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Small Scale Performance Evaluation Of A Multi-Effect Humidification-Dehumidification System In Makurdi

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ABSTRACT: *A multi-effect humidification (MEH) -dehumidification solar desalination system utilizing a solar collector was designed and evaluated. A blackened aluminium storage tank was used for the feed water and was positioned so that water enters the collector by gravity for the passive test and through the pump for the active case with slight preheating. The heated water exits the collector into the desalination chamber made up of a humidifier and a dehumidifier. The ambient, collector inlet and outlet water, evaporator and condenser temperatures were measured hourly as well as the volume of water produced 10.00 to 16.00 hours. The collector was able to achieve a mean elevation above the inlet condition of about 20.8^{0}C and 29^{0}C respectively for the active and passive cases. The mean collector, water production and the overall efficiencies were computed as 0.51, 0.50 and 0.256 respectively for the active case while the corresponding values for the passive case were 0.69, 0.55 and 0.37. The respective mean daily yields of the active and passive options were 0.298 cm^3 and 2.39 cm^3 per unit volume of evaporator, 0.098 cm^3 and 0.785 cm^3 per unit volume of condenser or 0.0035 cm^3 and 0.028 cm^3 per cm^2 of collector aperture. A good potential for the system to contribute significantly to the production of safe drinking water in relatively larger quantities especially with passive option exists.*

KEYWORDS: Multi-effect Humidification-dehumidification, solar collector, performance evaluation, active test, passive test, desalination, drinking water

I. INTRODUCTION

Drinking water of acceptable quality has become a scarce commodity. In many places of the world only brackish or polluted water is available [1]. This leads to an increasing interest in new desalination technologies. In many arid regions of the world, and especially in the Middle East, where conventional sources of fresh water (e. g., rivers, lakes and ground water) are not readily available, seawater desalination will continue to supply drinking water [2]. 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. Thus, provision of portable water is one of the basic infrastructural facilities for upliftment of the standard of living of people, as well as rapid industrialization of any nation [3]. In Makurdi, the Benue state capital, residents face acute shortage of drinking water despite the prolonged greater Makurdi water works [4].

Sources of raw water (ground water, upland lakes, rivers, canals and lowland reservoirs, rain etc.) are usually contaminated either by the presence of dissolved solid, salts or pathogens in the water. However, water meant for human consumption must be free from chemical substances and micro organisms in amounts which constitute health hazards. Potable water must not only be safe and free from dangers to health, it must be of good chemical and physical quality so as to be acceptable to the people. The water must not be turbid, (i.e. cloudy), it must also be colourless, tasteless and odourless [3, 5].

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. 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 [1, 3, 5].

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 [6, 7]. Desalination of sea water could also be carried out by distillation or reverse osmosis, 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 [8-10]. 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 the use of fossil fuel [11-13].

Desalination is a water treatment process that converts brackish or saline water to freshwater by removing dissolved minerals from the water. A proven technology that has been used for many years, desalination is increasingly common in areas with scarce water supplies. However, because of its relatively high cost, it is generally used only if fresh water supplies are limited. Water desalination technologies can be categorized on the basis of the energy used to run them, usually thermal or electric. The technologies utilizing thermal energy are known as the multi-stage flash, multiple-effect distillation and vapour compression [13-15]. The desalination technologies that use electric energy rely on a membrane system, such as reverse osmosis and electro dialysis. There are also other technologies that rely on solar energy or combined electric and thermal energy. Each of these technologies has advantages and disadvantages, based on the quantity and quality of the required water and the location. Desalination processes require large amounts of thermal or electric energy; however, advances in desalination technology continue to make these processes more efficient [15-17]**.**

Recent investigations have focused on the use of renewable energy to provide the required power for the desalination processes. The most popular renewable energy source is solar energy [18-21]. An emerging technology for smaller scale desalination systems is solar multi-effect humidification-dehumidification. This process uses solar energy to evaporate fresh water, which is condensed on a cool surface and collected. Solar desalination systems are simply and easy to operate and maintained. The main idea of the multi-effect humidification-dehumidification solar desalination system is based on the evaporation of water and the condensation of steam to and from humid air. The humid air circulation driven by natural convection between evaporator tower (humidifier) and condenser tower (dehumidifier). Evaporator and condenser are located in the same insulated box. The heated seawater from central receiver is distributed onto the evaporator tower through a vertically hanging sprayer and is slowly trickling downwards. The condenser unit is located opposite to the evaporator. Here the saturated air condenses on a single tube copper coil. Water with ambient temperature was used as a coolant for the condenser. The distillate runs down to a collecting tank. Two modifications were introduced on the desalination chamber to enhance the desalination system productivity. The first modification was using water jacket at one side of the dehumidifier tower to increase the condensation surface. The second modification was to use seven flat mirrors to concentrate solar radiation on one side of the humidifier tower (0.003 m ordinary window glass) to heat the humid air to increase the system productivity [22, 23]**.**

