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Design, Construction and Testing of a Model Thermosiphonic Solar Water Heater

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ABSTRACT:

A thermosiphonic solar water heating system that uses a simple flat plate collector to heat water and in which circulation takes place with natural convention. The system was designed, constructed and tested at Yelwa campus, ATBU Bauchi with latitude 10.33^0N and longitude 9.83^0E. The system was designed to heat a total of 15litres of water between 50^0 and 80^0 at the worst and best month of the year respectively. The system was designed using weather data of Bauchi state and the resulting parameters of the design was used to construct the system. It was tested between December and January. Two tests were carried out on the system; for the system with ordinary collector, and that with diffusers incorporated within the collector risers. The first system (without diffusers) has an efficiency of 52.6% and was able to generate collector outlet temperature of 61^0C and water mean temperature of 60^0C at an average daily solar radiation of 912W/m^2. In contrast, the second system (with diffusers) has an efficiency of 58.6% and was able to generate collector temperature of 70^0C and water mean temperature of 68^0C at an average daily solar radiation of 913.3W/m^2. It was concluded from the results that incorporating diffusers within risers improved the performance of the system by 6.6%.

INTRODUCTION

Several challenges such as increase in oil demand and oil price rise, depletion of oil reserve, reduced availability of fossil fuels, ozone layer depletion, health hazards, global climate change and other air pollution issues caused mainly by burning of hydrocarbons as source of heat energy, has led to the drive to use environmental friendly and renewable alternatives sources of heat energy to eliminate or minimize these negative effects. Presently, solar and other alternative energy sources like wind and geothermal are being harnessed for various applications such as power generation, air conditioning, space heating, domestic hot water system etc.

Supply of hot water account for a high level of energy demand in homes. This calls for the utilization of a cheap and renewable energy sources to provide an effective and efficient supply of hot water for maximum energy savings.

Renewable energy resources of which the sun is a good example are those resources which undergo faster replenishment rate within a relatively short time than the rate at which they are utilized or depleted. The energy of the sun is generated from its nuclear fusion of its hydrogen into helium, with a resulting mass depletion rate of approximately $4.7\text{x}10^6$tons/second. The earth's population currently needs 15 terawatts of power in total, but the solar radiation that reaches the earth on a continuous basis amount to 120,000 terawatts; hence, just a fraction of the suns energy reaching the earth will cover the bulk of energy requirements. (Bradke *et al.*, 2011)

In harnessing the solar energy for heating, the solar radiation has to be converted to heat energy. Solar energy collectors, the device used to convert the solar radiation to heat, usually consist of a surface that efficiently absorbs radiation and convert this incident flux into heat which raises the temperature of the absorbing material. A part of this energy is then removed from the absorbing surface by means of heat transfer fluid that may either be liquid or gaseous.

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Several systems have been built to convert solar energy to heat which are broadly classified into: focusing and non-focusing type concentrators. The simplest of which is the flat plate collector (non-focusing type), which uses a flat plate absorbing surface laid with grids of fluid carrying tubes for heat transfer. The flat plate collector absorber is made of high thermally efficient material usually copper or aluminium plate, painted with a selective black coating for high absorbing power. The flat plate is used where temperature needed is at a range of 40^oc and 80^oc and generally has an efficiency of about 40%. They have advantage of using both beam and diffused solar radiation, not requiring orientation toward the sun, no significant optical loss term; and requiring little maintenance.

The aim of this project is to design, construct and test a model thermosiphonic solar water heater.

Solar water heaters are classified based on the designs, which are adopted to suit a specific purposes and climatic conditions. Natural circulation solar water heaters (which are also called the thermosyphon water heater) are the simplest form of solar water heater due to its simplicity of construction, design, utilization and maintenance. The design choice is based on number of factors: economic, climatic, availability of materials among others. Design factors such as area of the collector, nature of the absorber plate material, storage tank capacity have been shown to affect the performance of natural circulation solar water heaters (Ismail *et al.,* 2015).

MATERIALS AND METHODOLOGY

System Design Assumptions

In the design analysis of the system, the following assumptions were made:

1. The collector operates in steady state.
2. Temperature gradient through the cover thickness is negligible.
3. There is one-dimensional heat flow through the back and side insulation and through the cover system.
4. The temperature gradient around and through the tubes is negligible.
5. The temperature gradient through the absorber plate is negligible.
6. Fluid flow distribution is one dimensional.
7. Temperature distributions in the collector tubes and the storage tank are linear.
8. Flow inside the tubes is laminar and uniformly distributed.

