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Determination of the performance characteristics of a modified solar water heating system

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Abstract: Heated water is very essential for domestic, agricultural, commercial as well as industrial operations. Obtaining hot water usually comes with a cost. Though conventional water heating systems exist, however, the operational cost and environmental impact of this method is contributing seriously to the already worsened energy situation in Nigeria. Solar water heating system (SWHS) is a practical application to replace the conventional electrical water heater. The low efficiency of solar water heaters has been the main reason why many people still prefer the conventional methods. To improve on the performance characteristics of the existing solar water heater, a modified version was developed by re-shaping the solar collector and making it adjustable so that it could attract maximum solar radiation. The pipe was replaced with another pipe of smaller diameter to allow for more heating surface area using the same collector frame. The tank and the sides of the collector frame were lagged with a special polysterine material to reduce heat loss due to radiation and a unidirectional control valve was introduced to the tank so that the already heated water that can be preserved in the tank. Tests were carried out on the existing as well as the modified heaters. The results obtained show a significant improvement on the performance of the SWHS. The inlet average temperature increased form 24.64 ^oC to 35.14^oC while the outlet temperature increased from 51.53^oC to 60.73^oC which corresponds to an improvement in the performance of the system's inlet water temperature of 15.65% and outlet water temperature of 15.14%.

Keywords: Solar Energy, Heating System, Modified System, Collector Design, Solar Insulator

1. Introduction

Warm water is a necessity in most homes for various chores including but not limited to bathing, cooking, washing and sterilization of babies' accessories. In agriculture, warm water is needed for pen cleaning in piggeries, dairy operations like cleaning or sterilizing equipment and to warm and stimulate cow's udder [1]. Obtaining hot water usually comes with a cost. Water is heated using conventional energy sources such as wood and coal in the rural areas while electricity, kerosene and liquefied petroleum gas (LPG) are used in the urban areas. It has been reported that energy consumed in the residential sector is about one-third of the total delivered energy [2] and more than a quarter of this energy is used for heating applications.

Various water heating schemes evolved over time to satisfy human needs, the choice of the type and method depends on the resources available and the derivable benefits. Some of the water heating methods are highlighted below:

1.1. Storage Water Heaters

Storage water heaters remain the most popular type for residential heating needs. The systems involves the heating of water stored in a tank using conventional fuel options such as electricity, natural gas, oil, and propane [3]. It is cheap to install and very efficient. However, the water is constantly heated in the tank hence energy can be wasted even when heated water is needed at that time. This makes the storage water heaters method very expensive to operate. This is called standby heat loss. Also, burning of these fuels can contribute to environmental pollution.

1.2. Heat Pump Water Heating

Heat pump water heaters use electricity to move heat from air and transfers it to heat water instead of generating heat directly using a compressor and evaporator are built into the water heater unit [4]. The benefit of electric heat pump water heater is that though it runs on electricity yet is roughly three times more efficient than a conventional electric and that makes it highly cost effective advantage over time. When used in the right environment, it saves energy, money and reduces greenhouse gas emissions. A major drawback of electric heat pump water heaters is that the initial purchase price and installation cost may be higher than for a traditional electric water heater.

1.3. Tankless Water Heaters

Tankless water heaters use conventional method (gas, electricity, wood or coal) to heat the water on an as-needed basis without storing any heated water in a tank of any kind [5]. This method is preferred to storage waters in that money is not being spent heating a tank full of water and keeping it hot. Hence savings on energy costs as the boiler does not need to operate frequently. One of the disadvantages of the tankless water heater is that it is somewhat expensive to install.

2. Alternative Energy Sources for Water Heating

The challenges with the use of conventional energy sources for water heating include its availability and the high cost of obtaining these fuels [6]. Also, environmental concerns and the need to de-carbonize water heating processes has made it imperative to source for alternative heating techniques using non- conventional means like the solar energy.