They are also environmentally friendly because they do not require fossil fuels. In locations with abundant sunshine, such as Makurdi the state capital of Benue state, Nigeria, solar desalination is a potentially viable option, especially for small-scale plants in remote locations. Multi-effect humidification-dehumidification solar system was suggested as an efficient method for the production of desalinated water, initially for small quantity in remote arid areas. The desalination chamber consists of humidifier and dehumidifier towers. The circulation of air in the two towers was obtained by natural convection [23].

Drinking water is a major problem within Makurdi despite the on-going greater Makurdi water works. Providing sufficient quality 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 [4, 12].

Nigeria, like other countries in the sub-Saharan region is blessed with abundant sunshine all year round. Nigeria is located within the Sun Belt (between 20^0 - 30^0 N and 20^0 - 30^0 S) and receives as much radiation as 490 W/m^2 each day [24]. Makurdi, the location of this study, is on latitude 7.7^0 and longitude 8.73^0 and receive an average insulation of 35430 kJ/m^2/day from an average 6.13 hours of sunshine with the highest and lowest in August and December respectively [25]. It has an altitude of 104 meters above sea level.

The abundant solar radiation and water resource in River Benue Makurdi, could be harnessed for the production of drinking water as for remote areas in town. 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. Since the viability of solar distillation as a major player in the drinking water provision mix depends largely on the yield, focus. In this paper, the performance evaluation of a multi-effect humidification and dehumidification system for water desalination

II. MATERIALS AND METHODS

The solar collector used for the study was a flat plate collector, similar in design and configuration to the flat plate collector used in study carried out by [12]. The materials selected for the construction were based on the recommendations of [26, 27] and include aluminium sheet, Plain widow glass sheet, Copper tubes (evaporator coils), Wood (soft wood), ½” ply wood sheets, Black oil paint, Saw Dust, PVC plumbing valve and pipes, Water pump and hose, PVC gum, Silicone sealant, Wood adhesive (Top gum). The materials selected for the storage tank include, Thick aluminium sheet, Putty, Plumbing PVC pipes, Black paint. The materials selected for the desalination chamber include, Sprayer, Light gauge aluminium sheet, PVC rubber, Putty, Copper tube, Black oil paint, Epoxy glue, Water pump, Water hose

The flat plate solar collector was designed to have a length of 200 cm and a width of 100 cm with fourteen parallel copper tubes 188 cm each running along the length of the panel with 6 cm gap between the tubes. The fourteen 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 panel are given in Table 1 below.

Table 1: Design Specifications for the Solar Collector

Parameter	Dimensions
Width of glass	100 cm
Length of glass	200 cm
Area of glass cover	20000 cm^2
Thickness of glass	0.4 cm
Width of aluminium sheet	100 cm
Length of aluminium sheet	200 cm
Area of aluminium sheet	20000 cm^2
Diameter of tube	1 cm
Tube spacing	6 cm
Plate to cover spacing	3 cm
Collector box	100 x 200 cm
Height of box	9 cm

The box, housing which provides the strength needed, was constructed with fasteners according to the design specifications from Table 1. Appropriate holes were drilled in the box to allow for the inlet and outlet copper tubes. The wooden box was designed with a height of 9 cm. Glass of thickness 4 mm with length and width according to the specifications given in Table 1 was used as cover plate. The function of the glass is to prevent heat lost by the plate by radiation. The glass was pasted on top of the wooden box using silicone sealant. The gap between the cover glass and the plate was 3 cm. The space underneath the plate (between the plate and the base of the box) was packed with rice husk as insulation to prevent heat loss through the plate by conduction. The plate was constructed using 3 mm thick aluminium sheet. The sheet was cut to size using cutting scissors according to the design specifications in Table 1. The 10 mm diameters (O.D) copper tube was bend to form a continuous loop on the top surface of the aluminium plate, with ten parallel copper runs along the length of the plate. The copper tubes were attached to the upper surface of the plate by using screw fasteners. 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 copper tubes. The orthographic representation of the flat plate collector is shown in fig. 1.