Design Considerations

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

1. A design month which would be determined from the mean daily heat load (W) and the mean daily solar irradiance (W/m^2) from the months of the year;
2. The amount of water required to determine the system load;
3. The range of operating temperatures between 0^0C and 100^0C for the selection of material.

Collector Area (A_C)

Collector area (AC) is the ratio of the quantity of heat required (Q_w) to raise the temperature of water from T_{in} to T_{out} to the energy absorbed by the collector over a specified period of time. The collector area is given by (Nosa et al., 2013):

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$$Collector\ Area\ (A_C) = \frac{Q_W}{\mu I} = \frac{M_W C_W\, \Delta T}{\mu I} \quad \ldots (1)$$

And,

$$Q_w = M_w C_w (T_{out} - T_{in}) = \rho V C_w (T_{out} - T_{in}) \quad \ldots (2)$$

Where

Q_w = Useful energy absorb by the water

μ= Viscosity of water at temperature 80^0C = 0.355kpa (EngineeringToolBox.com)

I = average insolation constant

M_w = Mass of water

C_w = specific heat capacity of water

ΔT = change in temperature of water

T_{in} = water inlet temperature to the collector

T_{out} = water outlet temperature from the collector

Also,

$$A_C = L_C \times W_C \quad \ldots (3)$$

Where,

L_C is the length of collector (m)

W_C is the collector width (m)

Volume of water on the collector plate is given by:

$$V = \frac{\mu \times Re}{\rho \times D} \quad \ldots (4)$$

Where

Re = Reynolds no. for lamina flow

ρ = Density of water

μ = Viscosity of water at temperature 80^0C = 0.355kpa (EngineeringToolBox.com)

D = Diameter of riser tubes (Nosa et al., 2013).

Collector Risers and Headers

Total Volume of header, $V_H = \frac{\pi {D_H}^2 L_H}{4}$ … (5)

Total volume of risers, $V_R = \frac{\pi {D_R}^2 L_R}{4}$ … (6)

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$$\text{Riser spacing} = \frac{W_C}{number\ of\ risers} \quad \ldots (7)$$

Where,

V_H is the volume of the header

D_H is the diameter of the header

L_H is the length of the header

V_R is the volume of the risers

D_R is the diameter of the risers

L_R is the length of the risers

W_C is the collector width

Design of the cold and hot water (Cylindrical) storage tank

Volume of storage tank (V_T) = Area (A_T) × Height (H_T)

Where,

$$A_T = \frac{\pi D_T^2}{4} \quad \ldots(8)$$

Therefore,

$$V_T = \frac{\pi D_T^2}{4} H_T \quad \ldots(9)$$

And the diameter of the tank is given as

$$D_T = \sqrt{\frac{4V_T}{\pi H_T}} \quad \ldots(10)$$

RESULTS AND DISCUSSION

System Final Optimum Design Parameters

Table 0 shows the system calculated optimum design parameters for the construction of the flat plate collector and storage tank (15liters capacity).

Table 0: system parameters

Description	Value/Type
Total aperture area, A_c	$0.5m^2$
Risers and headers tube material	Copper
Number of riser tubes	9
Number of header tubes	2

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Diameter of risers	12mm
Diameter of headers	15mm
Length of risers	0.855m each
Length of headers	0.58m each
Absorber plate material	Aluminum
Absorber plate coating	Black paint
Glazing	4mm glass
Collector insulation	Sawdust
Collector tilt angle, β	25^0
Storage tank material	PVC and mild steel
Storage tank capacity	15L
Diameter of storage tank	210mm
Height of storage tank	450mm
Storage tank insulation	Hard foam

System Performance Testing

In order to determine the overall system performance, two tests was conducted;

a. the system performance with ordinary flat plate collector; and

b. the system performance with diffusers incorporated within the risers of the collector.

These systems were tested from 8am to 5pm. The water inlet temperature (T_{in}), collector outlet temperature (T_{out}), the water mean temperature in the storage tank, (T_{mean}), and the ambient temperature (T_a), was measured by a thermometer for each hour. Also, the solar radiation intensity (I) for each hour was measured by a pyranometer. Table 1 to Table 6 shows the results obtained for 3 days of testing for each systems.

