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Investigation of the suitability of a flat plate collector in a multi-effect humidification (MEH) system in Makurdi

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Abstract
A flat plate solar collector was designed, constructed and the performance with regards to suitability for use in a multi-effect humidification (MEH) system evaluated in Makurdi. 17.7^o was used as the angle of tilt for the collector. A blackened storage tank was provided to supply slightly pre-heated water to the collector. 10 mm diameter copper pipes were formed into loops to serve as the water passages. A flow rate of 0.0034 kg/s was used for the passive system while 0.0039 kg/s was used for the active one. The hourly ambient temperature, initial and final water temperatures, the outer surface cover temperature of the collector and the incident radiation were measured daily from 08.00 to 17.00 hours for 8 days. The efficiencies of the collector were computed from the measured data. The experimental results showed that the mean temperature of the water from the collector was 48.44^{0}C for the passive option and 45.54^{0}C for the active one on hourly basis. These values are lower than the minimum required for the operation of a MEH system. The respective efficiencies on daily basis were 0.71 and 0.60. Further work will focus on increasing the resident time of the water within the collector.

Keywords: flat plate collector, multi-effect humidification, suitability, passive, active, resident time.

1. Introduction

The availability of potable water in sufficient quantities to individuals or communities in developing countries is still a major problem. Also in many arid regions of the world, and especially in the Middle East, where conventional sources of fresh water are not readily available, sea water desalination will continue to supply potable water. In Makurdi, the Benue state capital, residents face acute shortage of drinking water despite the existence of the greater Makurdi water works. Apart from drinking, cooking and general domestic uses, pure water is needed to meet requirement of pharmacology, medical, chemical and industrial applications such as food processing industries [1].

Drinking water infested with pathogens or which contain unacceptable levels of dissolved contaminants or solids in suspension when consumed leads to widespread acute and chronic illness and is a major cause of death in many developing countries. In 2006, water borne diseases were estimated to cause 1.3 million deaths each year while about 1.1 billion people lacked proper drinking water [2]. It is also reported that, every year, over 200,000 South African children drink themselves to death. Diseases caused by contaminated water kill thousands of South African children every year. More tragic is the fact that, these deaths could have been prevented if all children had access to safe drinking water [3].

Over the decades, many technologies/techniques have been developed in different parts of the globe to treat water and make it suitable for required demands. In general, the methods used in a water treatment plant include physical processes like filtration and sedimentation, biological process such as slow sand filters or activated sludge chemical process such as flocculation and chlorination and use of electromagnetic radiation such as ultra violet light. Desalination of sea water could also be carried out by distillation or reverse osmosis [4 -7]. Reverse osmosis is a pressure – driven process that forces the separation of fresh water from other constituents through a semi permeable membrane. This is usually the preferred method in large-scale desalination implementations where electricity is cheaply available. Distillation can be achieved by the relatively cheaper use of solar thermal systems. Here, solar energy is collected and converted into electrical or mechanical energy to initiate the process. Solar desalination systems are simple and easy to operate and maintain since they have no moving parts. They are also environmentally friendly because they do not require fossil fuels [8-11].

An emerging technology for smaller scale desalination systems is solar multi-effect humidification (MEH)-dehumidification. This process uses solar energy to evaporate fresh water, which is condensed on a cool surface and collected, hence removing dissolved minerals from the water. The basic principle of the operation of multi-effect dehumidification system is based on the principles of evaporation and condensation. This process has proved to be very efficient in producing high quality drinking water. In this system, the critical parameter is the temperature of the feedwater between the exit of collector sub-system and the evaporator/condenser sub-system [12-16].

For locations with abundant solar radiation almost all year round, such as Makurdi [17-19], solar desalination is a potentially viable option, especially for small scale plants in remote locations. Also, there is abundant supply of brackish water in the shape of the River Benue which can be useful for larger scale application of solar distillation. This study is ultimately aimed at increasing the quantity of drinking water produced by the multi-effect humidification (MEH)-dehumidification system using the available materials and the environmental conditions in Makurdi. The immediate focus is however, on the investigation of the performance of a flat plate collector that could be used to obtain feedwater at the necessary condition for the operation of a MEH system.

