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Evaluation of the Thermal Performance of a Thermo Syphon Water Heating System Using a Compound Parabolic Solar Collector

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Abstract -The performance evaluation of a thermo-syphon water heating system using a compound parabolic solar collector is presented. The system investigated consists of a compound parabolic collector, an absorber/receiver, a hot water storage tank, a cold water storage tank, water returning pipe and the support stand. Cold water is stored in an upper bigger cold water tank and this water flows by gravity through a pipe passing through the focus of a compound parabolic collector into a lagged lower tank where it is stored for use. Series of performance tests were carried out on the system under high intensity solar insolation using the prevailing climatic condition in Owerri, Imo state Nigeria. Results obtained show that the thermo syphon system can produce domestic heating water of temperature of about 90^{0}C. The temperature profiles plotted indicate that the system designed is strongly dependent on the prevailing weather condition.

Keywords: **thermo-syphon, compound parabolic collectors, insolation, efficiency.**

I. INTRODUCTION

Solar collectors are the key component of active solar water -heating systems. They gather the sun's energy, convert its radiation into heat, and then transfer that heat generated to a fluid. The heat generated could then be utilized in solar water-heating systems, solar pool heaters, and solar space-heating systems. There many types of collectors, prominent amongst them are the flat plate and Compound parabolic Concentrators (CPC) type. To achieve temperatures in excess of approximately 80°C from a solar collector, the solar radiation has to be concentrated. Because the relatively low temperatures attainable when flat plate collectors are used, therefore the concentration of solar radiation becomes necessary Rabl[1]. By using internal reflectors, the hot absorber area can be reduced and this reduces the heat losses. CPCs (Compound parabolic Concentrators) are here the optimal choice, since they have the capability of reflecting to the absorber all of the incident radiation. CPCs are non-imaging concentrators. They have the capability of reflecting to the absorber all of the incident radiation within wide limits. Their potential as collectors of solar energy was pointed out by Winston [2]. CPC solar collector can not only gather the solar beam to the receiver with a reflector/refractor but also utilize the beam and diffuse solar irradiation like a flat plate solar collector. Therefore, CPC solar collectors are always efficient than typical flat plate solar collector Yong et al [3] In this paper, the use of the compound parabolic collector in the operation of a thermo-syphon system is highlighted The solar thermo-syphon system basically has three components namely: the storage tank, the solar collector and the piping. Thermo-syphon systems do not have pumps rather circulation of the fluid depends on the siphoning principle occasioned by thermal effect due to density differential and gravity. Thus, the heating of a specific amount of liquid usually causes its expansion by volume and hence a reduction in its density. If that is the case, when a column is heated unequally, a density differential would result which causes the fluid being heated to flow without any external power source other than solar radiation.

II. SYSTEM DESCRIPTION

Schematic diagram of the thermo-syphon system under analysis is illustrated in Fig (1). It is made a CPC collector, an absorber pipe, two water storage tanks, return pipe and a support stand. The CPC has a compound parabolic reflecting surface whose line focuses on a cylindrical copper receiver/absorber surrounded by a glass envelope. The receiver is used to receive incident radiation energy is covered with a selective surface of high solar absorptance (αr) and low emittance (εr), whilst the reflector is consist of several mirror sheets cut into size with high reflectance (ρm) and glued on the surface of the curvature .The absorber pipe is made of a copper tube painted black with inner and outer diameters of 13mm and 15mm respectively. The location of the absorber is at the focal point of the CPC collector. This is to facilitate the heat transfer between incident solar radiation and the absorber material. To further enhance the heat transfer from the concentrated ray to the receiver, the receiver was covered with a glass tube and insulators at the edges to minimize heat conduction the receiver and the reflector. The Water used as heat transfers medium flows through the receiver tube and the tank. To suppress convection losses from the receiver a glass envelope is placed around it. A transparent cover is fitted to protect the reflector surface from deterioration; and also it reduces the rates of heat loss from the receiver envelope configuration. On the other hand to reduce heat losses to the ambient the underside of the reflector is covered in insulation. The present system operation is very simple, when water is

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poured into the cold water chamber, and the control valve turned on, the water flows under gravity into the receiver/absorber tube. At the absorber section, heat is transferred from the copper tube to the circulating water and is consequently heated. The heated water then flows into the returning tube against gravity thereby restricting the heated water from flowing into the storage tank. At this section the thermo-syphoning effect comes into play. As the temperature of the water increases, its density reduces while the mass remains constant in other to balance the effect of the reduction in density, there is a resultant increase in volume which consequently pushes the water level further along the returning pipe. Further increase in temperature reduces the water density and increases the volume of the water thereby causing the heated water to flow into the insulated tank.