Table 1: Results obtained on Day 1 [for risers without diffusers]

Time	8am	9am	10am	11am	12pm	1pm	2pm	3pm	4pm	5pm
I (W/m^2)	794	858	940	984	996	991	986	930	864	460
T_a (^0C)	20	22	23	24	26	26	26	26	26	25
T_{in}(^0C)	24	28	33	42	46	55	57	58	58	58
T_{out} (^0C)	26	32	37	44	48	56	59	60	58	58
T_{mean}(^0C)	25	28	33	42	46	55	57	58	58	58

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Table 2: Results obtained for Day 2 [for risers without diffusers]

Time	8am	9am	10am	11am	12pm	1pm	2pm	3pm	4pm	5pm
I (W/m^2)	836	956	958	973	998	988	976	978	930	533
T_a (^0C)	18	19	20	24	26	26	28	28	26	26
T_{in}(^0C)	24	28	33	40	49	56	58	60	59	58
T_{out} (^0C)	22	32	36	42	52	57	60	61	60	58
T_{mean}(^0C)	20	28	33	40	49	56	58	60	59	58

Table 3: Results obtained for Day 3 [for risers without diffusers]

Time	8am	9am	10am	11am	12pm	1pm	2pm	3pm	4pm	5pm
I (W/m^2)	93.6	256	400	440	460	430	458	301	297	98
T_a (^0C)	13	13	22	24	25	27	27	27	24	24
T_{in}(^0C)	23	26	28	34	40	46	48	50	50	48
T_{out} (^0C)	23	29	32	38	43	48	50	50	50	48
T_{mean}(^0C)	23	26	28	34	40	46	48	50	50	48

Table 4: Results obtained for Day 4 [for risers with diffusers]

Time	8am	9am	10am	11am	12pm	1pm	2pm	3pm	4pm	5pm
I (W/m^2)	90.1	300	397	399	468	455	392	321	164	60.5
T_a (^0C)	20	20	22	23	24	24	26	25	25	22
T_{in}(^0C)	23	25	28	34	40	46	50	51	50	50
T_{out} (^0C)	24	26	32	37	42	48	51	51	50	50
T_{mean}(^0C)	22	25	28	34	40	46	50	51	50	50

Table 5: Results obtained for Day 5 [for risers with diffusers]

Time	8am	9am	10am	11am	12pm	1pm	2pm	3pm	4pm	5pm
I (W/m^2)	827	848	866	998	1001	1010	994	930	900	638
T_a (^0C)	24	25	25	27	28	30	32	33	33	32
T_{in}(^0C)	25	30	38	42	54	60	64	66	66	66
T_{out} (^0C)	28	36	40	46	56	62	66	68	66	66

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T_{mean}(^{0}C)	25	30	38	42	54	60	64	66	66	66

Table 6: Results obtained for Day 6 [for risers with diffusers]

Time	8am	9am	10am	11am	12pm	1pm	2pm	3pm	4pm	5pm
I (W/m^2)	883	896	860	980	986	1001	1020	998	860	649
T_a (^{0}C)	25	27	27	26	27	28	29	30	29	27
T_{in}(^{0}C)	25	32	41	48	56	62	66	68	68	68
T_{out} (^{0}C)	28	34	42	52	58	63	68	70	68	68
T_{mean}(^{0}C)	25	32	41	48	56	62	66	68	68	68

The graphs Fig.1 to 6 below shows the rate of change of the collector output temperature (T_o) and the water mean temperature (T_m) within the storage tank for each test days respectively.

