c(T2 - T1)}{ApG}$ (6)

Solar thermal efficiency can be estimated as [20]

$$\eta_c = \frac{\dot{m}c(\Delta T)}{ApI} \quad (7)$$

Where $\Delta t = T_2 - T_1$ and I = Radiation Intensity (W/m2).

From (7) mass flow rate will be

$$\dot{m} = \frac{\eta cApI}{C(\Delta T)} \quad (8)$$

The mass flow rate can be defined as

$$\dot{m} = V_r DA_f \quad (9)$$

where, $Vr =$ volumetric flow rate of water (m^3/s)

D = density of water = 10^3 kg/m^3

A_f = area of flow of water (m^2)

Equating (8) and (9), we obtain:

$$V_r DA_f = \frac{\eta cApI}{C(\Delta T)} \quad (10)$$

Hence, $V_r = \frac{\eta cApI}{C(\Delta T)DAf}$ (11)

The Volumetric flow rate of water used can also be represented as $\frac{V}{t}$

Where V = volume of water and t = time of flow.

Hence the volume of water heated will be

$$V = V_r t \quad (12)$$

4.0. RESULTS FROM MODELLING

4.1 Analysis of Volume of Water Heated with varying Collector Areas

Results from already experimented system will be adopted from [20] and analysed. The work carried out in Akure involved a thermo-siphon system tilted at an angle of 20^o to the horizontal, and an insulated 50 litre tank placed 70cm above the collector. The inlet temperature increases slightly during the day. The outlet temperature rises significantly until it peaks at 2.00 p.m. and then starts to reduce due to decline in solar irradiance. The collector efficiency increases slightly until 2.00 pm and thereafter it increases sharply and peaks at 92% at 4.00 pm. This may be due to the fact that the temperature of water coming into the inlet of the flat plate collector has increased slightly due to convection heat transfer in the storage tank. . It can also be attributed to a sharp drop in radiation intensity.

With the mass flow rate obtained at 2.9kg/hm^2, specific heat capacity of water (C) = 4.18KJ/kg^{o}C and area of collector plate = 0.54m^2, thermal efficiency was calculated as:

$$\eta_c = 22.35 \frac{\Delta T}{I} \quad (13)$$

Table 1 shows the average results between 9am and 4pm.

Table 1: Average Reading of the Solar Water Heating system over a week

Hour	**T_{air} (^oC)**	**T_{in} (^oC)**	**T_{out} (^oC)**	**Radiation intensity (I) W/m^2**	**Collector Efficiency (η_c)**
9.00	28.4	28.9	35.8	126.05	6%
10.00	29.6	30.5	41.6	176.91	10%
11.00	31.1	32.6	47.8	210.91	12%
12.00	32.6	34.4	56.4	233.20	15%
13.00	34.1	36.8	65.6	258.66	19%
14.00	34.8	38.3	69.9	280.55	27%
15.00	32.9	39.1	64.5	228.00	60%
16.00	31.3	39.2	58.6	198.93	92%

Approximate ambient temperature $T_{air} = 38.15^oC$
Approximate temperature of water entering the collector = 34.98^oC
Approximate temperature of water leaving the collector = 55.03^oC
Approximate radiation intensity = 214.15 W/m^2
Approximate efficiency of collector = 30%

From equation (11) volumetric flow rate is given as

$$V_r = \frac{\eta c A p I}{C(\Delta t) D A f}$$

Where the specific heat capacity of water (C) = 4.18KJ/kg^{o}C, density of water (D) = 10^3 kg/m^3 and the total flow area was obtained at 9.02×10^{-4} m^2. The Volumetric flow rate average will be

$$V_r = \eta_{c(av)} A_p \frac{214.15}{4.18 \; X \; 20.05 \; X \; 1000 \; X \; 0.0009}$$

For an average temperature difference of 20.05^{o}C from the table above volume of water being heated every hour is approximated as

$$V_r = 2.84\, \eta_{c(av)} A_p \qquad (14)$$

4.2 Comparison between Collector Area and Efficiency of the Solar: According to [6, 21] the efficiency of the solar collector is directly related to the heat losses from the surface of the collector. Table 4.2 shows the varying area and efficiency and the resulting volumetric flow.