Providing sufficient quantity of potable water by relatively cheap and environmentally clean methods has been a major research focus and solar desalination has been prominent with new methods such as the multi-effect humidification and dehumidification system being attempted in order to increase water yield [20]. Obtaining the feedwater at the necessary condition is very critical to the operation of this system. Drinking water is a major problem within Makurdi despite the on-going greater Makurdi water works. The objective of this study is to design, construct and evaluate the performance of a flat plate solar collector for water heating, suitable for use in a multi-effect humidification and dehumidification distillation system. The abundant solar thermal radiation and brackish water from the River Benue in Makurdi, makes it suitable for the installation of solar distillation systems in various parts of the town for provision of drinking water. Several efforts have been made recently by the Energy Research Group in this Department in the past but most of them have been limited to the simple basin water still and some modifications made to it [21]. Since the viability of solar distillation as a major player in the drinking water provision mix depends largely on the yield, focus is been shifted to the MEH system for which the solar collector is very central.

Materials and Methods

The materials and equipment used for the study include aluminum sheet, plain widow glass sheet, copper tubes (evaporator coils), soft wood, ½" ply wood sheets, black paint, rice husk, PVC plumbing valve and pipes, hose, PVC gum, silicone sealant, wood adhesive (Top gum), and pressure gauge. Others include 1 Hp centrifugal pump, jerry cans, provision for connection to the mains, solarimeter (sun meter), digital thermometer, and calibrated measuring cylinder

The flat plate solar collector had an aperture of 200 by 100 cm with seven parallel copper tubes 185 cm each running along the length with 12.5 cm spacing between the tubes. The seven parallel tubes were formed by bending and attached to the plate using rivets. The collector has a glass cover at the top and the rice chaff as insulator beneath the plate. The collector box was made of wood with ½ inch plywood sheet as the base of the box. The design specifications for the solar collector are given in Table 1.

The plate was constructed using 3 mm thick aluminum sheet. The sheet was cut to size using tin snip according to the design specifications in Table 1. The 10 mm diameter copper tube was bent to form a continuous loop on the top surface of the absorber plate, with seven parallel runs along the length of the plate. The copper tubes were attached to the upper surface of the plate by cold riveting. The upper surface of the plate together with the copper tubes were painted black to enhance absorption of heat to heat up the water flowing through the tubes. The casing was constructed according to the design specifications from wood. Appropriate holes were drilled in the box to allow for the inlet and outlet tubes. The wooden box was designed with a height of 8 cm. Glass, having a thickness of 4 mm with length and width according to the specifications was used as cover plate. The function of the glass is to prevent heat loss from the plate by radiation. The glass was secured on top of the wooden box using silicone sealant. The gap between the cover glass and the plate was 3 cm. Rice chaff was used as insulation material for the collector to prevent heat loss by conduction.

Table 1: Design Specifications for the Solar Collector

Parameter	Dimensions
Width of glass	100cm
Length of glass	200cm
Glass cover area	20000cm^2
Thickness of glass pane	0.4 cm
Width of aluminum sheet	100cm
Length of aluminum sheet	200cm
Area of aluminum sheet	20000 cm^2
Diameter of tube	1cm
Tube spacing	12.5cm
Plate to cover spacing	3cm
Collector box	100×200cm
Height of box	9cm

A storage tank was designed to serve the solar panel. It was designed to have a capacity of 0.02 m^3 of water. The equation for the volume of a cylinder (v = $\pi r^2 h$) was used to design the tank. The tank has a height of 45 cm and a diameter of 24 cm. The equation, p = $2\pi r$ was used to calculate for the perimeter of the tank, which was found to be 75 cm. Thick plain aluminium sheet was cut to size, and folded to form a cylinder. This was joined by brazing. The top and bottom covers for the tank were also cut to size and brazed. A mixture of putty and a hardener was applied on the brazed joints to provide a water tight seal. The design specifications for the storage tank are shown in Table 2 below.