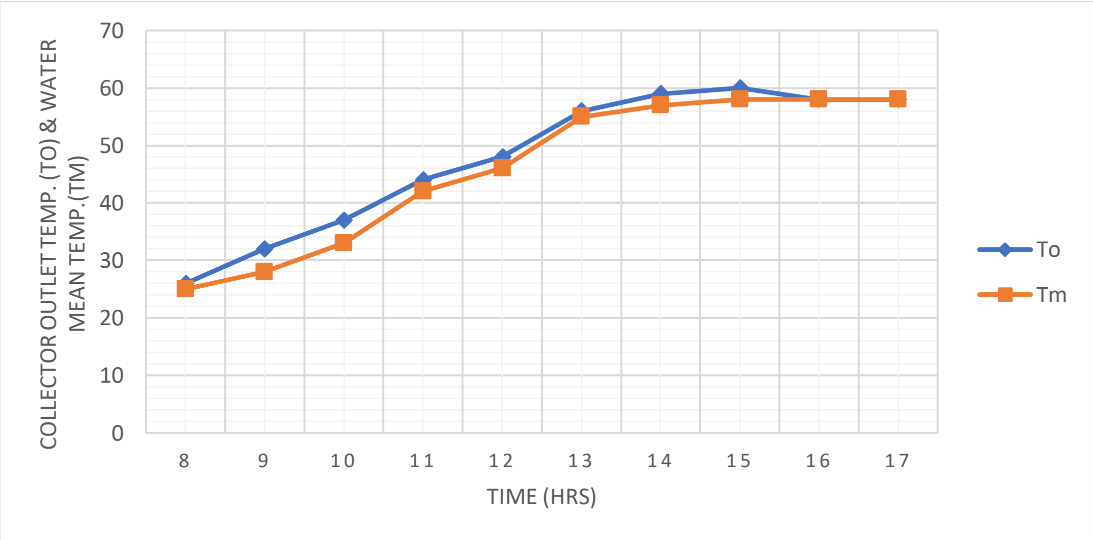

Fig. 1: graph of collector outlet temperature (T_o ^{o}C) & water mean temperature (T_m ^{o}C) against time (hrs) for Day 1

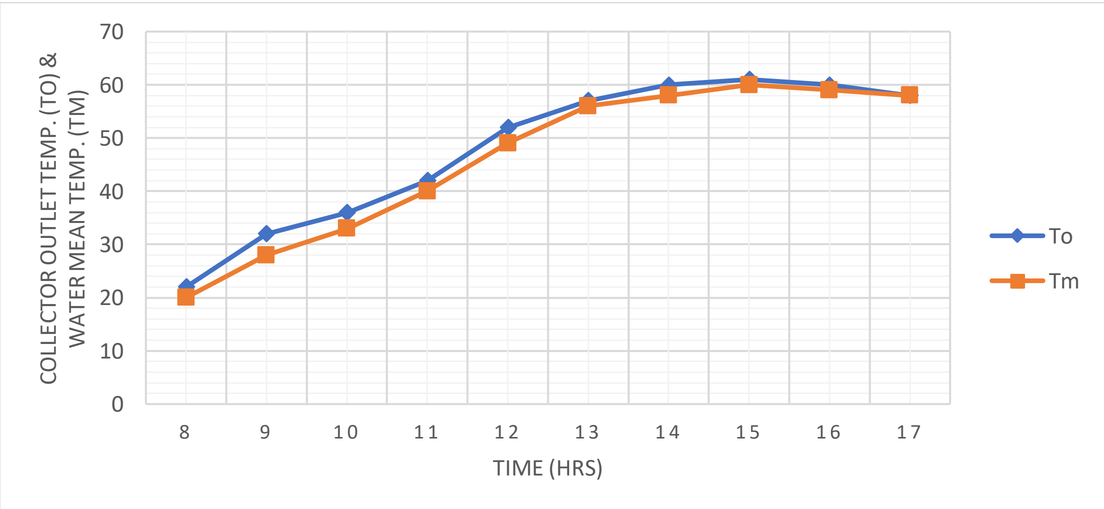

Fig. 2: graph of collector outlet temperature (T_o ^{o}C) & water mean temperature (T_m ^{o}C) against time (hrs) for Day 2

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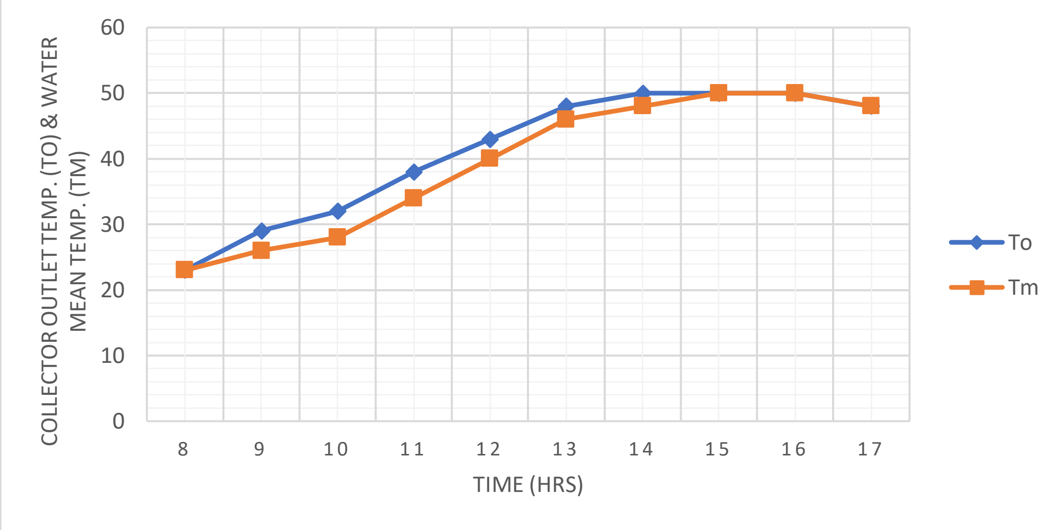

