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INVESTIGATING THE PERFORMANCE OF A SOLAR COLLECTOR WITH PLASTIC BOTTLES AS GLAZING COVER

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ABSTRACT

Conventional flat plate collectors have found widespread use in both domestic and industrial applications. Despite the high potential for solar collectors in areas with enormous solar energy resource, one major factor limiting its uptake, most especially in low-income communities of sub-Saharan Africa, is its high initial cost. The replacement of flat glazing cover with transparent Polyethylene Terephthalate (PET) plastic bottles has been identified as one way of minimising cost. PET bottles constitute a significant percentage of the waste stream and can be upcycled at no cost. This also contributes to reducing plastic waste in the environment. This study investigates the performance of a solar collector design with plastic bottles as glazing cover. The collector system simply consists of a serpentine arrangement of copper tubes inserted in PET bottles enclosed in an insulated casing. Aluminium foil sheet was used as diffuse reflector in order to maximise solar radiation absorbed by the absorber pipes. Experimental studies carried out under ambient weather conditions in Zaria, Nigeria; Solar Irradiation ranged from 750 to 950 W/m^2, ambient temperatures ranged from 20 to 32 °C and wind speed was in the range 0.5 to 3 m/s. The measurements were used to estimate the standard parameters for predicting and evaluating the performance of flat plate collectors such as the instantaneous efficiency. This analysis, which indicated promising performance results, is important for optimising design and operating parameters for this low-cost solution.

1. INTRODUCTION

The nature of present day human activities is mainly characterised by various forms of energy needs. Drastic developments in transportation, communication and other technological sectors have been witnessed over the years which in turn, have brought about enormous energy requirements. This has led to heavy reliance on conventional energy sources which include coal and other fossil based fuels. In the face of threats posed by worsening environmental and climate conditions, it has become imperative to promote cleaner methods of energy production. It is as a result of this, that solar energy being the largest renewable energy source has gained increased attention. However, research and development is still ongoing with a view to improving efficiencies of existing devices and minimising cost of devices used to harness solar energy.

One of the most common methods of harnessing solar energy is by using solar collectors to capture solar radiation and thereafter convert it to heat. Solar collectors have found use in both household and industrial applications but have suffered minimum patronage in rural areas of most developing countries. Despite the available vast solar resource in these communities, they find it difficult to adopt solar thermal devices for their energy needs mainly due to the high initial cost involved. Solar collectors consist mainly of an absorber to capture solar radiation, transparent cover to reduce convection and radiation losses and back insulation to minimise conduction losses. The performance of a collector is highly affected by the properties of these components. As such, the high cost associated with solar collectors is mainly due to the choice of component materials with favourable properties of ensuring heat retention within the collector.

A key component in a collector assembly is the glazing cover and therefore contributes significantly to the total cost of the system. The idea of replacing glass cover with plastic bottles was first conceptualized by Jose Alano in 2002. Even though the major aim was to recycle waste materials, the initiative was widely adopted in Brazil and by 2008, over 13,000 solar heaters were already in use

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(https://www.theecologist.org/). Since then researchers have carried out investigations on modified versions of this concept.

Lenz et al., [1] evaluated three systems of solar thermal panels using low-cost materials- PVC lining, PET bottles and aluminium cans. The experiments were carried out in Paraná, Brazil. The data was collected over a period of 30 days in which the computer record data simultaneously from each system every hour between 1000hrs and 1600hrs. The results from his findings found that the aluminium cans proved to have the maximum efficiency from the three materials with an efficiency of 41.6% and reaching temperatures up to 54.3°C. The second most efficient is PVC lining achieving up to 39.4% efficiency and finally the least efficient out of the three is PET bottles achieving 34.5%. Although aluminium was the most efficient, it was the most difficult material to work with and the most likely to cause physical injury out of the three. Cuts to the skin can easily occur as the material is sharp and this could lead to the spread of potentially harmful diseases such as HIV.