Table 2: Varying thermal efficiencies and areas with effect of volumetric flow rate

S/N	Average Solar Thermal Efficiency $\eta_{c(av)}$ (%)	Area of Solar Collector A_p (m^2)	Volumetric Flow rate V_r (m^3/h)
1.	30	0.54	0.46
2.	40	0.64	0.72
3.	50	0.74	1.05
4.	60	0.84	1.43
5.	70	0.94	1.87
6.	80	1.04	2.36
7.	90	1.14	2.91

From Table 2, it is seen that an increase in plate of collector will result in an increase in volumetric flow if there is an increase in the efficiency of the system or an average temperature different of 20.05^{o}C between the temperature of water flowing out and the temperature flowing into the collector.

S/N	Average Solar Thermal Efficiency $\eta_{c(av)}$ (%)	Area of Solar Collector A_p (m^2)	Volumetric Flow rate V_r (m^3/h)
1.	30	0.54	0.46
2.	30	0.64	0.54
3.	30	0.74	0.63
4.	30	0.84	0.71
5.	30	0.94	0.80
6.	30	1.04	0.89
7.	30	1.14	0.97

Also an increase in the area without an increase in efficiency will affect the volumetric flow positively, increasing the amount of water that can be heated in an hour, but not as much increase as when the efficiency increases [22].

From equation (12), we see a direct proportionality between volumetric flow and volume. Therefore the larger amount of water to be heated, the efficiency and area of solar collector affect the time it would take to heat the water for an average 20.05^{o}C temperature difference.

Fig 1, Fig 2 and Fig 3 show diagrammatic views of Radiation intensity versus Hours, temperature difference (ΔT) versus Hours, and volumetric flow rate at constant and varying efficiencies versus collector Area.

