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Performance analysis of a vacuum tube solar water heater

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Abstract
Solar water heating is one of the most successful applications of solar thermal technologies. Extensive research is being performed to further improve the performance of solar water heating. This research is aimed at investigating the performance analysis of a vacuum tube solar water heater. The method adopted involves the use of the measure of solar water heater performance which is the collector's collection efficiency (η), which is a generalization from the Hottel Whillier equation. The results obtained shows that the solar water heater performs at 64% efficiency. The results also imply that the system can heat water to a suitable temperature at sunshine hours (9:00am to 4:00pm) local time and can be used to heat water for domestic, commercial and industrial uses.

Keywords: Energy, solar, tube collectors, sunshine hours, wind speed

1. Introduction

Energy is one of the basic and essential requirements of all living beings. Since the conventional energy resources are fast depleting and cost of energy is increasing, it is very important to conserve energy. Most of the power is produced by the use of fossil fuels, (like coal, oil gas etc.) which emit tons of carbon dioxide and other forms of pollutions every second and more importantly, the current trend signifies that the world is losing all its fossil fuels at a rapid pace. The main solution to get rid of this problem is to effectively make use of the Renewable Energy Sources available around us [1].

Renewable energy is energy that is collected from renewable resources, which are naturally replenished on a human timescale, such as sunlight, wind, rain, tides, waves, and geothermal heat. Renewable energy often provides energy in four important areas: electricity generation, air and water heating/cooling, transportation, and rural (off-grid) energy services [2]. Considering solar energy alone, about 10,000 times the amount of energy consumed each day worldwide strikes the earth from the sun in that same day (3×10^{24} J/year) [3]. The potential of renewable energy sources is enormous as they can in principle meet many times the world's energy demand. Renewable energy sources such as biomass, wind, solar, hydropower and geothermal can provide sustainable energy based on the use of routinely available indigenous resources. Renewable energy resources exist over wide geographical areas, in contrast to other energy sources, which are concentrated in a limited number of countries [4].

An import-independent, inexhaustible, and clean energy acquisition method needs to be developed for the betterment of humanity. In the United States alone, water heating accounts for 20% of all household energy use. There are several types of water heating systems, but the most predominately used is the conventional water heater. Majority of conventional water heaters are powered by electricity derived from fossil fuels. One emerging alternative water heating method is solar water heating. Solar power is import-independent, inexhaustible, clean, and is one of the best candidates for fossil fuel replacement [5].

Solar water heating (SWH) is the conversion of sunlight into heat for water heating using a solar thermal collector. A variety of configurations exist based on geographical location to provide solutions in different climates and latitudes [6]. SWHs are widely used for residential and some industrial applications. A sun-facing collector heats a working fluid that passes into a storage system for later use. SWH are active (pumped) and passive (convection-driven). They use water only, or both water and a working fluid. They are heated directly or via light-concentrating mirrors. They operate independently or as hybrids with electric or gas heaters. In large-scale installations, mirrors may concentrate sunlight onto a smaller collector. Presently, the global solar thermal market is dominated by China, Europe, Japan and India, although Israel was one of the first countries to mandate installation of SWH in 1980, leading to flourishing industry. Solar water heating is one of the most successful applications of solar thermal technologies. It provides environmentally clean energy and has enormous potential within domestic and industrial sectors. Solar water heaters are categorized into three main types: thermosyphon, built-in-storage, and forced circulation [7].

The solar collector is the engine of any solar water heater, with flat plate and evacuated solar tube collectors the most common ones. Solar vacuum tubes have always been the most efficient solar power production systems but were more expensive than other flat panel systems. However, the growing demand of solar energy and modern manufacturing techniques has driven down the cost such that vacuum tube technology provides the greatest return on investment versus any other solar collector system. The principle behind solar vacuum tubes is simple. A solar vacuum tube works similar in design to a coffee thermos. It consists of two layers of glass with a vacuum in between the layers. The outer layer of the solar tube is Borosilicate glass which is very low in iron and allows 98% of light energy to pass through. The 2nd inner layer has very special coatings applied to it.