Table 2: Design Specifications for the Storage Tank

Parameter	Dimensions
Height of tank	45cm
Diameter of tank	24cm
Perimeter of tank	75cm
Volume of tank	20000cm^3

The test rig consists of the storage tank linked to the collector using a combination of PVC pipes and rubber hose with provisions for temperature measurement using the thermometers. The storage tank was located 1.40 m above ground level for the passive set up and on the ground the pump between it and the collector for the active one. For both set ups, the water was not recycled. The solar collector is installed with the inlet on the ground and with an angle of tilt of 17.7^0. A thermometer was used tank to measure the initial temperature of the water at the outlet of the storage tank. Another thermometer is installed on the outlet pipe of the collector to measure the outlet temperature of the water. Fig. 1 shows a schematic diagram of the set up.

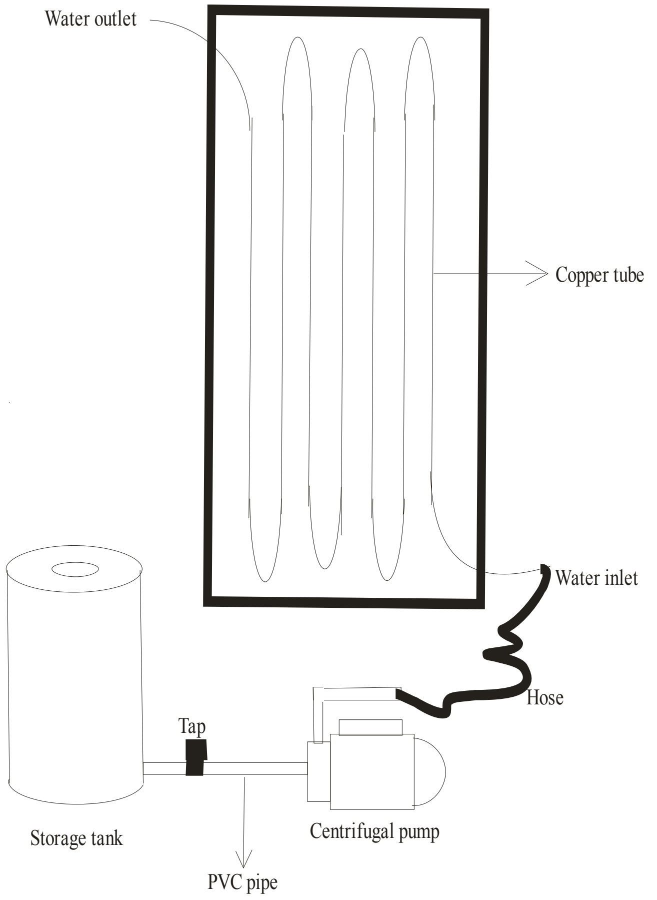

Fig 1: Schematic diagram of the Active System

The storage tank was first filled with water to full capacity. Water from the tank is released to the collector by opening the ball valve. The valve on the storage tank was regulated such that, water flows through the collector at an appropriate flow rate to ensure a reasonable resident time in the collector and absorb heat by conduction from the black–coated copper tubes. The heat transfer rate can be estimated using the equation $Q = Wc\Delta T$, where W = mass flow rate of fluid, c = specific heat of the fluid at constant pressure and ΔT= the temperature rise. Water leaves the collector from the collector's exit. A thermometer was used to measure the final temperature of water.

The ambient temperature, water inlet temperature, the outer temperature of glass panel and the final temperature of water from the panel were taken hourly from 8:00 am to 5:00 pm using a digital thermometer. The hourly solar radiation values were also taken. Plate 1 shows the active experimental set up. Some of the collector parameters were then plotted to investigate their relationships.

Plate 1: The arrangement of Active system while in operation

Results and Discussion

Figs. 2 and 3 show the variation of the mean ambient temperature with time of the day and days respectively for the passive and active collectors. The figures show clearly that the mean ambient temperature for the period during which the active test was carried out was higher than that for the passive test both on hourly and daily basis. It is important to note this because the ambient temperature is crucial to the operation of all solar thermal systems and in comparing the two options in this study, this observation underscores the conclusion that the passive option showed better prospects apart from other operational characteristics.