A solar hot water system uses energy from the sun to heat water. Through specially designed solar collectors, sun’s rays can be harnessed to heat the water, which then flows to a storage tank.

Two important components of the solar water heating system are the collector and storage tank. Various system designs can be classified as passive or active and as direct (also called open loop) or indirect (also called closed loop).Passive water heater systems operate without pumps and controls and can be more reliable, more durable, easier to maintain, longer lasting, and less expensive to operate than active systems. Active solar water heaters incorporate pumps and controls to move heat-transfer fluids from the collectors to the storage tanks. Both active and passive solar water-heating systems often require conventional water heaters as backups, or the solar systems function as pre-heaters for the conventional units because of their low efficiency. The main advantages of this heating system are the fact that it is cheap to run and it does not cause pollution, as conventional heating systems do. A disadvantage of solar water heaters, however, is the fact that the cost of installation is very high compared to conventional water heaters but this cost can be off-set after a period [6]

3. Materials and Methods

In designing a solar water heating system, the following parameters determine the efficiency of the system.

3.1. Solar Collector

The heat benefit of a solar heating system depends on the amount of solar energy that can be captured. Hence, the solar collector is the most important part of the solar heating system. The collector design is a function of the amount of solar insolation (which is the amount of electromagnetic energy i.e. solar radiation incident on the surface of the earth) [7] available in a particular place at a time. The size of a solar collector that is required in any application depends on the level of solar insolation of that region.

The solar insolation of any place can be gotten by measuring the radiation value generally expressed in $kWh/m^2/day$. This is defined as the amount of solar energy that strikes a square meter of the earth's surface in a single day. This value is averaged to account for differences in the days' length.) Using a pyrometer, recording and analyzing the data using a Computer, the monthly or yearly values can be gotten for any particular locality.

3.2. Efficient Heat Transfer

The solar heat energy absorbed by the metallic tube has to be transferred to the water to be heated. Therefore, thermal conductivity is of high priority in a solar Water Heating System. The tube has to be made of a material that has high thermal conductivity, cheap and non corrosive as the tube will always be in contact with water. Copper materials (pipes and fins) meet the highlighted characteristics.

The diameter of the pipe to be used should be such that it allows more heating per surface area. Smaller diameter pipes should be preferred to larger diameter pipes.

3.3. Glaze Material

All solar radiation passing through the glazing material must be transmitted into the copper pipe/tube, so as to heat the water to a higher temperature. Transmittance varies not only for different materials but also varies with the wavelength of the radiation. The glazing should be very transparent to incoming shortwave radiation but opaque to outgoing long wave (thermal) radiation, because radiant losses account for over 70 per cent of collector heat loss [8]

3.4. Absorptance and Emissivity

The percentage of incoming radiation that is absorbed by a material is referred to as its absorptance and is a measure of the ease with which a material or surface collects energy. [9]

The best materials are those with high absorptance and very low emittance. Black paint has absorptance rate of 0.95 and emissivity of 0.875 This makes it a good choice for the SWHS [10]

3.5. Collector Casing

The purpose of the casing is to provide thermal insulation for the collector to prevent heat loss into the environment. Insulating materials like wood or ceramics with proper lagging could be ideal.

3.6. Area of Collector

The surface area of the collector is another important design factor to be considered. The efficiency of a flat plate collector is given as the heat gained by water with respect to the actual solar energy received by the flat plate collector expressed as

$$mcp\Delta T = A_c I\eta \quad [11] \tag{3.1}$$

where m = mass of water in Kilograms (kg)

cp =Specific heat of water(J/g°C)

ΔT = Temperature difference (Outlet Temperature – Inlet Temperature °C)

A_c = Area of Collector

I = intensity of solar radiation, (W/m^2)