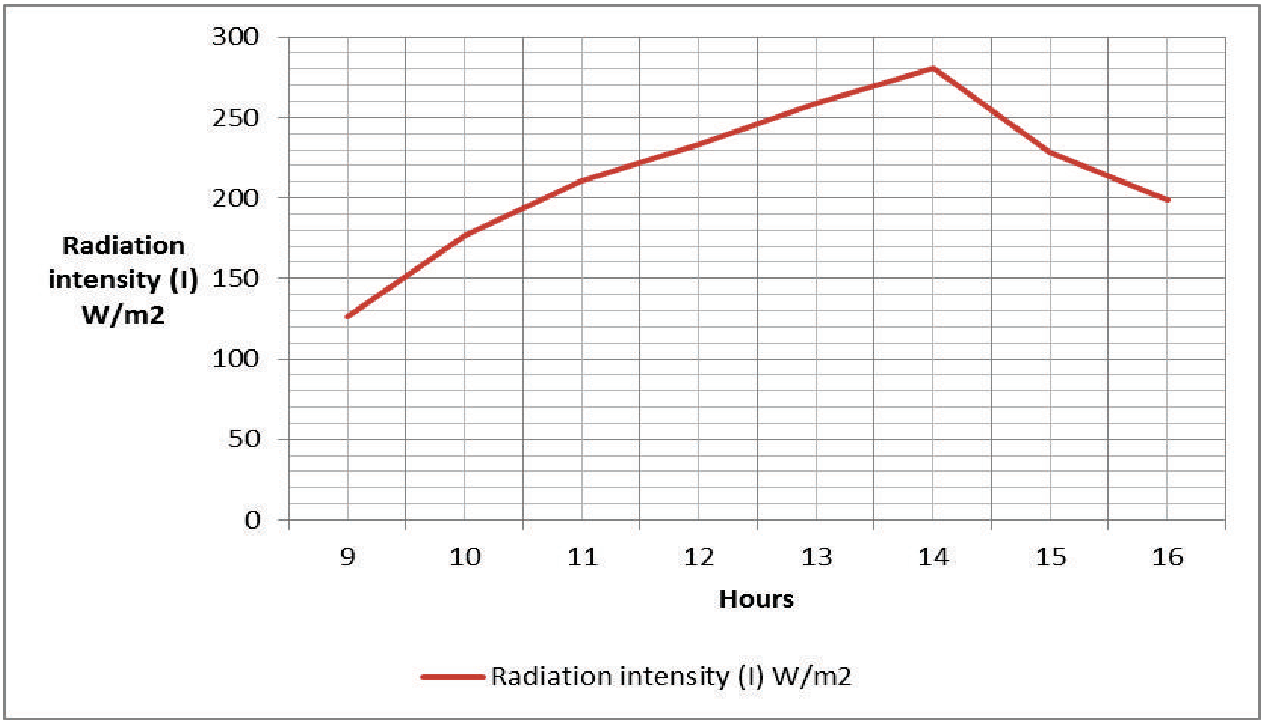

Fig 1: Plot of Average Hourly Radiation intensity

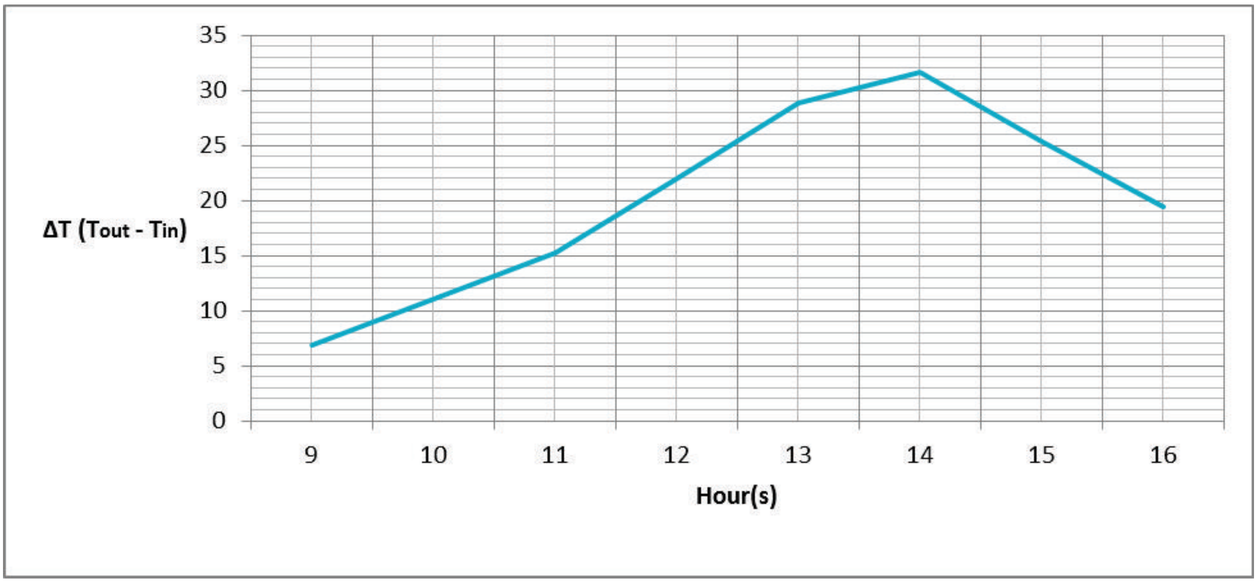

Fig 2: Plot of the average Hourly Temperature difference ($T_{out} - T_{in}$)