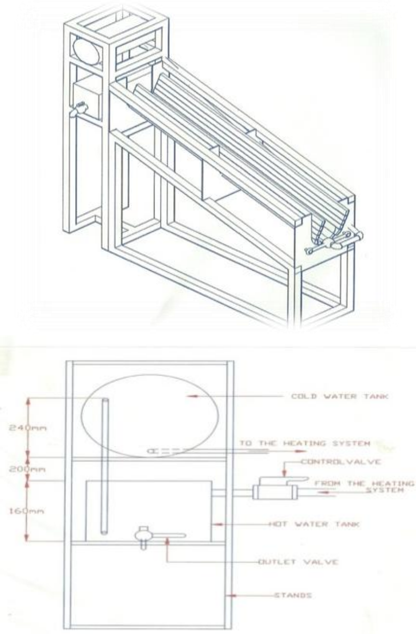

Fig 1 the CPC thermo –syphon system

III. MATERIALS AND METHODS

The present study is aimed at satisfying the domestic the heating need of people in Nigeria, Africa and Middle East generally where the solar insolation is sufficient enough to raise the temperature of water to domestically required temperature of between 80^0C and 100^0C. The tropical climate here does not permit freezing and snow formation as temperature hardly drop so low , hence the use of antifreeze ,auxiliary heaters and thermostatic switch are not necessary. The flow of water round the system makes us use of the basic heater transfer of conduction through metallic conductors and thus corrosion of the metallic component becomes a major consideration in material selection. Hence materials were selected in such a way that corrosion effect was minimized to the barest minimum. This was achieved by using mirror as to cover the reflector. Copper was used for the absorber pipe while painted mild steel tanks were used for the cold and hot water tank. The maximum effect of the incident radiation occurs when the intercepting surface is in such a position as to have the ray normal to it. To achieve this, the collector was tilted at an angle of $\Theta+15^0$, where Θ is the local latitude of Nigeria which approximately 6^0.

IV. THEORETICAL ANALYSIS OF CPC SOLAR COLLECTORS

Compound parabolic collectors are analyzed based on their optical and thermal behaviors.

V. OPTICAL ANALYSIS OF THE CPC SOLAR COLLECTOR

The concentration ratio is defined on a geometrical basis and is expressed in terms of the total receiver areas [6]:

$$C_r = {}^{1}/_{\sin\theta} = \frac{A_c}{A_r} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .1$$

Since the system designed is a stationary CPC collector its optical property may not perform optimally. For a stationary CPC, the angle θ depends on the motion of the sun in the sky therefore; the orientation of the CPC plays a very prominent role in enhancing the optical performance of the collector. In the present work, the CPC orientation is in N–S direction and tilted from the horizontal such that the plane of the sun's motion is normal to the aperture.

VI. THERMAL ANALYSIS OF THE CPC SOLAR COLLECTOR

The generalized thermal analysis of a concentrating solar collector according to ref [4] is similar to that of a Flat Plate Collector. However, it is usually necessary to derive the appropriate expressions for the collector efficiency factor F; the loss coefficient U_L and the collector heat removal factor F_R: For the loss coefficient standard heat transfer relations for glazed tubes can be used. [4] The instantaneous efficiency of a concentrating collector may be calculated from an energy balance of its receiver. Under steady-state conditions, the useful heat delivered by a solar collector is equal to the energy absorbed by the heat transfer fluid minus the direct or indirect heat losses from the surface to the surroundings.