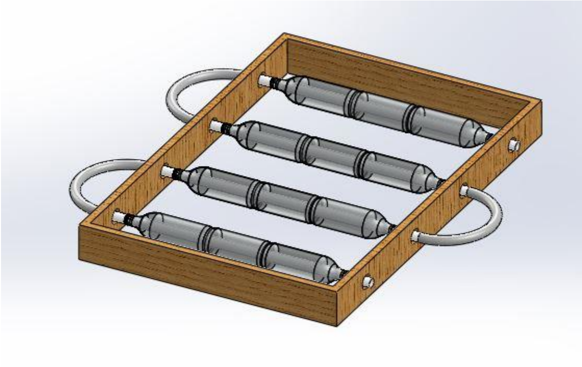
Similarly Patel [2] developed a 3D CAD model of a solar thermal collector with plastic bottle cover and carried out simulations to investigate the thermal behaviour. A prototype was then built and experiments carried out, using a 1000W halogen light as solar simulator, in order to evaluate the performance for a range of operating conditions. Hussein [3] also fabricated a 0.4425m^2 area collector using 1.5litre plastic bottles as transparent cover. Experimental analysis was carried out with the bottle filled with a phase change material (petroleum jelly). Solar radiation was simulated using halogen lamps with radiation ranging from 500W to 2500W. Temperatures of up to 48°C were recorded which shows the capability of heat storage with the inclusion of phase change material. Juanicó and Di Lalla,[4] designed and modelled a low cost solar water heater using LDPE (low density polyethylene) hose as absorber and recycled PET bottles as transparent cover. Simulations were carried out for a 100m, 1.5” diameter hose using the Argentinian weather data. The results indicated that the system had an average efficiency of 64%. de la Torre, (2011) [5] designed and fabricated a solar water heater prototype using PET bottles and CPVC pipes. The outer surface of the pipes and the inner surface of the bottle were coated with black plastic cement, thereby serving as receiver. Experiments carried out in Guatemala during the month of October yielded storage tank temperatures of 41 to 48°C. Lenhart [6] patented a solar air heater using discarded metal can bodies and transparent POP bottles connected end to end. A blower positioned in one of the absorber tube forces air through the channel into the space to be heated.

In the present study, the feasibility of using PET bottles as transparent cover for solar water heaters in Zaria, Nigeria (lat 11.0855° N, long 7.7199° E) is explored. A prototype is designed, fabricated and experimental investigations carried out by operating the collector assembly under ambient weather conditions in Zaria.

2. METHODOLOGY

2.1 The System Description

The system consists of 13 rows of 15mm diameter copper pipes, 1700mm long passing through the center of 630mm diameter cylindrical cover. The copper pipes are coated with black paint to maximize radiation absorption while 50cl plastic bottles were connected together to form a long row of transparent cover. This arrangement resulted in a total aperture area of 1.194m^2. The pipes are connected at the protruding ends using short hose pipes to form a serpentine arrangement. The whole assembly is then housed in a wooden frame as shown in Figure 1a below. Aluminum foil was lined below the plastic bottles to serve as diffuse reflectors to enhance solar radiation incident on absorber tubes. A 25litre container was used as the storage tank from where water is continuously circulated with the aid of a 12V DC pump. The storage tank was not insulated since the main aim of this work is to investigate the collector performance. Supports were attached at the rear, such that the collector tilt angle was 21°, which is the optimum collector tilt angle for Zaria, Nigeria [7].



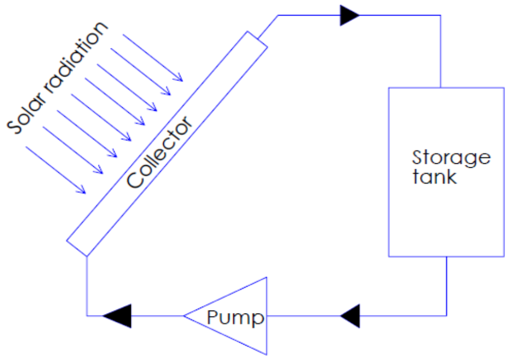


Figure 1: Schematic representation of (a) the solar water heater (b) The system Figure 2: Closed loop setup for solar water heater

2.2 Working Principle

Solar radiation incident on the collector surface is transmitted through the cover, absorbed by the pipe and converted to heat which is then transferred to water flowing through the tubes. The plastic cover serves to minimize convection losses thereby ensuring heat retention within the bottle. Water is heated up in the collector as it flows from the inlet to the outlet, after which it gets to the storage tank. The layout of the arrangement is shown in Figure 1b with the direction of flow as indicated by the arrows.

