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Design, Construction and Experimental Study of the Thermal Performance of a Parabolic Cylindrical Trough Solar Air Heater

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Abstract

Solar energy currently represents the most abundant inexhaustible, non-polluting and free energy resources that could be used economically to supply man's increasing energy demands. This paper presents the experimental study of the performance of a parabolic cylindrical trough solar air heater. The solar air heater is a double-flat-plate collector type, constructed with galvanized square pipes and assembled into a parabolic cylindrical trough solar collector, capable of generating heat after being reflected and concentrated on the absorber.

A centrifugal fan was used to provide air circulation through the solar collector. The experimental test conducted to evaluate the thermal performance of the solar air heater showed that the maximum temperature attained was 97°C with an overall thermal efficiency of 65%.

***Keywords**: Solar energy, non-polluting, inexhaustible, free energy resources, absorber, centrifugal fan, air circulation, solar collector.*

Introduction

'Solar air heating' is defined as the process for supplying heat from a solar collector through which air is circulated. In most space heating applications, the heat may be supplied directly to a living space, industrial drying or heating chamber as needed and may also be supplied to some heat storage device for later transfer to living space or industrial heating units. The economic importance associated with domestic heating by solar energy as the source of heat, outweighs that of using non-renewable fossil fuel as an energy source. In addition to its non-polluting nature, solar energy is a free gift of nature not subjected to future depletion, unlike oil reserve and mineral deposit, which are subject to depletion in the near future, and their pollusive nature when used as a source of energy for heating.

In spite of these limitations the earth and its atmosphere receives continuously 1.7 x 10^{17} W solar radiation. A world population of 10.6 billion with a total power need of 10 kW per person would require about 10^{11} kW of energy. It is thus apparent that if irradiant on only one percent of the earth's surface could be converted into useful energy, then ten percent efficiency solar energy could provide all the energy needs of the people on earth. This figure is often quoted by solar energy enthusiasts, but unfortunately the nature of this energy source has technical problems and economical limitations that are not apparent from this microscopic view of the energy budget. The principal limitations are that:

(i). The solar energy received on earth is of small flux density (due to atmospheric scattering and abortion), making it necessary to use large surfaces to collect solar energy for large scale utilization, for which the larger the surface, the more expensive the delivered energy;

(ii) It falls in remote areas and would thus require some means of transportation to be useful to an industrialized nation;

(iii) It is intermittent in nature (thus its regular daily cycle 'rotation', and its regular annual cycle 'revolution') (Keith, *et al.* 1994).

In spite of these limitations, solar energy is essentially inexhaustible and potentially capable of meeting a significant portion of the nation's future energy needs with minimum of adverse environmental consequence. The indications are that solar energy is most promising of the unconventional energy sources. Despite all this encouraging assessment of the potentials of solar energy, considerable technical and economic problems must be solved, so that large-scale utilization of solar energy can occur. The future of solar power development will depend on how we deal with a number of serious constraints including scientific and technological problems, marketing and financial limitations, and political and legislative actions favoring conventional and nuclear power. In addition, the education of engineers will have to change its focus from non-renewable fossil fuel technology to renewable power sources (Smith, *et al.* 1981).

There appears to be a general agreement that the most significant of the renewable energy sources is the solar radiation, and it is the objective of this paper to present the thermal performance analysis of a solar energy utilization system, in particular the concentrating type solar air heater.

Although in Nigeria at present, solar energy is not use as primary source of energy. This is because research work is still going on to determine how best to harness it for human consumption. This research and development effort to develop economical systems of harnessing solar energy is necessary to rescue people from the problems created by high demands and low supplies of energy resources as a result of an increase in technology and population.

Considering the fact that other energy sources emits exhaust stream, which is usually polluting and in most cases poisonous, research into solar energy is thus justified, since it is a clean, non-polluting, reliable and free source of energy. Solar energy is used in many ways, particularly for hating and cooling purposes. The least that could be mentioned in favor of solar heating is that, it is a reliable option for providing hygienic and non-populating heating systems for a single house or small agro-allied industries in many places of the world including Nigeria.

In Nigeria, the use of solar energy is very attractive due to its geographical location. Nigeria lays within the tropics between latitude 4^o to 15^oN and longitude 3^o to 15^oE (Ezeilo 1998), thus situated within a region of high solar radiation. The radiant energy from the sun can neither be monopolized nor exhausted. For millions of years, it has been and will continue to be a supply with no fear of future depletion; it is a reliable source of energy that man can depend upon to cater to his increasing energy demands.