VII. USEFUL ENERGY DELIVERED FROM THE CONCENTRATOR

The useful energy collected from a collector can be obtained from the following formula [8]:

$$q_u = I_b \eta A_c - A_r U_l (T_f - T_a) ..2$$

Evaluating this useful energy delivered in terms of the length of the collector, the equation 2 can be rearranged and expressed with reference to the local receiver temperature T_r as

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$$\dot{q}_u = \frac{q_u}{L} = \frac{I_b \eta A_c}{L} - \frac{A_r U_l (T_f - T_a)}{L} \ldots 3$$

If the equation (2) is further expressed in terms of the energy delivered to the fluid at the fluid temperature of T_f
Then

$$\dot{q}_u = \frac{\left(\frac{A_r}{L}\right)(T_r - T_f)}{\left\{\frac{D_o}{h_{fi} D_i} + \frac{D_o}{2k}\ln\frac{D_o}{D_i}\right\}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .4$$

Eliminating T_r from equation (3) and equation (4), then $\dot{q}_u$ becomes

$$\dot{q}_u = \frac{\acute{F} A_a}{L}\left[I_b \eta - \frac{U_L}{C}(T_f - T_a)\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots . . 5$$

VIII. TEMPERATURE DISTRIBUTION IN FLOW DIRECTION

To tap the net energy generated, the working fluid enters the absorber tube and pick up the useful energy given by equation 2 at all point along the tube length. Consequently, the temperature of the fluid increases from the T_{fi} at entry to T_{fo} at the exit.

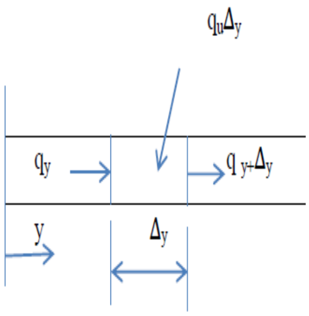

Fig 2 Temperature distributions in the flow direction

From the figure 2 above, the energy balance on an elemental portion of the receiver tube is given as:

$$\dot{q}_y + \dot{q}_u \Delta y - \dot{q}_{y+\Delta y} = 0 \ldots\ldots\ldots\ldots\ldots\ldots . . 6$$

$$\dot{q}_y + \dot{q}_u \Delta y - \dot{q}_y + \frac{\partial \dot{q}_y}{\partial y}\Delta y = 0 \ldots\ldots\ldots\ldots .7$$

$$\frac{\partial \dot{q}_y}{\partial y}\Delta y + \dot{q}_u \Delta y = 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 8$$

But $q_y = \dot{m} C p T_f$

So that the equation becomes

$$\frac{\dot{m} C p d T_f}{dy} - I b \eta A a - A r\ UL(T_f - T_a) \ldots\ldots\ldots . . 9$$

Solving for T_f in the equation 9, we have

$$T_f = T_a + \frac{I_b}{U_L} + \left(T_{fi} - T_a - \frac{I_b}{U_L}\right) e^{-\left(U_L A_r / \dot{m} C_p\right)} \ldots\ldots\ldots 10$$

IX. ENERGY REMOVAL

The ideal rate of energy removal is that of heat gain by the working fluid given by:

$$q_f = \dot{m} C_p (T_{fo} - T_{fi}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots .11$$

The thermal efficiency:

The solar radiation incident on the receiver of the CPC collector transfers a certain quantity of solar energy to the fluid working which is carried away as useful energy. However losses of energy to the surroundings by different modes of heat transfer are inevitable. The estimation of overall heat loss coefficient ($\boldsymbol{U_l}$) is the most important in the design of solar collectors. Based on unit receiver area, $\boldsymbol{U_l}$ is given by [9] as

$$U_l = \frac{1}{A_r}\left[\frac{1}{(h_{c,r-c} + h_{r,r-c})A_r} + \frac{1}{(h_{c,r-c} + h_{r,r-c})A_c} + \frac{1}{(h_{c,r-a} + h_{r,r-s})A_c}\right]^{-1} \ldots\ldots 12$$

In the CPC solar collector the useful energy is extracted in the form of heat by fluid flowing inside the receiver tube. The expression for the useful heat derived from the collector, Q_u can be written as:

$$Q_u = \dot{m} C_p (T_0 - T_i) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 13$$

Thus the efficiency of the collector can be calculated from,

$$\eta = \frac{Q_u}{A_a H_t} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .14$$

Where H_t is the total solar radiation incident on the collector surface.