Fig. 3: graph of collector outlet temperature (T_o °C) & water mean temperature (T_m °C) against time (hrs) for Day 3

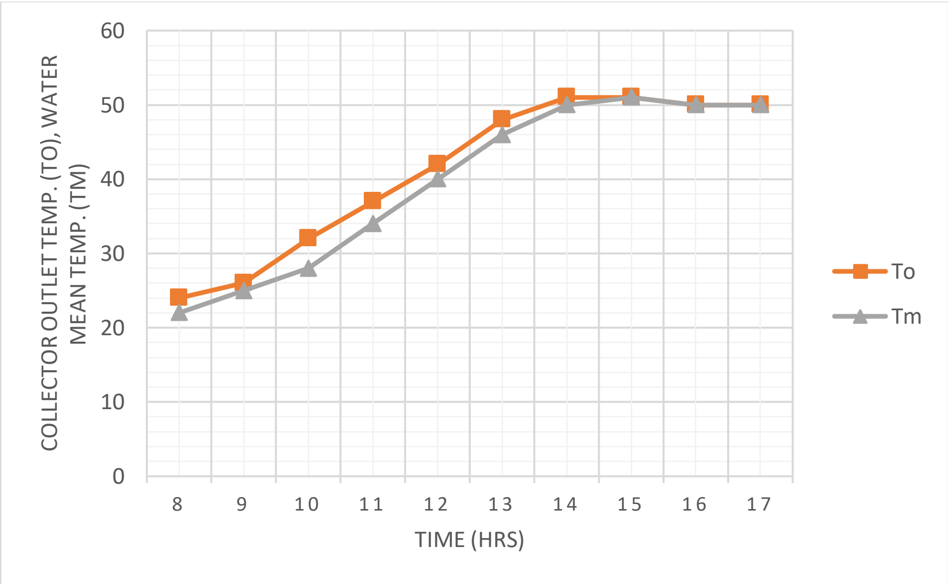

Fig. 4: graph of collector outlet temperature (T_o °C) & water mean temperature (T_m °C) against time (hrs) for Day 4

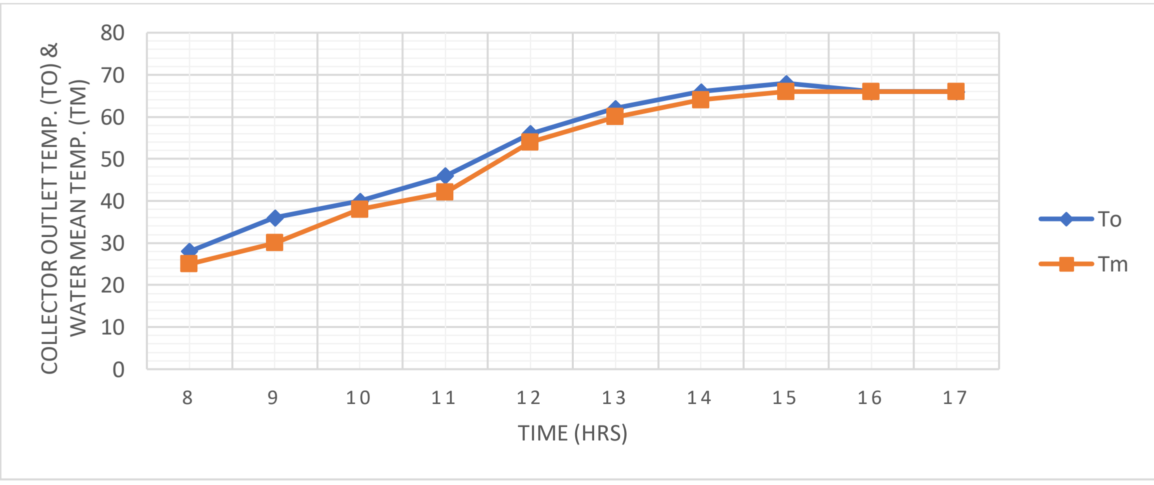

Fig. 5: graph of collector outlet temperature (T_o °C) & water mean temperature (T_m °C) against time (hrs) for Day 5