η = Collector efficiency

Therefore,

$$A_c = \frac{mcp\Delta T}{I\eta} \tag{3.2}$$

but efficiency , η is given as [12]

$$\eta = F_R\tau\alpha - F_R U_L \left[\frac{Ti - Ta}{I}\right] \tag{3.3}$$

where F_R = Collector heat removal factor

I = Intensity of solar radiation, W/m^2 27

T_i = Inlet fluid temperature, °C

T_a = Ambient temperature, °C

U_L = Collector overall heat loss coefficient, W/m^2 K

τ = Transmission coefficient of glazing

α = Absorption coefficient of plate

The equation (3.3) shows that the efficiency of a flat plate collector is dependent on the Transmission coefficient of glazing (τ), the Absorption coefficient of plate, collector heat removal factor (F_R), intensity of solar radiation (I), ambient temperature (T_a), inlet fluid temperature (T_i) and the collector overall heat loss coefficient (U_L).

For the SWHS from the efficiency equation, F_R, τ, α and U_L are fixed by the collector design. T_i, T_a and I are variables determined by the application. This simply implies that the solar collector efficiency can change when T_i, T_a and I are changed.

4. The Existing Solar Water Heating System

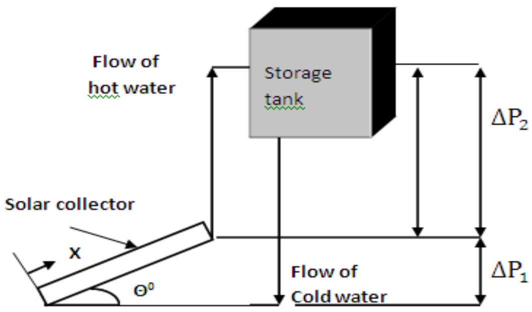

Figure 1. *The schematic diagram of a natural circulation solar water heater*

The existing SWHS is a natural circulation solar water heating system whose schematic diagram is shown in Figure1. The system consists of a flat-plate solar collector, storage tank and connecting pipes. The plate of the solar collector has the water pipes and headers in the grooves to maintain good contacts. The Pipe is 9m long and has a diameter of ¾ inches with a single glass cover of 4mm and an Aluminum foil of 0.8m x 0.45m. The concept on which the SWHS operates is based on the thermosyhon principle. A thermosyphon solar water heater relies on warm water rising, a phenomenon known as natural convection, to circulate water through the solar collector and to the storage water tank [14]. Temperature in the storage water tank is a function of the buoyancy-induced flow of heated water from the water heater to the tank while cooler water in the tank flows down pipes to the bottom of the solar collector, causing circulation throughout the system. The water storage tank is attached to the top of the solar collector. The connection between flat-plate collector and the storage tank are in two parts; the return pipe and the flow pipe. The return pipe connects the outlet of the storage tank and the inlet of the collector together; while the flow pipe connects the outlet of the collector and the inlet of the storage tank together. The flat-plate collector is oriented in such a way that it receives maximum solar radiation during the desired season of use. The absorbing surfaces were painted with black paint. Being a natural convection system, the water flows through the pipes by the thermosyphonic force and enters the storage tank. The existing system is as shown in Figure 2.

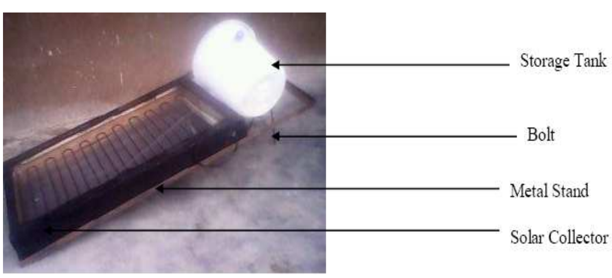

Figure 2. *The existing solar water heating system*

5. Modifications Made to the Existing System

In other to improve on the efficiency of the existing system, the following modifications were made to produce the modified version shown in Figure 3.