X. RESULTS AND DISCUSSION

The figs 3-6 show the results obtained using the system designed. Fig 2 shows the estimated solar insolation profile obtained from previous work by the authors [8, 9] and the thermal efficiency of the CPC collector. The results obtained in fig 3-fig 6 has a similar profile as the solar radiation figure obtained in fig 2. This clearly indicates that the performance of the system is strongly depended on the prevailing weather condition. Fig 3-6 illustrates the variation of the temperatures of the ambient air, inlet water and outlet water temperatures on hourly basis. As shown, the increase in the outlet water temperature corresponds to the increase in the solar irradiation graph plotted and mass flow rates in fig 2 .This is very indicative that the outlet water temperature of the water is strongly dependent on the prevailing weather condition. Similarly, the mass flow rate profile plotted along the temperature profile increases as the temperature increases. This increase is justified because thermo-syphon principle is dependent on the variation in water density. It is a common knowledge that increases in temperature give rise to a correspondent decrease in density of the substance. Since the mass of water is constant, it is the volume of the substance that will increase in that prevailing circumstance. Subsequent

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decrease in density results to further increase in volume and mass flow rate of the substance respectively. In fig 2, the thermal efficiency of the CPC increases as the outlet water temperature increases and decreases as the outlet temperature decreases. This may be attributed to the fact that the thermal efficiency of the collector dependents on the inlet and outlet temperatures respectively