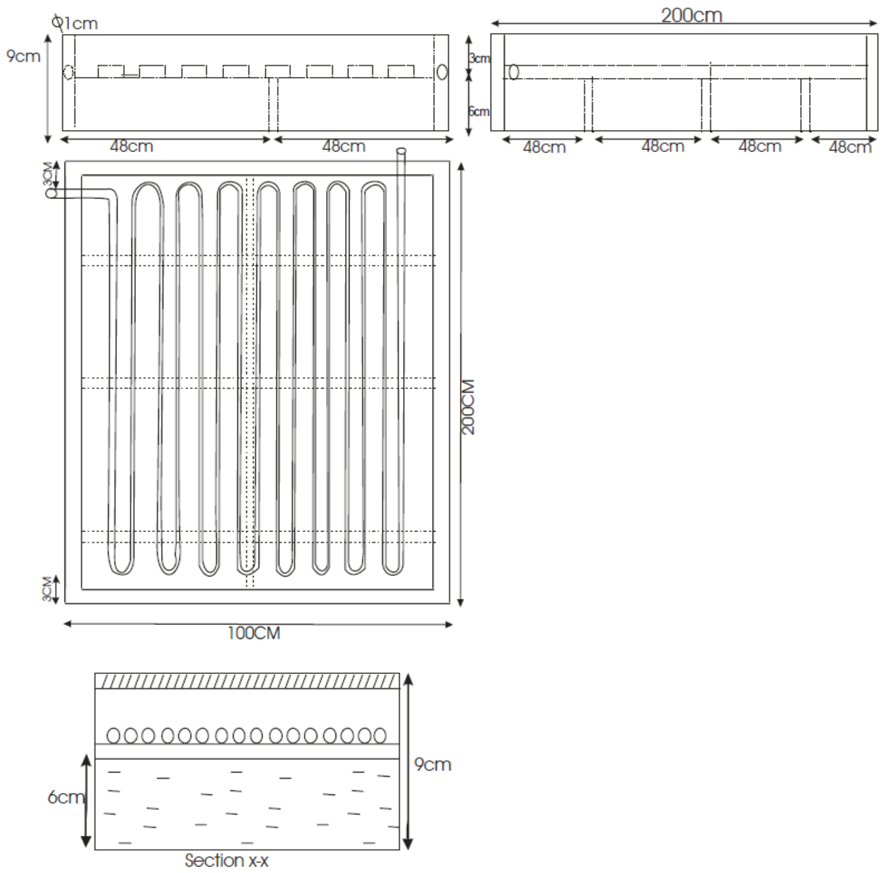

Fig. 2: The Flat Plate Collector in 1st Angle Projection

A storage tank was designed to serve the solar collector. It was designed to have a capacity of 0.032 m^3 (32 l) of water. The equation for the volume of a cylinder was used to design the tank. The tank has a height of 45cm and a diameter of 30 cm. The equation was used to calculate for the perimeter of the tank, which was found to be 88 cm. Thick plain aluminium sheet was cut to size, and bend 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 hardening substance 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	45 cm
Diameter of tank	30 cm
Perimeter of tank	94 cm
Volume of tank	32000 cm^3

The desalination chamber is divided into two parts, evaporator and condenser towers. The evaporator was designed to have a capacity of 235 cm^3 of water. The equation for the volume of the cone was used to designed the cone, it has a height (h) of 14 cm, radius (r) of 4 cm and slant height (l) of 15 cm. light aluminium sheet was cut to size, and bend to form a cone. A paste of putty and epoxy glue was applied on the welded edges to prevent leakages.

The condenser was designed to have a capacity of 716 cm^3 of vapour. The equation for the volume of the cone was used to design the cone; it has a height (h) of 19 cm, radius (r) of 6 cm and slant height of 20 cm. Light aluminium sheet was cut to size, and bend to form a cone. The joint was fabricated; a mixture of putty and a hardening substance (epoxy glue) was applied on the fabricated joint to provide a air tight seal. The design specifications for the desalination chamber are shown in Table 3 below. Plate 1 shows a photo of the components of the desalination chamber.