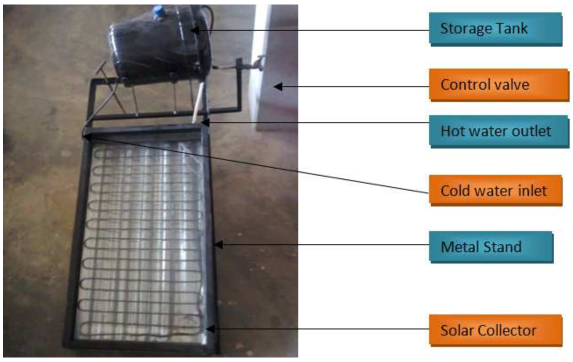

Figure 3. *The modified solar water heating system*

- The solar collector was re-shaped and also made adjustable so that it could attract maximum solar radiation. Aluminum foil was placed at the back of the wooden case so that any solar radiation not absorbed by the collector on the first pass will bounce back over the collector for secondary absorption.
- The pipe was replaced with another pipe of smaller diameter to allow for more heating surface area using the same collector frame.
- The tank and the sides of the collector frame were lagged with a special polysterine material to reduce heat loss due to radiation.
- A unidirectional control valve was introduced to the tank so that the already heated water that can be preserved in the tank.

6. Tests, Results and Discussion

The two systems (existing and modified) were placed side by side in the open atmosphere for a period of seven days between the hours of 8:00 and 18:00. The ambient temperature (T_{am}) was read as well as inlet water temperature (T_{in}) and the outlet temperature (T_{out}) for both systems. The obtained readings are as tabulated in Table 1 for the existing and Table 2 for the modified system. The hourly average for both systems is also shown in Tables 1 and 2 while the graphical presentation of the hourly average data is as shown in Figure 4.

Table 1. *performance record of the existing system.*

Time	Parameters	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Week Average (Existing)
8.00	$T_{am}(^oC)$	25.50	25.00	24.00	25.00	25.70	24.00	25.50	24.96
	$T_{in}(^oC)$	22.00	28.00	23.00	23.50	27.00	25.00	25.70	24.89
	$T_{out}(^oC)$	37.50	31.00	30.00	35.00	35.00	33.00	38.00	34.21
9.00	$T_{am}(^oC)$	26.00	26.00	25.00	26.00	26.00	25.50	27.00	25.93
	$T_{in}(^oC)$	26.20	27.50	24.00	24.50	25.00	26.60	27.00	25.83
	$T_{out}(^oC)$	50.00	35.00	37.50	39.00	45.00	40.00	39.00	40.79
10.00	$T_{am}(^oC)$	30.00	26.50	28.00	26.00	27.00	28.00	27.00	27.50
	$T_{in}(^oC)$	28.00	28.00	28.40	26.00	28.00	27.00	28.00	27.63
	$T_{out}(^oC)$	52.00	50.20	63.50	44.00	55.00	50.50	60.60	53.69
11.00	$T_{am}(^oC)$	29.80	28.00	28.00	27.00	30.00	28.00	29.00	28.54
	$T_{in}(^oC)$	31.00	30.20	31.00	27.50	30.50	29.00	31.00	30.03
	$T_{out}(^oC)$	70.00	63.00	68.00	57.00	65.00	63.00	64.50	64.36
12.00	$T_{am}(^oC)$	30.00	30.00	28.50	29.00	31.00	28.00	30.50	29.57
	$T_{in}(^oC)$	33.00	32.00	30.00	32.00	33.00	32.00	31.00	31.86
	$T_{out}(^oC)$	73.00	52.00	76.00	48.00	72.00	67.00	69.00	65.29
13.00	$T_{am}(^oC)$	31.00	29.00	28.00	31.00	32.00	29.00	30.00	30.00
	$T_{in}(^oC)$	35.50	32.50	31.50	33.00	33.00	32.00	31.00	32.64
	$T_{out}(^oC)$	70.00	68.00	49.50	61.00	67.00	65.00	67.00	63.93
14.00	$T_{am}(^oC)$	28.20	32.00	28.00	29.50	29.70	26.00	28.00	28.77
	$T_{in}(^oC)$	33.00	33.20	32.00	30.00	33.00	31.00	32.00	32.03
	$T_{out}(^oC)$	52.00	68.00	48.00	67.00	65.00	64.00	66.50	61.50
15.00	$T_{am}(^oC)$	28.00	31.00	28.00	31.00	29.00	28.00	31.00	29.43
	$T_{in}(^oC)$	29.90	34.00	32.00	32.90	32.00	31.00	33.00	32.11
	$T_{out}(^oC)$	50.00	63.00	48.50	72.00	62.00	61.00	63.00	59.93
16.00	$T_{am}(^oC)$	29.00	26.00	28.50	29.50	29.00	28.00	29.00	28.43
	$T_{in}(^oC)$	30.00	30.20	32.00	33.00	32.00	29.00	31.00	31.03
	$T_{out}(^oC)$	46.00	38.50	44.00	52.00	47.00	45.00	51.00	46.21
17.00	$T_{am}(^oC)$	26.50	26.50	28.00	28.50	27.00	26.00	28.00	27.21
	$T_{in}(^oC)$	28.00	29.00	29.00	32.00	29.00	28.50	29.00	29.21
	$T_{out}(^oC)$	31.00	33.20	55.50	43.00	45.00	43.00	44.00	42.10
18.00	$T_{am}(^oC)$	25.00	25.00	28.00	27.00	26.00	24.00	26.00	25.86
	$T_{in}(^oC)$	28.00	28.50	29.00	30.00	28.00	28.00	30.00	28.79
	$T_{out}(^oC)$	29.00	31.00	34.40	31.00	41.00	38.00	39.00	34.77