The variation of the ambient temperature with time of the day expectedly exhibited a polynomial trend with maximum values occurring between 13.00 and 15.00 hours for both the passive and active options as shown in fig. 2. The ambient temperature reached respective maximum values of 33.3 ^{0}C and 34 ^{0}C for the passive and active setups on hourly basis with the corresponding mean values being 31.02 ^{0}C and 32.28 ^{0}C. These confirm that higher ambient temperatures were recorded during period for the active tests. On daily basis, the respective mean values attained were 30.89 ^{0}C and 31.95 ^{0}C. The respective variations in fig. 3 however, indicate that the daily values did not follow any particular pattern. This is can be traced to the fact that the daily weather patterns for the periods of the tests were consistently not uniform.

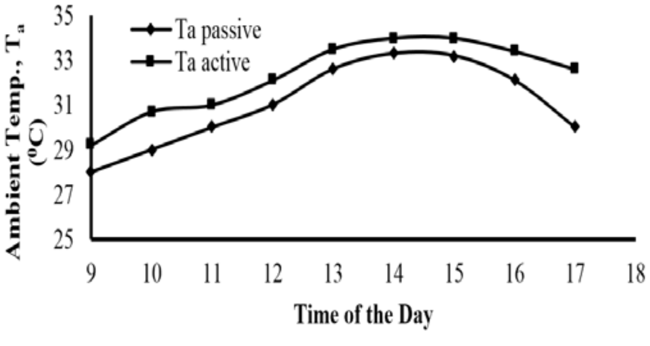

Fig 2: Mean Hourly Variation of Ambient Temperature

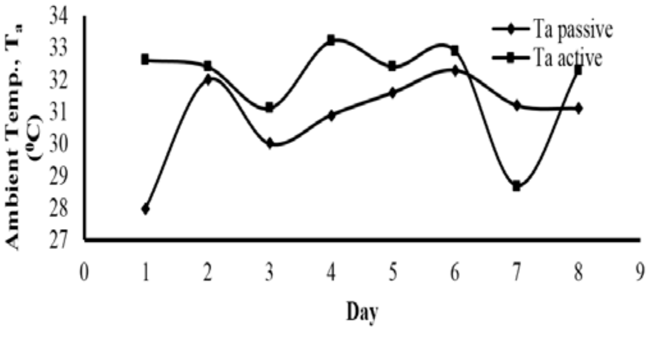

Fig 3: Mean Daily Variation of Ambient Temperature

Figs. 4 and 5 show the variation of the mean collector outlet temperature with time of the day and days respectively. The daily values also varied in a slightly polynomial pattern directly as a result of the ambient temperature patterns for both the passive and active tests. However, the values for the active tests exhibited a linear characteristic up till about 15.00 hours before flattening out. The key period with potential for the use of the collector for the multi-effect humidification (MEH) system as shown in fig. 4 is between 11.00 to 17.00 hours. This is because the water outlet temperature steadily increases towards maximum before stabilizing above ambient temperature.

The passive option recorded higher outlet temperatures generally as expected because the water had a longer resident time within the collector because the driving force was gravity and convectional currents. On hourly basis, the maximum values attained for the two options were 56 ^{0}C and 53.3 ^{0}C translating to mean values of 48.44 ^{0}C and 45.54 ^{0}C respectively. The respective maximum values on daily basis were 54 ^{0}C and 50.2 ^{0}C with mean values of 48.44 ^{0}C and 44.09 ^{0}C. These are below the minimum value of temperature required (about 70^{0}C) for the water exiting the collector in order to be suitable for use in a MEH system. The minimum value most likely could not be attained due to the few runs of the copper tubing in the collector. This means that increasing the number runs will enhance the increase of the resident time of the water within the collector thereby directly influencing the temperature rise above ambient.