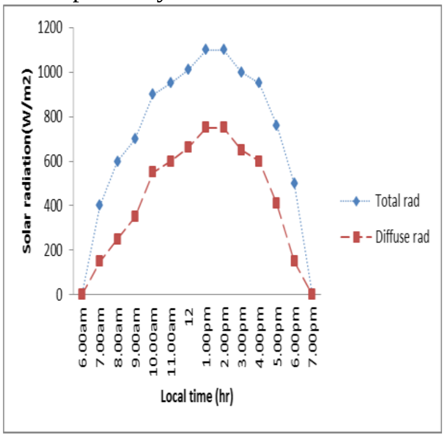

Fig 3 estimated solar insolation

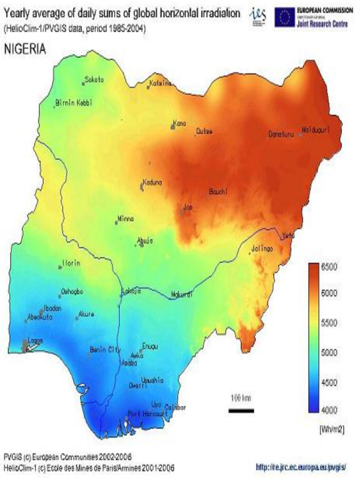

Fig 4 solar radiation incident profile for Owerri 2/8/08

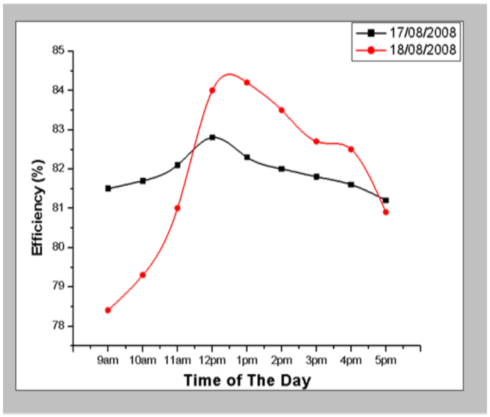

Fig 5 efficiency of the system

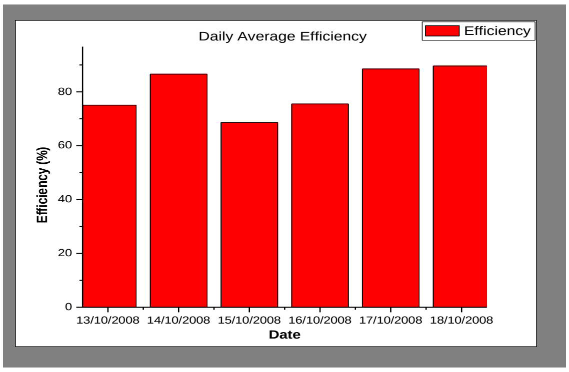

Fig 6 Daily Average Efficiency

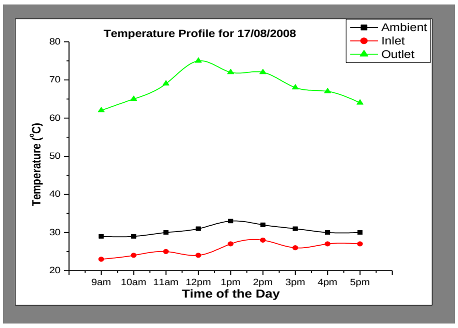

Fig 7 Temperature profile and outlet water mass flow rate obtained on 2/8/08

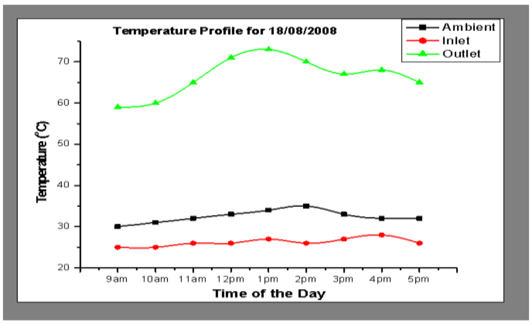

Fig 8 temperature profile and water mass flow rate obtained on 3/8/08

The system's efficiency is low due to the inability of the collector to transfer the total incident ray to the absorber tube. This may be attributed to the material used in the construction of the collector. The collector has mirrors cut into smaller pieces. These pieces were embedded on the surface of the sheet metal that was folded. Thus a rough reflector surface of the collector results to poor reflection of the incident ray thereby reducing the optical efficiency of the system. This is because some of the rays that would have been radiated to the absorber are scattered before they get to the absorber tube. From here a good correlation may be established between system efficiency and the optical property of the collector surface. Secondly, another cause of the low system efficiency of the compound parabolic collector may be attributed to the heat loss from the absorber surface. The system designed has an absorber pipe that was not covered; convective heat transfer due to a movement thus will remove the accumulated heat on the absorber surface thereby reducing the amount of heat transfer to the working fluid.

XI CONCLUSION AND RECOMMENDATION

An experimental study is performed to evaluate the thermal performance of a compound parabolic collector thermo-syphon system under the prevailing climatic condition in Owerri, Imo State. The experimental study identified the effect solar irradiation on the performance of the system as well as the effect of the ambient weather conditions on the total net heating of water. The results are summarized as follows:

- The experimental results showed that insulated water tank containing water 200 litres of water can be heated from an initial temperature of about 25.8 to 99.1^{o}C using the CPC thermo-syphon system.
- The study also showed that the absorber surface temperature can go above 100^{0}C under the Owerri climate.
- The heating power obtained during the experiment gave a net heating power of about 3952kJ.
- The efficiency for the system ranges over 43-69%. The poor efficiency value may be attributed to high relative humidity value for Owerri region, which affects the net cooling of the system.
- The thermal capacitance of absorber components has a large effect on the performance of the system and should be maximized.
- The daytime cooling experiment showed that a temperature depression of about 3.5^{o}C can be achieved by the incorporation a heat exchanger (room convector).
- The performance of the CPC thermo-syphon system is highly dependent on the prevailing weather condition and as such environmental limitation may be a major constraint to the performance of the system within regions of different climatic condition.

The incorporation of the CPC thermo-syphon system to a building for domestic water heating is feasible and can reduce greatly the cost of heating in a building. For an average building in Nigeria, a total of 100 litres of hot water is needed daily especially during the morning and evening periods. The cost of providing the amount of water is equivalent to a heating power of 2940kJ.The above results therefore indicate that:

- The compound parabolic collector thermo-syphon system can be used to heat water for domestic use in buildings in the tropical region.
- The system performance can be improved significantly by incorporating a transparent cover over the collector to prevent dust from accumulating on the surface of the collector. In the same vein, the water tank must be properly insulated to reduce excessive heat loss during night and preservation of the heated water during the day.
- Economically, with the compound parabolic collector thermo-syphon system developed in this study will compete favorably with conventional electric powered heating system. Depending on geographical location, could become the preferred choice due to high cost of energy.

The energy cost of equivalent of about 294kJ could be saved with the incorporation of this system in a building.

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