2.3 Collector Performance Analysis

The basic method of measuring collector performance is to expose the operating collector to solar radiation and measure the fluid inlet and outlet temperatures and the fluid flow rate. The useful gain is then calculated by [8]:

$$Q_u = \dot{m} C_p (T_o - T_i) \tag{1}$$

The instantaneous efficiency is then defined as:

$$\eta_i = \frac{Q_u}{A_c G_T} \tag{2}$$

The thermal performance curve is obtained by plotting η_i as a function of $\frac{T_i - Ta}{G_T}$, so that a least square fit could be used to evaluate constants such that:

$$\eta_i = F_R(\tau\alpha) - c_1 \frac{T_i - Ta}{G_T} \tag{3}$$

Where $F_R(\tau\alpha)$ is normally referred to as the intercept efficiency and

$$c_1 = F_R U_L \tag{4}$$

Many solar heating collectors can be characterized by the intercept and slope [i.e., by $F_R(\tau\alpha)$ *and* $F_R U_L$] [8].

2.4 Experimental Setup

Performance evaluation is carried out by installing and testing the collector at the workshop section of the Department of Mechanical Engineering, Ahmadu Bello University, Zaria, Nigeria. The experimental set up is shown in Figure 2. During the test period, solar radiation intensity and wind speed readings were taken using a solarimeter, anemometer respectively. Also, ambient, absorber, storage, collector inlet and outlet temperatures were measured using Type T thermocouples. A delta – T data logger was configured to record all readings at an interval of one minute. The experiment was carried out for three days on the 4th, 5th and 6th of March, 2020. The solar collector was positioned in the north-south direction, tilting towards the south.

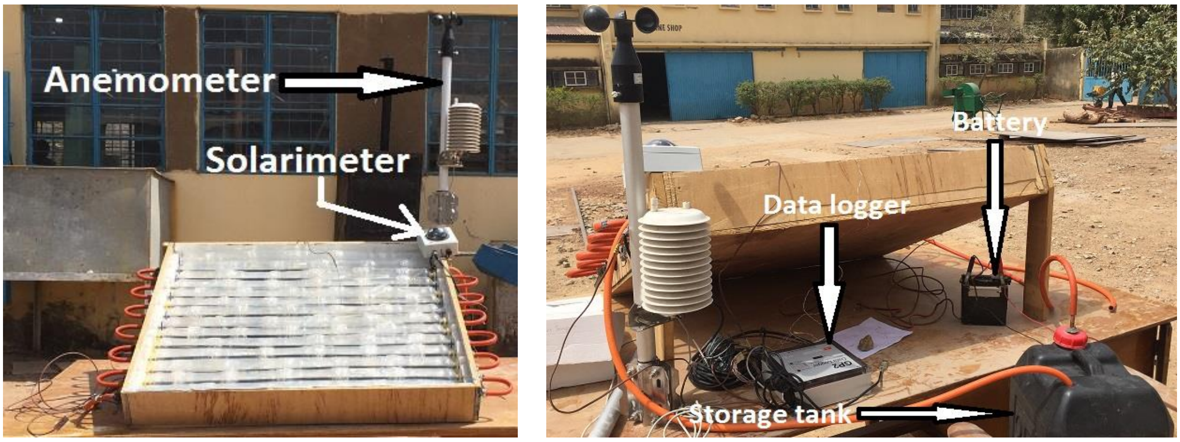


Figure 2: Actual experimental setup showing various components

2.5 Experimental procedure

The storage tank was filled with 20 liters of water from the mains after which the pump, powered by a 12V dry cell battery was switched on. Water was circulated through the system at a constant mass flow rate of 0.04kg/s. Experiments were conducted for five hours daily from 10:00am to 3:00pm

3. RESULTS AND DISCUSSION

The solar radiation and wind speed readings for the first and last days of the experiment are shown in Figure 3