Fig. 5 confirms the earlier assertion that weather patterns during periods for both tests were not quite similar with significant daily variations.

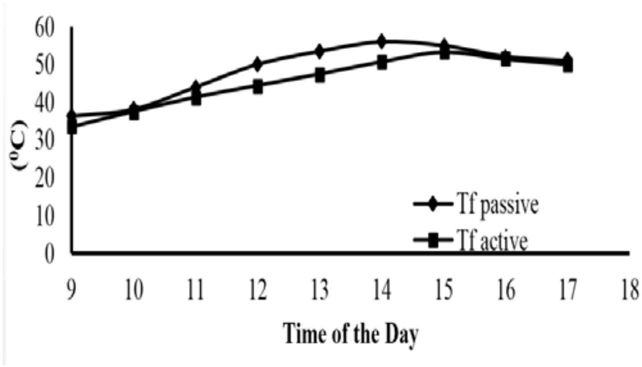

Fig 4: Mean Hourly Variation of Collector Outlet Temperature

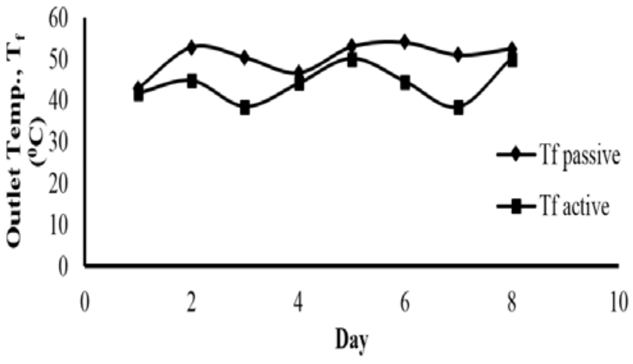

Fig 5: Mean Daily Variation of Collector Outlet Temperature

Figs. 6 and 7 show the variation of the mean hourly outlet temperature of water from the panel with ambient temperature for the two options respectively. The linear trends clearly show that the water outlet temperature increases with the ambient temperature. This shows the potential of utilizing a MEH system incorporating a solar collector exists for locations with high mean temperatures which justifies the investigation in Makurdi [Itodo and Fulani, 2004]. The relationship for the active option had a higher R^2 value of 0.925 as against 0.868 for the passive option indicating a stronger linear correlation. This can be attributed to the better mixing of the water occasioned by the pumping action. The equations obtained for both options were

$T_{fp} = 3.5618T_a - 62.051$ and $T_{fa} = 3.9133T_a - 80.768$.

These are invaluable for further investigation on this work, where T_{fp} and T_{fa} represent the respective collector outlet temperature for the passive and active options. By defining the expected range of T_f, the expected T_a can be computed which will determine the possible arrangement for pre-heating to make up for the deficit in the recorded ambient temperature values. The arrangement used in this study is the provision of a blackened reservoir. The results show that the mean hourly elevation of the collector inlet temperature, T_i, above the ambient temperature of 1.37 and 2.61 ^{0}C for the passive and active options respectively. On daily basis, the corresponding values were 1.69 and 1.8 ^{0}C. This slight pre-heating shows the existence of the potential to make up for the deficit in the ambient temperature required to obtain the range of output temperature needed for the operation of a MEH system. The fact that the values obtained for the period of the active tests also derives from the higher ambient temperatures for reached.

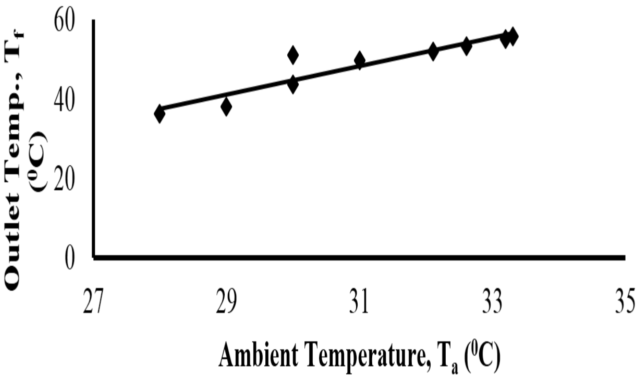

Fig 6: Variation of Hourly Outlet Temperature with Ambient Temperature for the Passive option