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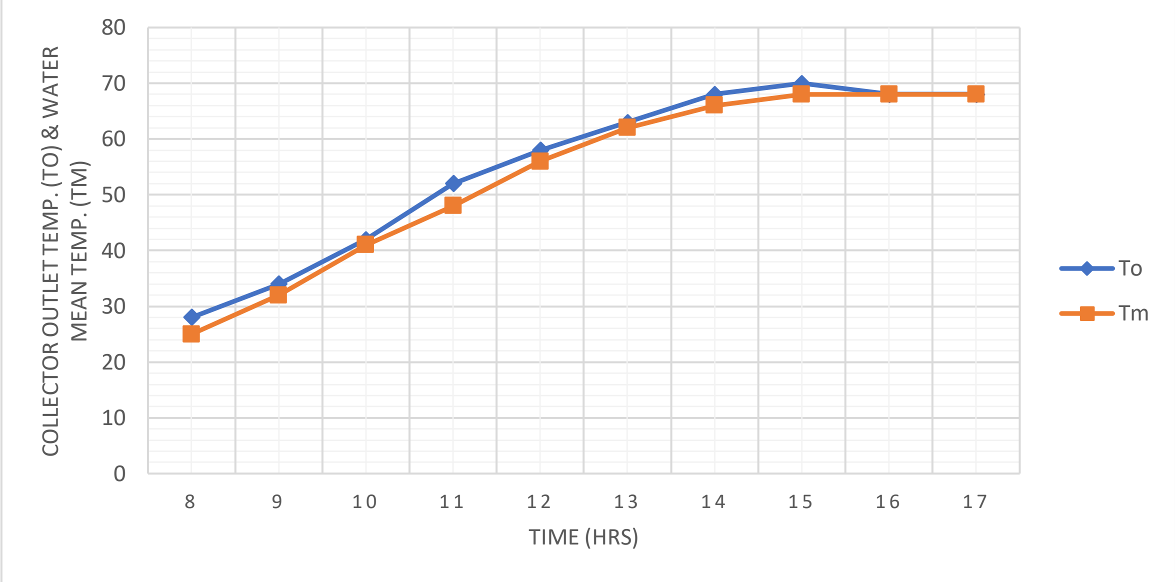

Fig. 6: Graph of collector outlet temperature (T_o °C) & water mean temperature (T_m °C) against time (hrs) for Day 6

System Performance Evaluation

The first system tests (without diffusers within risers) were conducted on Day 1, 2 and 3 respectively. The system was able to generate collector outlet temperature of up to 61^0C and mean water temperature of up to 60^0C at an average daily solar radiation of 912.6W/m^2. Also, the second tests (with diffusers incorporated within risers), were conducted on Day 4, 5 and 6 respectively. The system generated collector outlet temperature of up to 70^0C and mean water temperature of up to 68^0C at an average daily solar radiation of 913.3W/m^2.

Comparing the results obtained both systems, it can be deduced that incorporating diffusers in the collector tube risers improved the efficiency of the system by up to 6.6%. It can also be deduced from the graphs fig. 4, 5 and 6 above that the temperature difference between the collector outlet temperature (T_o) and the mean water temperature (T_{mean}) was at most 2^0C, which shows that the diffusers had no significant effect on the heating time of system.

Physical impact of diffusers on the Reynold's number or laminar flow distribution

Although the nominal Reynolds number of the working fluid remains within the laminar regime, the insertion of diffusers induces localized flow separation, secondary circulation, and periodic boundary-layer redevelopment. As a result, the flow departs from classical fully developed laminar behavior, leading to enhanced convective heat transfer without a formal transition to turbulence

CONCLUSION

A thermosiphon water heater was successfully constructed to heat 15liters of water above 70^0C under the climatic conditions of Bauchi, ATBU Yelwa Campus. It was also discovered that incorporating diffusers at the collector risers improved the system efficiency by up to 6.6% compared with the ordinary collector.

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