Table 3: Design Specifications for the Desalination Chamber

Parameter	Dimensions
Height of evaporator	14 cm
Radius of evaporator	4 cm
Slant height of evaporator	15 cm
Volume of evaporator	235 cm^3
Height of condenser	19 cm
Radius of condenser	6 cm
Slant height of condenser	20 cm
Volume of condenser	716 cm^3

Plate 1: Photo of the Evaporator and the Condenser

The test rig consists of the storage tank, flat plate solar collector, desalination chamber, 0.5 Hp water pump (for the active test) and a thermometer. The storage tank is installed 99 cm above the ground level. The collector is inclined at an angle of 29.7^0 as the angle of tilt. A flexible hose connects the tank mouth piece to the collector inlet with the aid of a PVC gum and hose clip. The outlet of the flat plate collector is connected with the aid of epoxy and super glue to a sprayer which is located half way inside the evaporator. Heated water leaves the collector and is distributed into the evaporator tower through the hanging sprayer and slowly trickles downwards. Unvaporised water in the evaporator tower is collected downward to the storage tank while by natural convection water vapour is circulated into the condenser unit via a copper tube where the saturated air condenses inside the coned shape condenser layer. Cold water circulated by means of a small pump as a coolant for the condenser to transfer heat from it to the environment. The condenser chamber is located inside a water jacket. The distillate runs down to a collecting tank.

A thermometer was installed on the outlet port of the storage tank to measure the initial temperature of the water. Another thermometer was installed on the outlet pipe of the collector to measure the temperature of the water exiting from it. The volume and temperature of the distilled water from the condenser were also measured. Plate 2 shows a photo of the set up.

The storage tank was first filled with water to full capacity. Then, the valve on the mouth piece of the tank was opened so that water is drawn into the inlet pipe of the collector by the pump for the active test and by gravity for the passive test. A type K thermometer was used to measure the ambient and initial temperatures of the water before it enters the collector. The position of the tank permitted a water flow of about 0.00054 l/s for the passive option and the pump was regulated for the active option such that water flows through the collector at about 0.002 l/s in order to maintain a reasonable resident time within the black-coated copper tubes of the collector thereby absorbing more heat by conduction.

The final temperatures of water from the solar collector, the evaporator and the condenser as well as the temperature of the outer surface of the collector glazing were measured hourly from 10:00 am to 4:00pm. The hourly solar radiation values were determined using the estimation provided by [28]. Plate 2 shows the active experimental set up.

Plate 2: Photo of the active System

The vaporization ratio which is a measure of the efficiency of the evaporator in producing water at steady state as well as the collector efficiency was computed. This was computed as a ratio of the water produced to the feed water. The collector efficiency was computed using equation 1 according to [26, 27].

$$\eta = \frac{Q_U}{I_t \times A_c} = F_R \times \tau \times \alpha - F_R \times U_L \left(\frac{t_i - t_a}{I_t}\right) \qquad (1)$$

Where Q_U = useful energy delivered by collector (W), A_c = total collector area, (m^2), I_t = solar energy received on the upper surface of the sloping collector structure, (W/m^2), τ = fraction of incoming solar radiation that reaches the absorbing surface, transmissivity, α = absorptivity, U_L = over all heat loss coefficient, $W/\ m^{2}\ {}^{0}C$, t_i = temperature of fluid entering the collector, °C, t_a = atmospheric temperature, °C and F_R = heat removing factor. An estimate of the overall system efficiency was computed by multiplying the collector efficiency and that of the evaporator in producing water. Some of the measured and computed parameters were then plotted.

Results and Discussion

The results obtained from the tests are presented in the graphs below. The order adopted for each presentation is the results for the active system first and then the results for the passive system.

The mean ambient hourly and daily temperatures for the period of the active test were both 26^0C while the corresponding values for the passive test were 30^0C. This is untypical of Makurdi towards the end of the year [25]. However, this further stresses the fact that weather conditions no longer adhere strictly to the usual patterns as a result of climate change issues. It is therefore a reasonable justification for exploring ways of utilizing the potentially available energy for useful purposes such the provision of scarce quality potable water. The use of a black-painted reservoir for the feed water in the system produced a pre-heating []29 above ambient temperature by mean value about 4.4^0C and 2^0C for the active and passive options respectively. The slight pre-heating of the feed water enhances a more effective operation of the collector.

The mean hourly and daily temperatures at the outlet of the collector were about 51^0C and 61^0C for the respective options. The hourly mean values exhibited parabolic trends and peaked with 70.4^0C and 81.4^0C between 12.00 and 13.00 hours. These peak values expectedly corresponded to mean ambient temperatures of 29.4^0C and 34.6^0C respectively, translating to an elevation of the water temperature between collector inlet and outlet of about 35.3^0C and 44^0C. The daily mean values exhibited a more linear tendency than the hourly values which indicates that the conditions for the period of the study were reasonably similar from day to day for both options. The respective mean values of the available radiation also exhibited similar trends.