The major technologies used for solar energy conversion to heat are thermal processes comprising of solar collectors. The solar collector (solar absorber) is essentially the most important component of the equipment, which transforms radiant energy to heat energy from the hot air produced by this device. There are two basic types of solar collectors, the concentrating, and the flat-plate solar collectors.

The concentrating collector utilizes optical systems like reflectors, refractors, etc. to increase the intensity of solar radiation incidents on energy-absorbing surfaces. It has the main advantage of generating high temperatures, but is very expensive to fabricate compared to the flat-plate type. It operates only with direct beam radiation from the sun and only effective on clear sky days. The flat-plate collector has advantage of absorbing both beam and diffused radiation, and therefore, stills functions when beam radiation is cut off by the cloud. The area absorbing solar radiation is the same as the area intercepting solar radiation. However, flat-plate collectors are designed for applications requiring energy delivered at temperatures quite lower than 100^oC above the ambient temperature. The optimum direction of the collector is fixed with a slope equal to the latitude of the location for effective solar interception.

Design Analysis

The following assumptions were made in order to effectively design the solar air-heater:

i. the collector is thermally in steady state.
ii. the temperature drop across the thickness of the collector is negligible.
iii. heat flow is one-dimensional through the covers as well as through the base insulation.
iv. the header connecting the pipes covers only a small area of the collector and provides uniform flow to the tubes.
v. the sky is treated as a blackbody source for infrared radiation at an equivalent sky temperature.
vi. the irradiation on the collector plate is uniform.

Angle of Tilt

A suitable angle of tilt for fixed solar collector is within the range; latitude of the collector (L) +- 10o. For this design the angle of tilt is:

$$\beta = L + 10 \quad \text{..........................1}$$

Solar Insulation on the Collector Surface

Daily solar insulation on the collector surface and various latitudes in Nigeria was estimated by (Ezeilo 1998). An interpolation was made for Minna to get the average hourly as 802 W/m^2 K. For tilted surface

$$I_t = \frac{I_h Cos\theta}{Cos\phi_h} \quad \text{..........................2}$$

Collector Efficiency (η_c)

This is the ratio of the useful output energy (Q_u) to the input (Q_i) of a device.

The efficiency is therefore, given by:

$$\eta = \frac{\dot{m} c_p (T_o - T_i)}{I_t A_c \tau\rho\alpha} \quad \text{..........................3}$$

But theoretical efficiency is given as the Carnot efficiency:

$$\eta_T = 1 - \frac{T_1}{T_2} \quad \text{..........................4}$$

Determination of Collector (Absorber Plate) Area, A_c

From equation 3:

$$A_c = \frac{\dot{m} c_p (T_o - T_i)}{I_t \eta_c \tau\rho\alpha} \quad \text{..........................5}$$

Determination of Collector (Absorber Plate) Thickness (t)

The effective thickness of the absorber plate is determined from the relation.
Rate of heat absorption by air in the pipe = rate of heat given out by the square pipe absorber

$$\dot{m} c_p (T_o - T_i) = \frac{K_s A}{t}(T_o - T_a) \Rightarrow$$

$$t = \frac{K_s A (T_o - T_a)}{\dot{m} c_p (T_o - T_i)} \quad \text{..........................6}$$

$$for T_a \cong T_i, \Rightarrow T_o - T_a \cong T_o - T_i$$

$$\therefore t = \frac{K_s A_c}{\dot{m}\, cp} \quad \text{.......... .... 7}$$

Equation 7 gives the effective thickness of the collector.

Determination of Glass Cover Thickness (t_g)

Assuming 35% of the heat lost (Q_L) is through the cover, then heat lost through the glass cover is:

$$Q_{LG} = 0.35 Q_L \quad \text{..........................8}$$

After analyzing the total heat loss, the glass cover thickness is thus given as

$$t_g = \left[\frac{1}{0.35 U_L} - \left(\frac{1}{h_o} + \frac{1}{h_a}\right)\right] \bullet k_g \quad \text{..............9}$$

Determination of the Concentrator Minimum Insulation Thickness (t_s)

Considering the combined heat transfer mode across the concentrator, the minimum insulation thickness is given by:

$$t_s = \left[\frac{1}{0.65 U_L} - \left(\frac{1}{h_o} + \frac{t_m}{k_m} + \frac{1}{h_a}\right)\right] \bullet k_s \quad \text{.......10}$$