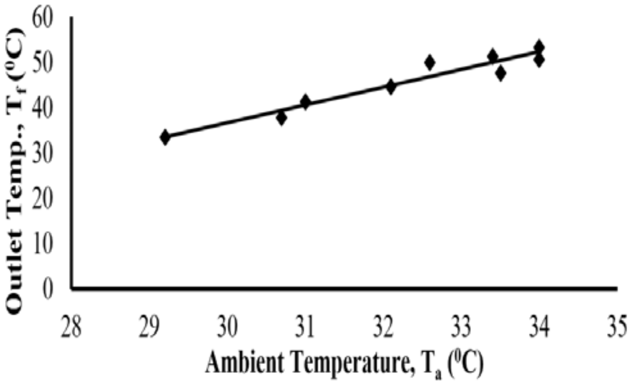

Fig 7: Variation of Daily Outlet Temperature with Ambient Temperature for the Passive option

Fig. 8 shows the variation of efficiency with time of the day for both options. The efficiency peaks and then reduces from 15.00 hour. This is in consonance with the temperature characteristics of the systems discussed so far. The values for the passive system were higher than those for the active one. This is because the passive option produced a higher mean elevation of water temperature above ambient. This temperature elevation is the driving force of the system. On hourly basis, the maximum values of efficiency for the two options were 0.73 and 0.69 with the corresponding mean values being 0.64 and 0.53 respectively. The respective values on daily basis were 0.87 and 0.79 (maximum) and 0.71 and 0.60 (mean). Hence, the efficiency computed on daily basis shows more of the capacity of the collector for producing temperature elevation of the water. For both options on hourly and daily basis, the passive option recorded higher efficiency values. This is simply because of the residency of the water within the collector to allow for the required heat transfer between the absorber and the water in the loops of tubing. Fig. 9 shows the characteristics for the systems on daily basis exhibited the trends already discussed for the temperature characteristics in the sense that no particular trend exists.

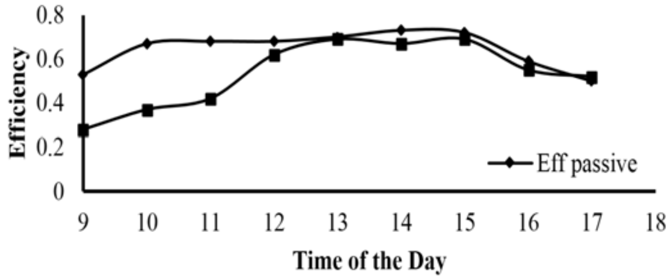

Fig 8: Variation of Collector Efficiency with Time of the Day

Fig. 10 shows the variation of efficiency with the available radiation for the passive option. The linear trend shows that efficiency is high when the available radiation reaching the collector is high. This agrees with the assertion of [22]. The active option also had a similar trend. On hourly basis, the maximum radiations available for the passive and active options were respectively 131 and 154.8 W/m^2.

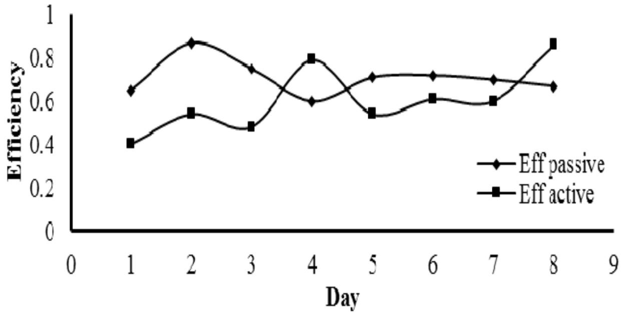

Fig 9: Variation of Collector Efficiency with Days

The respective mean values were 110.7 and 130.2 W/m^2. This pattern of radiation agrees with the observation highlighted earlier that the temperature values during the period of the active tests were higher. An expression relating the efficiency of the collector to the available radiation was formulated as shown below. The expression can be used during further studies on this work.