Fig. 2 shows the variation of the various measured system temperatures with time of the day. The evaporator temperature (T_v) was expectedly the highest and the figure shows that additional heating was achieved between the collector outlet and the evaporator. This resulted from the use of blackened aluminium sheet for the construction of the evaporator. The additional heating was necessary to compensate for the inability of the collector to achieve an outlet temperature of water close to 100^0C. The water outlet temperature (T_f) was the next followed by the water temperature at the collector inlet (T_i) and then the ambient temperature (T_a). The least of the system temperatures was that of the condenser (T_c) especially in the morning and in the evening. Generally, these temperatures exhibited the expected trends with the time of the day. However, this tendency was more clearly shown by T_v, T_f, T_i and T_a. A clustering of T_a, T_i and T_c for both options shows a good performance since the initial water and condenser temperatures were in the region of the ambient temperature.

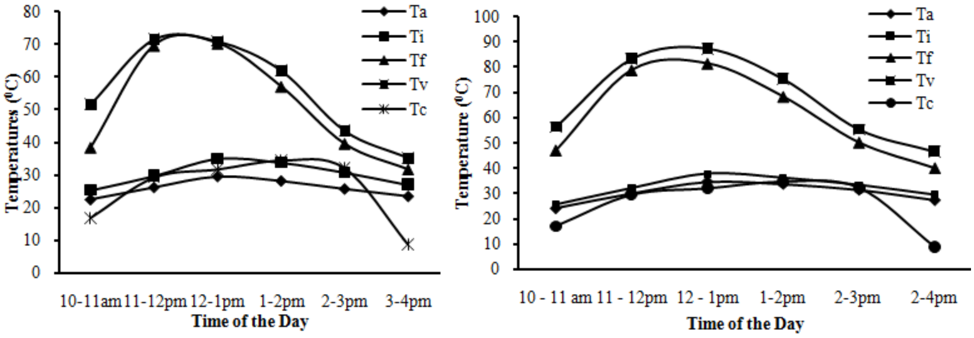

Fig. 2: Variation of the Mean Temperatures with Time of the Day

Fig. 3 shows the differences between some of the system measured temperatures. The highest difference was $T_v - T_c$ followed by $T_f - T_i$ and then $T_i - T_a$ in that order. This is expected and indicative of good performance because the driving force for water production is $T_v - T_c$ while $T_f - T_i$ shows that the collector produced the required significant temperature rise in the water. The patterns of these differences were similar for the two options though there was a slight difference for the passive option in terms of $T_v - T_c$ as shown in the figure. This was as a result weather fluctuation during the course of the passive test.

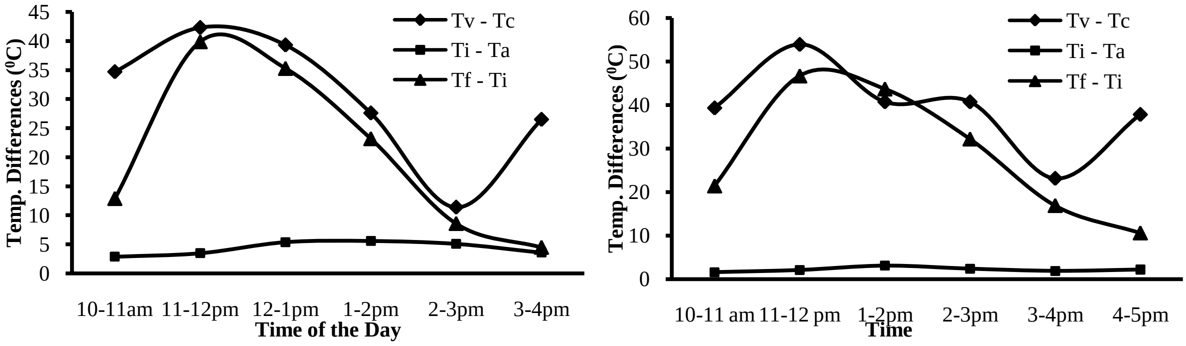

Fig. 3: Variation of Mean Temperature Differences with Time of the Day

Fig. 4 shows the variations of these temperature differences with days for the periods of the study. A similar pattern was observed except that on the 4^{th} day for the active option, $T_f - T_i$ was the highest. This was not expected and could be traced to the departure in the condenser temperature resulting slightly different daily weather conditions and probably because mean values were used. The passive option had more distinct trends for these temperature differences with the indication of better weather conditions in terms of solar radiation on the 4^{th} day.