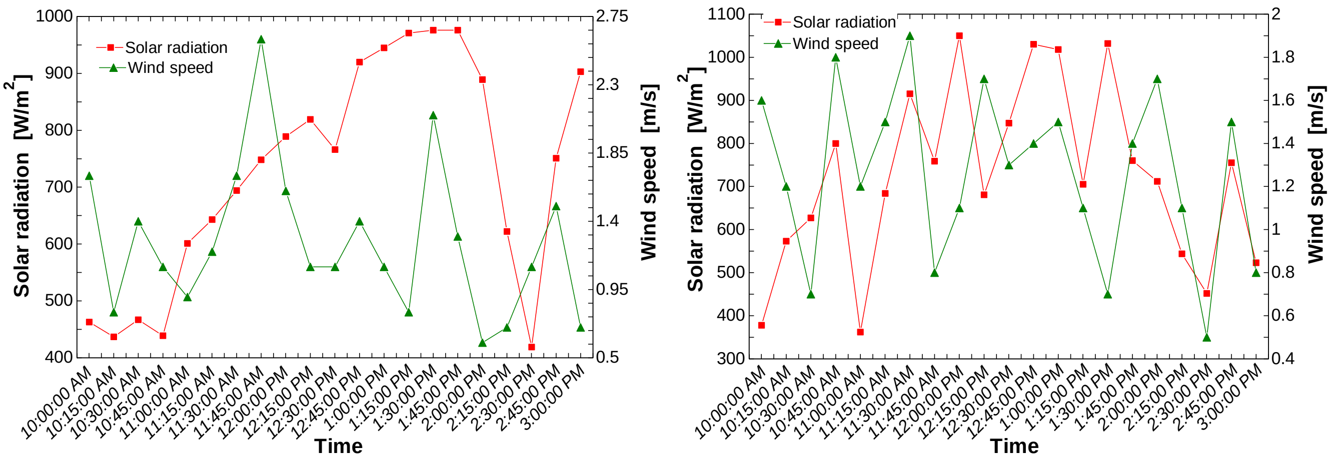


Figure 3: solar radiation and wind speed on (a) 4th March (b) 6th March

It was observed that the average radiation for 4th, 5th and 6th March were 725.6, 779.6 and 724.1W/m^2 respectively. This shows that the experiments were carried out on clear sky days. The average wind speeds for each day are also given as 1.26, 1.14 and 1.26 respectively. These results indicate that similar weather conditions were prevalent for the three days.

Figure 4 shows the temperature profiles of the various points of the collector (for the first and last days of the experiment). It can be observed from the graphs that the temperature of the PET bottle is quite high. This is probably due to convection losses from the absorber as a result of the enclosed air in the bottle. However a temperature difference of approximately 1°C between the collector inlet and outlet was achieved.