$T_{am}(^oC)$= ambient temperature
$T_{in}(^oC)$= inlet water temperature
$T_{out}(^oC)$= outlet water temperature

Table 2. *performance record of the modified system.*

Time	Parameters	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Week Average
8.00	T_{am}(°C)	25.50	25.00	24.00	25.00	25.70	24.00	25.50	24.96
	T_{in} (°C)	23.00	27.00	25.00	26.00	27.00	24.00	26.50	25.50
	T_{out} (°C)	39.00	37.00	33.00	37.00	48.00	36.00	39.50	38.50
9.00	T_{am}(°C)	26.00	26.00	25.00	26.00	26.00	25.50	27.00	25.93
	T_{in} (°C)	27.00	29.00	26.00	39.00	38.00	35.00	37.00	33.00
	T_{out} (°C)	53.00	52.00	42.00	47.00	59.00	60.00	63.00	53.71
10.00	T_{am}(°C)	30.00	26.50	28.00	26.00	27.00	28.00	27.00	27.50
	T_{in} (°C)	29.00	31.00	31.50	41.00	37.00	42.00	41.00	36.07
	T_{out} (°C)	54.00	56.00	56.00	46.00	68.00	69.00	72.00	60.14
11.00	T_{am}(°C)	29.80	28.00	28.00	27.00	30.00	28.00	29.00	28.54
	T_{in} (°C)	33.00	32.00	34.00	42.00	44.00	39.00	38.00	37.43
	T_{out} (°C)	76.00	64.00	74.00	59.00	71.00	69.00	71.00	69.14
12.00	T_{am}(°C)	30.00	30.00	28.50	29.00	31.00	28.00	30.50	29.57
	T_{in} (°C)	35.00	33.00	35.00	43.00	45.00	38.00	39.00	38.29
	T_{out} (°C)	78.00	62.00	77.00	57.00	74.00	68.00	69.50	69.36
13.00	T_{am}(°C)	31.00	29.00	28.00	31.00	32.00	29.00	30.00	30.00
	T_{in} (°C)	38.00	34.00	36.00	42.00	46.00	35.00	38.00	38.43
	T_{out} (°C)	75.00	72.00	67.00	73.00	71.00	72.00	68.00	71.14
14.00	T_{am}(°C)	28.20	32.00	28.00	29.50	29.70	26.00	28.00	28.77
	T_{in} (°C)	35.00	35.00	38.00	44.00	45.00	36.00	37.00	38.57
	T_{out} (°C)	56.00	70.00	65.00	79.00	67.00	68.00	69.00	67.71
15.00	T_{am}(°C)	28.00	31.00	28.00	31.00	29.00	28.00	31.00	29.43
	T_{in} (°C)	32.00	38.00	39.00	39.00	44.00	35.00	36.00	37.57
	T_{out} (°C)	54.00	68.00	63.00	75.00	65.00	65.00	67.00	65.29
16.00	T_{am}(°C)	29.00	26.00	28.50	29.50	29.00	28.00	29.00	28.43
	T_{in} (°C)	30.00	36.00	40.00	37.00	45.00	31.00	34.00	36.14
	T_{out} (°C)	50.00	60.00	62.00	73.00	51.00	62.00	65.00	60.43
17.00	T_{am}(°C)	26.50	26.50	28.00	28.50	27.00	26.00	28.00	27.21
	T_{in} (°C)	29.00	34.00	37.00	36.00	33.00	30.00	32.00	33.00
	T_{out} (°C)	47.00	58.00	60.00	71.00	48.00	61.00	63.00	58.29
18.00	T_{am}(°C)	25.00	25.00	28.00	27.00	26.00	24.00	26.00	25.86
	T_{in} (°C)	29.00	31.00	35.00	30.00	35.00	40.00	28.00	32.57
	T_{out} (°C)	43.00	52.00	56.00	63.00	46.00	58.00	62.00	54.29