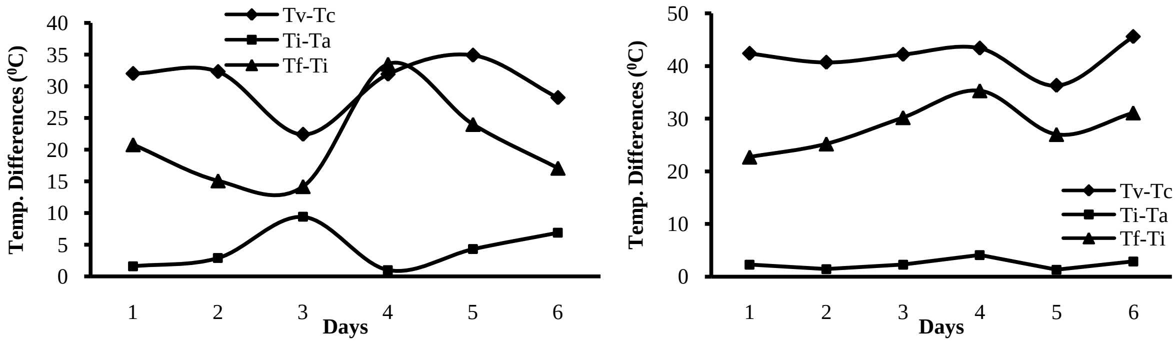

Fig. 4: Variation of Mean Temperature Differences with Days

The mean computed collector efficiencies on an hourly and daily basis for the active option were both 0.51. The respective values for the passive option were 0.65 and 0.69. These values compare favourably with values reported for the same location [12]. This indicates primarily that some attention was given to good construction and probably due to the time of the year that the study was carried out. For the present work, the efficiency of the collector therefore gives credibility to be overall system performance. Fig. 5 shows a variation of the collector efficiency with days for the period of the study. It shows that the peak efficiency for the period occurred on the 4th day of the study when the mean radiation available was the highest (190.1 W/m^2). This agrees with the general provisions for collector operation [27, 30]. Fig. 6 shows the variation of the water production efficiency with days. It is essentially the same as fig. 5 especially for the passive option. The variations of these efficiencies for the active system expectedly had some differences due to additional issues such as the fluctuation of power supply for pumping the water. However, the relationship between the daily values was smoother in fig. 5 probably because collector efficiency largely depends mostly of the available radiation while other factors such as relative humidity affect water production.

The mean water production efficiency for the active system was determined as 0.50 while that of passive system was 0.55. These were reasonably higher than values obtained by using some other systems like the simple basin water still in the same location. With efficiency in this range and better design, the prospects for the production of very significant quantities of drinking water by this method exist for this location. It can be theoretically assumed that the system is capable of producing safe drinking water half the volume of the feed water. Estimates of the overall system efficiencies were obtained as 0.256 and 0.37 for the active and passive options respectively which are acceptable for systems of this nature.

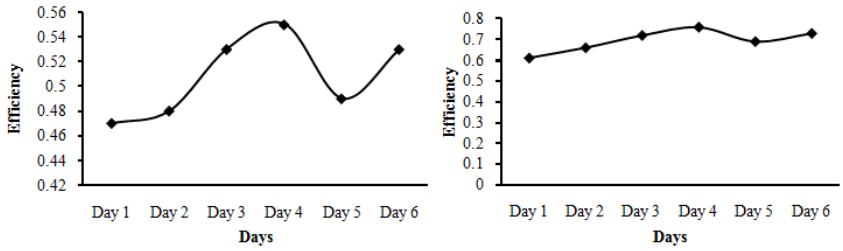

Fig. 5: Variation of Collector Efficiency with Days

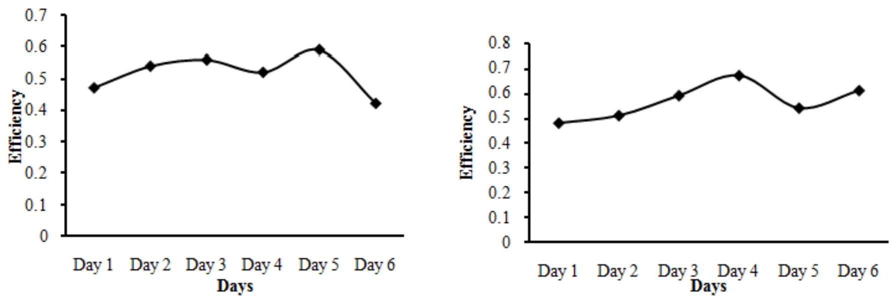

Fig. 6: Variation of Water Production Efficiency with Days

Fig. 7 shows the variation of the total volume of water produced with time for the period of the study. For the two options, very linear correlations were indicated with R^2 values of about 0.99 and 0.95 respectively. This is to be expected as the momentum for water production is cumulatively carried on during the course of the day. The relationships between the two quantities for this system are given by the trend equations in the respective graphs.