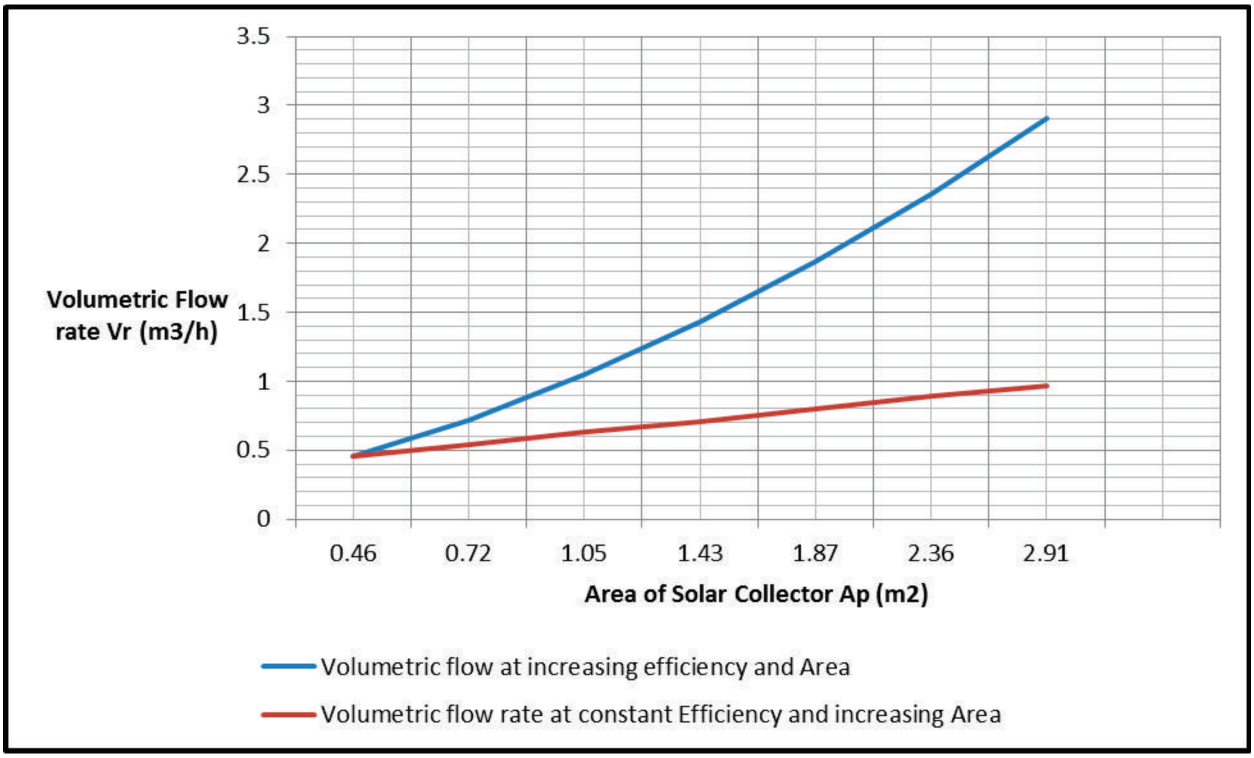

Fig 3: Volumetric flow rate versus Area of collector at constant and increasing efficiency

5. CONCLUSION

Selecting the right solar water heating system for a facility depends on three key factors like climate, budget, and water usage requirements. Solar water heating systems are economical, especially in commercial buildings when the energy used to heat water is significant. Although, the sun is capable of heating, its applications in water heating will be much effective when various factors such as safety, maintainability, and also efficiency of the system are considered. From equation (12), we saw a direct proportionality between volumetric flow and volume. Therefore, the larger the amount of water to be heated, the longer the time it will take. This is because the efficiency and area of solar collector affect the time it would take to heat the water for an average of 20.05^{o}C temperature difference. In climates like Nigeria, issues of overheating and freezing protection rarely occur as our temperatures are hardly extreme. This therefore makes solar water heating system very viable, cost effective and a good alternative to other forms of heating systems.

In general, the economic viability of a solar system depends, amongst other things, on the amount of annual sunshine, heating energy requirements, cost of the solar, temperature of hot water required, financing and incentives, as well as annual operation and maintenance costs. If these factors are put in place, solar energy will no doubt remain a veritable and viable alternative source of energy for domestic hot water requirements.

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