Friction Loss in Piping System

The shearing force at a fluid-solid interface causes frictional pressure losses in the flow through the pipe. For this design with 13-pipes of length L and 120-180° bends, the total friction pressure is given by:

$$\Delta P_t = \frac{\dot{m}(13U + 9\rho_a)}{a^2 \rho_a g_c} \quad \text{..........................11}$$

Methodology

The solar air heater was placed outside to absorb radiation from 1000 hrs to 1600 hrs. A centrifugal fan was used to blow air (at room temperature) into the heater through flow rate meter mounted at the inlet. The inlet and outlet temperatures for various flow rates were taking and recorded with the aid the inlet and outlet thermometers connected to the inlet and outlet pipes respectively. This experimental testing procedure was repeated for three days and the results are tabulated as shown in Table 1. Graphs of temperatures against local hours for various flow rates were plotted.

Results and Discussion

The results obtained from the experimental testing of the solar air heater are presented below.

Table 1. Experimental results for the three days

Criteira		Day 1			Day 2			Day 3		
Local time (hr)	Flow rate (kg/s)	T_{inlet} (°C)	T_{outlet} (°C)	Effici. (η)	T_{inlet} (°C)	T_{outlet} (°C)	Effici. (η)	T_{inlet} (°C)	T_{outlet} (°C)	Effici. (η)
00.00	10.75 x 10^{-5}	26.0	26.0	0.000	25.0	25.0	0.000	28.0	28.0	0.000
	21.5 x 10^{-5}	26.0	26.0	0.000	25.0	25.0	0.000	28.0	28.0	0.000
	32.25 x 10^{-5}	26.0	26.0	0.000	25.0	25.0	0.000	28.0	28.0	0.000
1000	10.75 x 10^{-5}	29.0	35.0	0.170	30.0	47.0	0.362	30.0	38.0	0.210
	21.50 x 10^{-5}	29.0	34.0	0.150	30.0	46.0	0.349	30.0	37.0	0.189
	32.25 x 10-5	29.0	31.0	0.065	30.0	45.0	0.333	30.0	36.0	0.166
1100	10.75 x 10^{-5}	31.0	78.0	0.602	32.0	74.0	0.568	35.0	62.0	0.435
	21.50 x 10^{-5}	31.0	76.0	0.592	32.0	73.0	0.562	35.0	60.0	0.416
	32.25 x 10-5	32.0	74.0	0.567	33.0	71.0	0.536	36.0	59.0	0.389
1200	10.75 x 10^{-5}	33.0	89.0	0.629	36.0	86.0	0.581	41.0	73.0	0.438
	21.50 x 10^{-5}	34.0	87.0	0.609	36.0	85.0	0.576	41.0	72.0	0.430
	32.25 x 10-5	34.0	85.0	0.600	37.0	83.0	0.554	42.0	70.0	0.400
1300	10.75 x 10^{-5}	33.0	92.0	0.641	38.0	97.0	0.608	43.0	83.0	0.481
	21.50 x 10^{-5}	34.0	90.0	0.622	39.0	96.0	0.594	43.0	81.0	0.469
	32.25 x 10-5	34.0	85.0	0.618	39.0	95.0	0.589	43.0	80.0	0.463
1400	10.75 x 10^{-5}	32.0	91.0	0.648	41.0	91.0	0.549	42.0	80.0	0.475
	21.50 x 10^{-5}	32.0	90.0	0.644	41.0	90.0	0.544	42.0	79.0	0.468
	32.25 x 10-5	32.0	86.0	0.628	41.0	89.0	0.539	42.0	77.0	0.455
1500	10.75 x 10^{-5}	30.0	86.0	0.651	40.0	73.0	0.452	40.0	70.0	0.429
	21.50 x 10^{-5}	30.0	85.0	0.647	39.0	72.0	0.458	40.0	68.0	0.412
	32.25 x 10-5	30.0	85.0	0.647	39.0	70.0	0.443	39.0	67.0	0.418
1600	10.75 x 10^{-5}	29.0	65.0	0.554	38.0	68.0	0.441	39.0	65.0	0.400
	21.50 x 10^{-5}	29.0	64.0	0.547	38.0	67.0	0.433	39.0	63.0	0.381
	32.25 x 10-5	29.0	63.0	0.540	37.0	66.0	0.439	38.0	62.0	0.387
1700	10.75 x 10^{-5}	28.0	53.0	0.472	35.0	57.0	0.386	35.0	50.0	0.300
	21.50 x 10^{-5}	28.0	51.0	0.451	35.0	56.0	0.375	35.0	48.0	0.271
	32.25 x 10-5	28.0	50.0	0.440	35.0	55.0	0.364	35.0	47.0	0.255