The hourly volumes of water varied strongly with a parabolic trend as expected with R^2 value of 0.94 and 0.98 for the respective options. This indicates that the water production rate increases to the peak value and then decreases to a minimum towards evening. This is shown in fig. 8. The relationships between the two quantities are given by the trend equations shown.

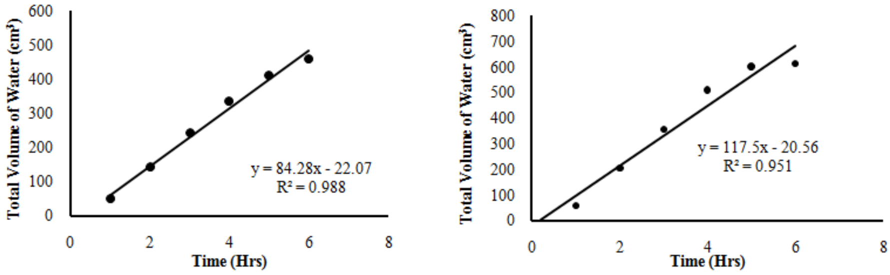

Fig. 7: Variation of total Water Volume Produced with Time

The total volume of water produced for the period of the study was 420.2 cm^3 for the active set up and 3,373 cm^3 for the passive option. This represents respective daily means of about 70 cm^3 and 562 cm^3. In terms of unit volume of evaporator, the yield for the active system was 0.298 cm^3 while that for the passive option was 2.39 cm^3. The respective values in terms of condenser volume were 0.098 cm^3 and 0.785 cm^3. Furthermore, based on unit square centimetre of collector aperture, the yields were respectively 0.0035 cm^3 and 0.028 cm^3. The foregoing indicate that the potentials for the system can be more effectively tapped by utilizing a larger collector aperture with more passes of tubing as well larger dimensions of evaporator and condenser than the ones utilized for this study. On an hourly basis, the mean volumes of water produced were about 272.9 cm^3 and 391 cm^3.

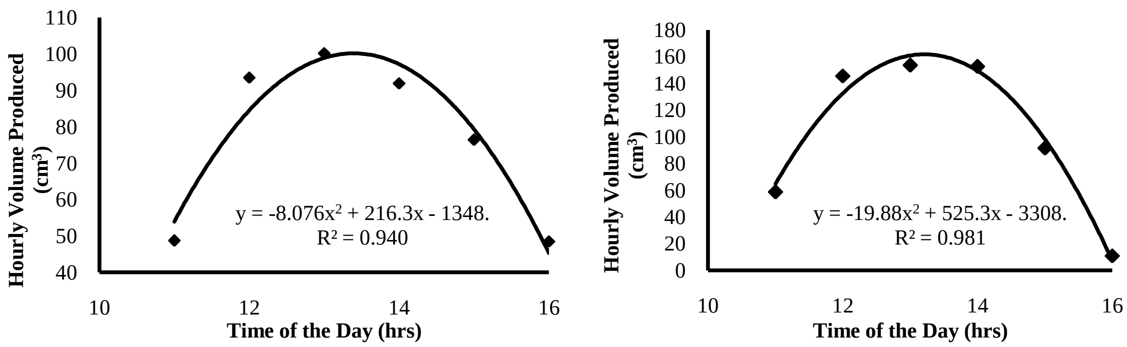

Fig. 8: Variation of Mean Hourly Volume of Water Produced with Time

Fig. 9 shows that a parabolic relationship exists between hourly overall system efficiency and volume of water produced. This further strengthen the fact already established that water production increases to a peak and then decreases in the evening. It can be conveniently assumed therefore that a plot of these values on a daily basis will also give a good linear relationship. The relationship for the hourly quantities had an R^2 value of about 0.89 and 0.78 with the trend equations are shown in the respective graphs for the two options.