$$\eta = 0.0045H + 0.143$$

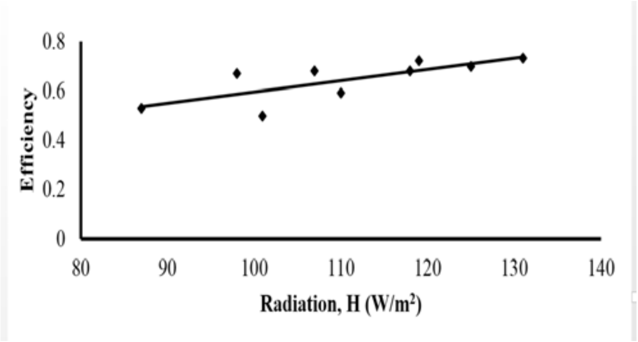

Fig 10: Variation of Collector Efficiency with the available Radiation for the Passive option.

Figs. 11 and 12 are attempts to draw the collector optimum performance curves for the two options studied. The curve ordinarily slants from left to right with the efficiency decreasing with increasing $(T_f - T_i)/H$ [23, 24]. The results for the passive tests had a pattern resembling the performance curve but were not as steep as shown in fig. 11. The results for the active option totally deviated from the expected orientation. This can be attributed to the peculiarities of the active system with particular regard to water residency in the collector, irregular flow as a result of fluctuation of power from the mains and the like. These further confirm that the passive option has more promise for applying in a MEH system apart from the fact that the cost of pumping power is also removed.

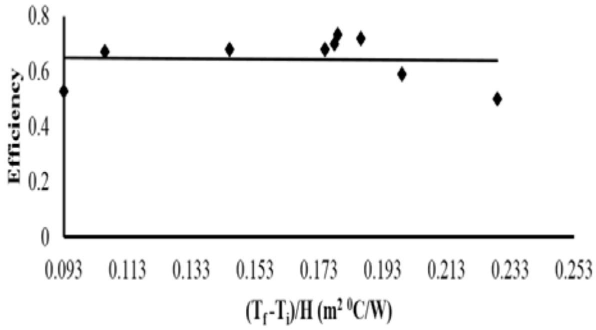

Fig 11: Optimum Collector Performance Curve for the Passive option.

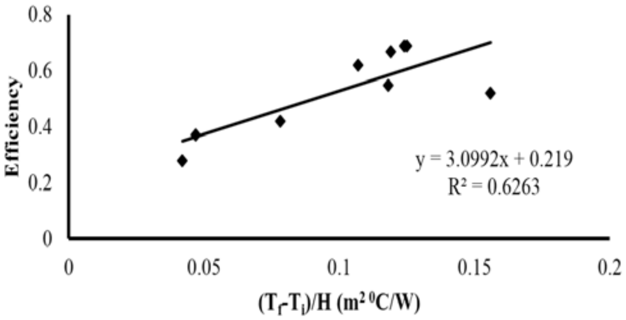

Fig 11: Optimum Collector Performance Curve for the Active option.

Conclusion and Recommendations

The practical operating conditions of a flat plate collector have been studied for both passive and active options. The collector in its present state will need to be modified in order to meet the minimum requirement for application in a MEH system. The results show that the performance of a flat plate collector depends basically on the radiation available and by extension the ambient temperature for a given collector aperture area. Makurdi has adequate radiation almost all year round. The passive system performed better in terms of the elevation of the water temperature above ambient. From the results available, it clearly shows that flat plate collectors can be installed in Makurdi for the provision of the feed water for multi–effect humidification–dehumidification systems.

Based on the results of this study, the following recommendations which are actually aspects for further development are hereby made:

(i) The use smaller diameter copper tubes in diameter (< 10mm) for the flat plate collector.
(ii) Increasing the number of runs of the tube so that water has more resident time in the collector thus absorbing more solar radiation.
(iii) Increasing the collector aperture area or used of modular configurations.

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