Vacuum tube collectors (VTC) are a way to reduce the heat loss, inherent in flat plates. Since heat loss due to convection cannot cross a vacuum, it forms an efficient isolation mechanism to keep heat inside the collector pipes. Since two flat glass sheets are generally not strong enough to withstand a vacuum, the vacuum is created between two concentric tubes. Typically, the water piping in a VTC is therefore surrounded by two concentric tubes of glass separated by a vacuum that admits heat from the sun (to heat the pipe) but that limits heat loss [8]. The inner tube is coated with a thermal absorber. Vacuum life varies from collector to collector, from 5 years to 15 years. A key point noticed for the cylindrical shape of the evacuated tubes is that, the tubes absorb heat from all direction i.e. active(direct) radiation and passive (diffuse). Also, the cylindrical fin provides better efficiency than any other shape of absorber fin. A key point noticed for the cylindrical shape of the evacuated tubes is that, the tubes absorb heat from all direction i.e. active (direct) and passive (diffuse) solar radiation. Also, the cylindrical fin provides better efficiency than any other shape of absorber fin.

In this paper, performance analysis of a vacuum solar water heater is presented. Plate 1 displays a typical water heater placed on a roof top.

1.1 Working principle of a vacuum tube solar water heater

The working principle of a vacuum water heater is based on a natural circulation of water within the system. The Principle is called '*Thermo syphon'* the key important point of this system is that: the evacuated tube solar collector is always tilted at a small angle so that the water in the tube can flow by force of gravity.

As the sun rays pass through outer glass tubes they are largely transmitted directly to the inner glass tubes due to vacuum presence. The inner glass tube outer surface is coated with selective material (usually black paint) the sun's rays are then absorbed and then converted into heat. As inner tube surface is heated up transfer of heat to the water take place by means of convection inside the inner tubes. The temperature of the water in the tubes rises making it less dense. Lighter and hot water naturally moves up to the top of collector and through the evacuated collector tube where it is collected and stored [9]. Simultaneously the higher dense water through U tube runs towards the bottom. The displacement circuit continues due to density change.

Plate 1: A Vacuum tube solar water heater on a roof

Nomenclature

A_a	Aperture area
G	Solar radiation
T_o	Outlet water temperature
T_i	Inlet water temperature
Q_{in}	Heat gain from each tube
$\dot{m}$	Mass of working fluid
C_p	Specific heat of water
T_{in}	Inlet water temperature
A	Area of the collector
T_a	Ambient temperature
T_t	Temperature of water in tank

1.2 Theoretical formulation

Aperture of the area for each vacuum tube is obtained from Equation (1) given by [8]

$$A_a = 0.33 \times \pi \times d \times L \times N_t \quad (1)$$

That d, L and N_t are diameter of inner tube, length of each tube and number of the tubes respectively. Rate of the heat gain that reaches to each vacuum tube is given by Expression (2);

$$Q_{tn} = \dot{m}.\dot{C_p}(T_{out} - T_{in}) \quad (2)$$

But the total heat gain for all the tubes of the collector can be calculated from Equation (3)

$$Q_{coll}\dot{} = N_t.Q_{coll} \quad (3)$$

The thermal efficiency was determined using a quadratic efficiency Equation, which is a generalization from the Hottel Whillier Equation (4).

$$\eta = \frac{mCp(T_{out} - T_{in})}{AG} \quad (4)$$

Where m is the mass of water, C_p is the specific heat capacity of water, To is the outlet temperature, Ti is the inlet temperature, A is the area of the collector and G is the solar radiation.

2. Experimental Procedures

The materials used include the following: Anenometer, Pyranometer, Digital data logger, Digital Multimeter, Collector, Storage tank, water, Insulator (55mm polyurethane foam), pipe, frame, and a Valve. The system was fabricated at the Sokoto Energy Research Centre (latitude $13.07°N$, longtitude $5.23°E$ and altitude 351m above sea level) Sokoto State, Nigeria.

A solar water heater with 12 vacuum tubes was used to heat the water in the tank. A Pipe that allows the flow of water from the tank to the vacuum tubes and back to the tank was attached between them, the valve was also attached to the pipes to direct and regulate the flow of water. The experiment was conducted for seven (7) hours at 30minutes intervals within a period of five days. The water previously in the tank was interchanged with a new one before the commencement of the research.