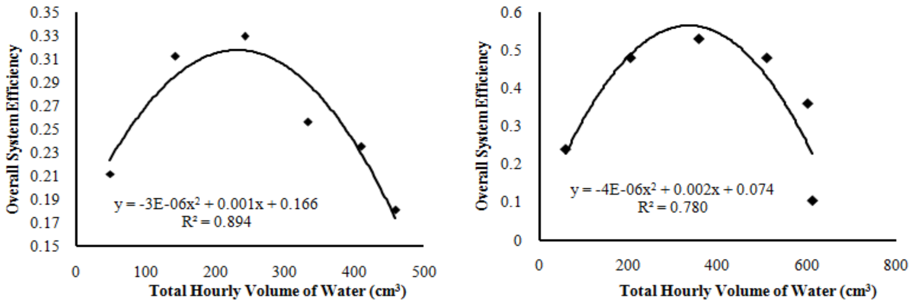

Fig. 9: Variation of Overall System Efficiency with Total Hourly Water Produced

Figs. 10 and 11 show the relationship between the volume of water produced and the available radiation on daily and hourly basis respectively for the period of the study. In fig. 10, the R^2 value for the active system indicates very poor correlation while that for the passive option was much better. A factor which could feature as a reason for this could be irregular power supply leading the flow fluctuation earlier mentioned from day to day. Another factor could be as a result unstable weather pattern from day to day during the study period. The R^2 values for the hourly data show polynomial patterns as expected. Again the passive option correlated better as shown in fig. 11. The respective trend equations are given in the figures. They can be used to estimate these values for systems of similar configuration and sizes.

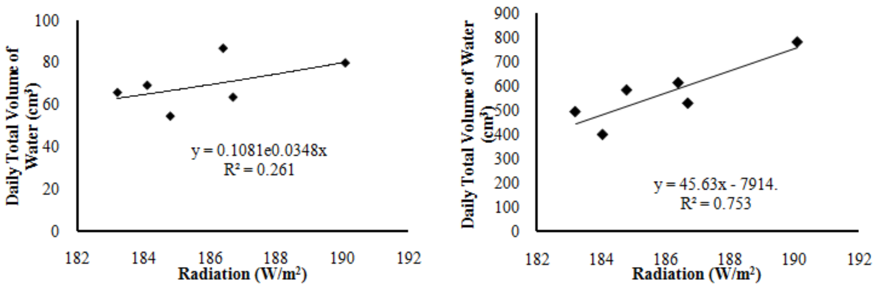

Fig. 10: Variation of Mean Total Daily Volume of Water with Mean available Radiation

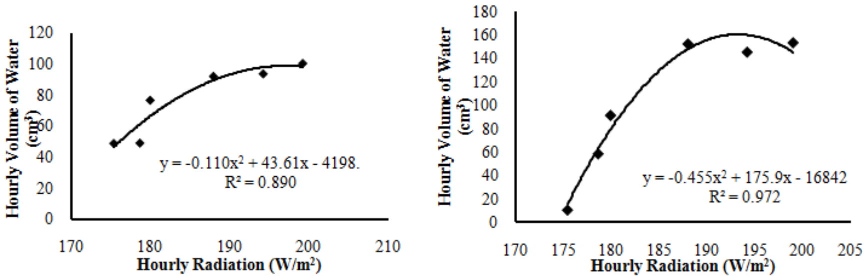

Fig. 11: Variation of Mean Hourly Volume of Water produced with Hourly Radiation available

CONCLUSION AND RECOMMENDATIONS

Having observed the practical operating conditions of the multi–effect humidification–dehumidification systems coupled with an active and a passive flat plate collector, it can be said, that, the optimum performance of a the multi–effect humidification–dehumidification systems depends on the insolation available to it. The system was found to show potentials and suitability for contributing to the provision drinking water for Makurdi and other areas with similar availability of radiation coupled with unavailability of drinking water. However, for the active system, power supply needs to be steady for greater effectiveness and the heat transfer surface areas need to be adequately large. This will translate to prohibitively larger costs that can negate the potentials of the system. Hence, the passive option has shown considerable potentials for utilisation especially with the virtually insufficient power supply. Apart from lower costs, it can be utilised in the many rural locations in Benue State.

Further work will be carried out with copper tubes of diameter less than 10 mm in order to increase the surface area of water flow through the copper tubes. Also, in order to ensure a longer resident time resulting in a higher collector output temperature, more passes of the copper tubes be considered for further work. Larger volumes of the components of the desalination chamber will also be investigated in order to increase the system productivity. However, this should be done bearing in mind the final cost of the system.

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