T_{am}(°C)= ambient temperature
T_{in} (°C)= inlet water temperature
T_{out} (°C)= outlet water temperature

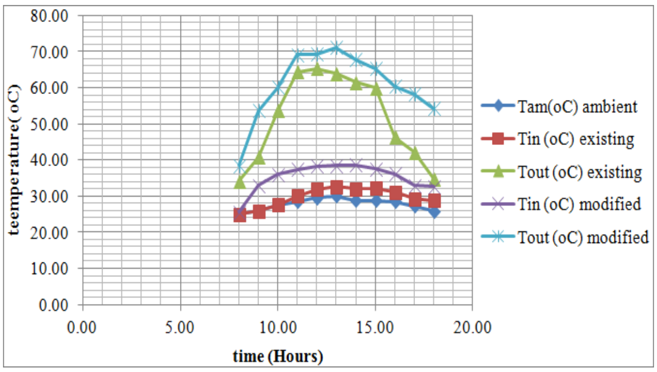

Figure 4. *The graphical presentation of the data of Table 3*

The results of Tables 1 and 2 and the graphical presentation of Figure 4 show a significant improvement on the performance of the SWHS. The inlet average temperature increased form 24.64 °C to 35.14°C while the outlet temperature increased from 51.53°C to 60.73°C which corresponds to an improvement in the performance of the system's inlet temperature of 15.65% and outlet temperature of 15.14%.

7. Conclusion

The performance characteristic of an existing solar water heater was improved upon by modifying some of the parameters. The modified version was developed by re-shaping the solar collector and also made adjustable so that it could attract maximum solar radiation. The pipe was replaced with another pipe of smaller diameter to allow for more heating surface area using the same collector frame. The tank and the sides of the collector frame were lagged with a special polysterine material to reduce heat loss due to radiation and a unidirectional control valve was introduced to the tank so that the already heated water that can be preserved in the tank. Tests were carried out on the existing as well as the modified heaters. The results obtained show a significant improvement on the performance of the SWHS. The inlet average temperature increased form 24.64 °C to 35.14°C while the outlet temperature increased from 51.53°C to 60.73°C which corresponds to an improvement in the performance of the system's inlet temperature of 15.65% and outlet temperature of 15.14%.

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