A calibrated T-type thermocouple was setup; the wire from channel 1 went into the inlet, the wire from channel 2 went to the outlet, the wire from channel 3 went into the tank and then the wire from channel 4 was placed in the surrounding to measure the ambient temperature. The pyranometer was setup by placing it in a flat surface such that the round ball falls into the circle; it was then connected to the digital multimeter. The water was then allowed to flow into the vacuum tubes and then back to the tank before the readings were taken. A continuous flow of water occurs in this experiment.

The pyranometer was used to capture global solar irradiation. The wind speed was recorded with the help of an anemometer.

The parameters were recorded as follows, inlet temperature (T_i), outlet temperature (To), ambient temperature (T_a), tank temperature (T_t), and solar radiation (G).

Plate 2: Diagram of the Full Experimental Setup at SER

3.0 Results and Discussion

Figure 1 shows the wind speed and solar radiation against time of the day. The maximum solar radiation obtained was 829W/m^2. The wind speed was higher during the late hours (3:00pm upwards) than in the noon hours. The maximum value of wind speed obtained was 3.44m/s. The lowest wind speed obtained was at 1:00pm Local time and was 1.24m/s, so also the solar radiation. This signifies that;

1. The lower the wind speed, the higher the solar radiation.
2. During noon hours, the solar radiation tends to have higher values and lower values for the wind speed.

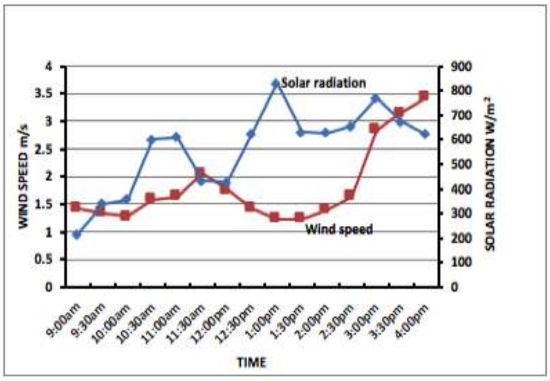

Fig 1: Graph of Solar Radiation and Wind Speed with respect to Time

Figure 2 depicts the relationship between the ambient temperature and the time of the day. It can be seen that the highest average ambient temperature obtained was 44.58^{0}C at the day time and decreases in the late hours. This may be attributed to the cloudy nature of the weather at the location. The maximum temperature of the water in the tank was 36.62^{0}C. This is analogous to the highest average ambient temperature obtained. This may be attributed to:

1. The fact that the temperature is highest during the noon hours (not constant)
2. The fact that the higher the ambient temperature; the hotter the working fluid (water).

The maximum temperature of the water at the outlet was 72.32^{0}C at 2:00pm Local time. This is also analogous to the highest ambient temperature and the maximum inlet temperature obtained. The outlet temperature is clearly greater than the inlet temperature at all instances.

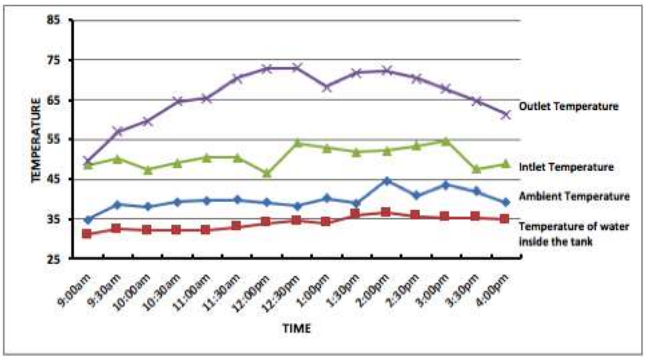

Fig 2: Graph of Average Values of Temperatures with respect to Time

4. Conclusion

The performance of any solar heating system is strongly dependent upon the operating characteristics of the various subsystems and, in particular, upon the characteristics of the heating method. In this work, the performance analysis of a vacuum tube solar water heater was carried out. The result shows that the performance depends on solar radiation and temperature. It also shows that the efficiency of the system is greater at mid-day. The system performs at 64% efficiency.

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