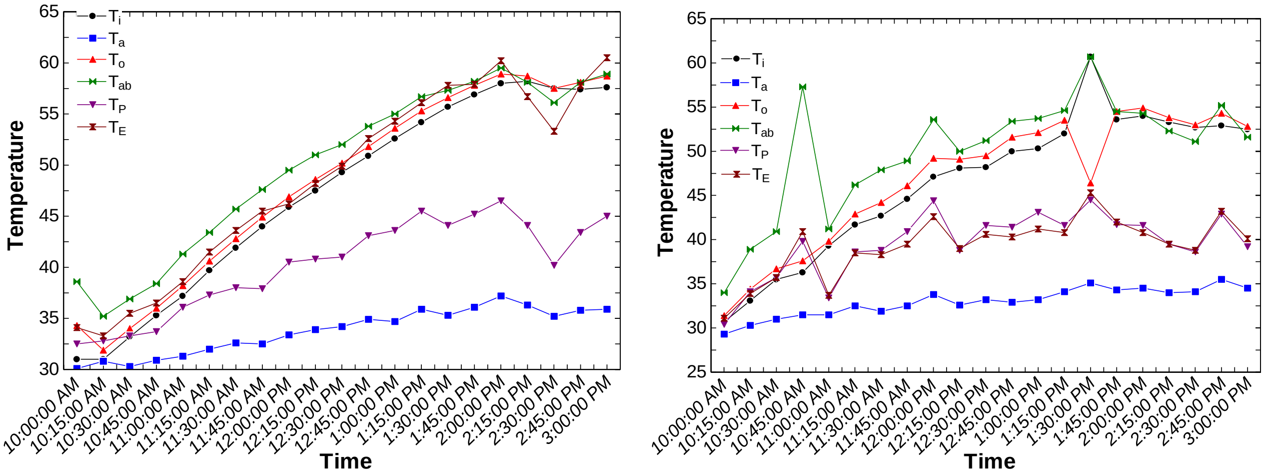


Figure 4: Temperature profiles for various points on (a) 4th March (b) 6th March

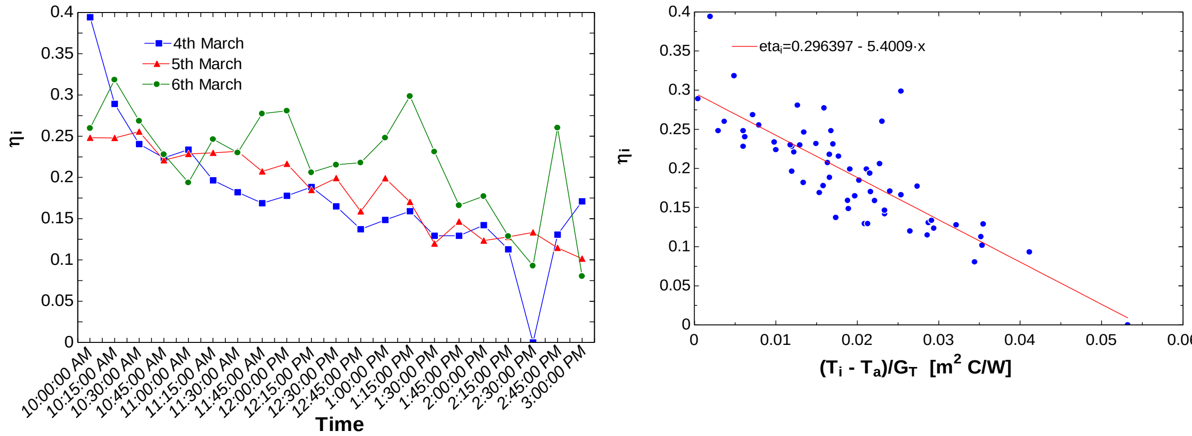


Figure 5: (a) Instantaneous efficiencies and (b) Thermal performance curve; for the three days

The instantaneous efficiencies were evaluated using equation (3) and the result plotted as shown in Figure 5a. It can be observed that the efficiencies decrease with increasing temperature. This is also because of increasing heat loss from the PET bottle due to enclosed air. Figure 5b shows a thermal performance curve using data from the 3 days. The equation of the least square fit is given as indicated in each of the graphs. It can be seen from the equations that the collector has an intercept efficiency of approximately 0.3 which is significantly lower than expected, however, considering the low production and running cost, it is still a viable option for low income communities.

4. CONCLUSIONS

A solar water heater was designed and fabricated using waste PET bottles as transparent cover. The system is a forced circulation system whereby a 12V DC pump is used to pump water.

Experiments were carried out for three days and analysis of the result shows that the collector has an intercept efficiency of 0.3. While this value might be low compared to conventional solar water heaters in the market, it is acceptable considering the low cost and availability of the materials used which has been a major factor hindering the uptake of solar water heaters in the rural areas of Nigeria despite the enormous solar resource available.

NOMENCLATURE

A_c Collector area, m^2
C_p Specific heat capacity of water, kJ/kgK
F_R Heat removal factor
G_T Total solar irradiance, W/m^2
Q_u Rate of useful Energy gain from solar collector, W
M Mass flow rate of water, kg/m^3
Q_u Rate of useful Energy gain from solar collector, W
T_o Collector outlet temperature, °C
T_i Collector inlet temperature, °C
T_a Ambient temperature, °C
T_{ab} Absorber temperature, °C
T_P Temperature of PET bottle, °C
T_E Temperature of enclosed air, °C
U_L Overall heat loss coefficient, W/m^2°C
τ Transmittance of transparent cover
α Solar absorptance
η_i Instantaneous efficiency

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