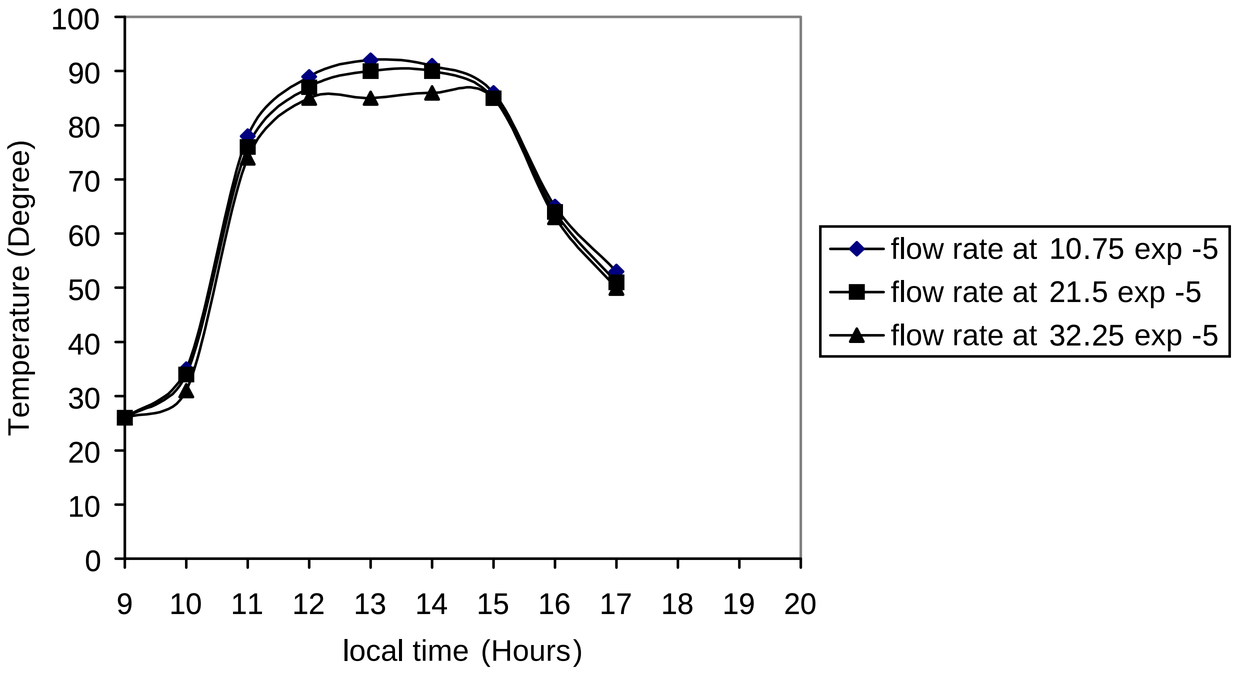

Fig 1. Graph of outlet temperature against local time

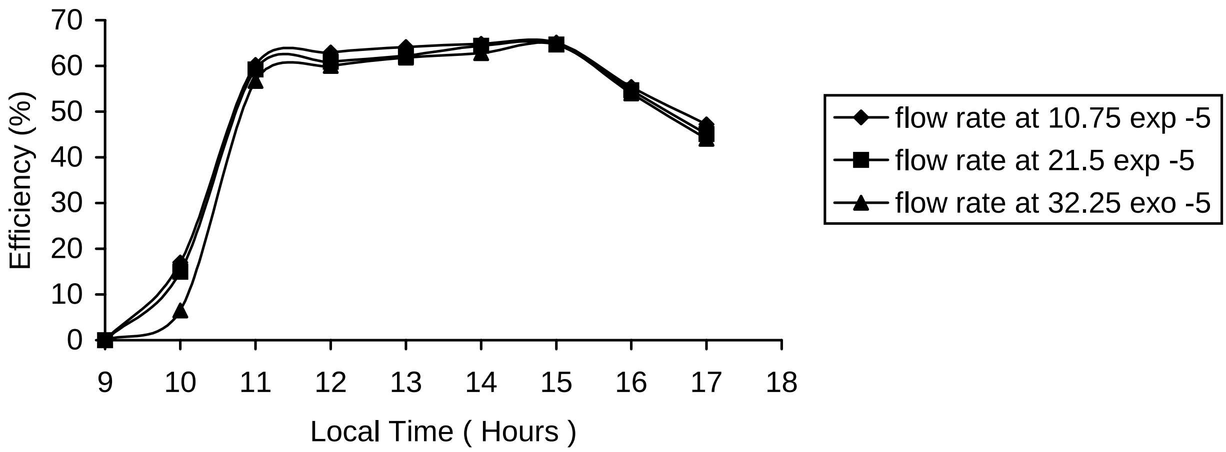

Fig. 2. Graph of efficiency against local time

From the graph of outlet temperature and efficiency against local time, the temperature and efficiency increases steadily and sharply with time for the results of days 1,2, and 3. The outlet temperature and efficiency increases slowly at 11:00 hours and attained peak values between the hours of 12:00 to 15:00, above which the temperature and efficiency decreases steadily with time as the sun goes down in the late afternoon. This shows that the heater performance was optimum in the afternoon between 12:00 to 15:00, when the solar radiation was hotter than the morning hours. The graph and the table shows the maximum temperature and efficiency attained by the heater for Days 1, 2 and 3 as: 92°C, 65%; 97°C, 61%; and 83°C, 48% respectively. These results obtained would have been higher if the experimental tests were to be conducted during clearer atmospheric conditions. The results of the experimental tests showed that the maximum outlet temperature T_{max} and efficiency η_{max} for Days 1 and 2 have close values, but the result for Day 3 shows considerable fall in the efficiency to 43% which was as a result of the thick harmattan haze and suspended dust particles that pollute the atmosphere, thereby absorbing some amount of radiation and scattering some (i.e. convert direct beam solar radiation to diffused radiation), hence reducing (to a great extent) the amount and intensity of the direct beam solar radiation reaching the collector surface.

The results also showed that the lower the airflow rate, the higher the outlet temperature and efficiency. Conversely, the higher the airflow rate, the lower the temperature and efficiency. From the graphs, both the maximum temperature and efficiency were attained with the air flow rate of 10.72×10^{-5} kg/s, but increasing the airflow rate used to 32.25×10^{-5} kg/s resulted in the decrease in the temperature and efficiency. The calculations of fluid flow through pipes shows that for the flow rate of air used during the Experimental testing, i.e. $m_1 = 10.72 \times 10^{-5}$ kg/s, $m_2 = 21.5 \times 10^{-5}$ kg/s, and $m_3 = 32.25 \times 10^{-5}$ kg/s gave Reynolds number $Re_1 = 288$, $Re_2 = 578$, and $Re_3 = 867$, respectively. Re flow through the pipe is Laminar in each case since the Re < 2100 (Douglas, *et al.* 1996) but for m = 0.0095 kg/s, Re = 25550 flow through the pipes becomes turbulent since Re > 6000. The Nusselt, Nu and Prandlt, Pr numbers for the flow through the system with m = 0.0095 kg/s was 63 and 0.76, respectively.

Although, the maximum temperature, T_{max} and efficiency, η_{max} so far attained by the heater was below that expected of the device as designed, it is still above that attained by (Olowe 1989) and (Obayomi 1992), that was 78 and 59°C, respectively. Moreover, the maximal temperature so far reached by the heater (i.e. 97°C) was on the average, good for industrial and domestic heating and drying purposes by solar energy which is free gift of nature, clean and free of atmospheric contamination.

Conclusion

The solar air heater is a fixed doubled flat-plate parabolic cylindrical trough collector type with tilt angle of 20° designed with locally available materials to produce hot air up to 120°C for domestic and industrial heating and drying processes. The experimental test conducted on the solar air heater produce an optimum performance of 65% efficiency and 97°C maximum temperature attained. This is sufficient for domestic and industrial drying purposes. It can be adopted mostly in the middle and northern part of the country, which are exposed to abundant solar radiation. Air heaters are more durable than the water heaters which are usually subjected to rusting and corrosion and hence less durable

It is implicitly hoped, that as engineers and scientists venture into serious research in various alternative energy sources (in which solar energy is the most potentially viable), the problem associated with the over dependence on fossil fuel as the only energy source will be a history left to be told to future generations.

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