THERMAL PERFORMANCE OF A CPC SOLAR WATER HEATER IN THE PRESENCE OF DUST PARTICLES FOR A SUSTAINABLE ENVIRONMENT

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ABSTRACT:

The current economic down turn coupled with the continuous increase in fuel price in the country makes renewable energy most especially solar energy an imperative alternative source of energy for domestic use. A compound parabolic concentrating (CPC) solar water heater operating on thermosyphonic process was designed and constructed for domestic utilization. The heater was tested during harmattan dust spell under very turbid atmospheric condition when the turbidity coefficient (â) is within the range 0.202 ? â ? 0.53 and its performance evaluated. The results indicated that the heater exhibited quite good performance with a maximum thermal efficiency of 44.85% while the lowest encountered in the early hours of the day is approximately 4%. Finally, smaller size dust particles have more effect on the heater's performance than larger ones.

1. INTRODUCTION

Solar equipment for harnessing energy are receiving great attention by many researchers in order to improve their efficiencies and adaptability. Solar energy provides for sustainable and environmentally friendly source of energy and unlike other conventional sources of energy that result in environmental pollution and their use leads to environmental degradation and illness to both animals and human. This has adverse effect on the economy. For example, recent World Bank estimates showed that the environmental and health costs of air pollution in China, primarily as a result of coal burning could total 13% of China's gross domestic product (GDP) by the year 2020 [1]. Another problem in the energy sector of the developing nations is that energy demand continues to rise rapidly while the conventional energy sources on which they over depend are continuously depleting. The shift from conventional energy to renewable energy is therefore vital if we truly intend to move the world from its present overdependence on fossil fuels. These traditional sources supply over 85% of all globally traded primary energy [2].

The direct use of solar energy for heating and cooling purposes via solar collectors is making significant contribution to the energy supply in the developed nations. For example, the calculated annual collector yield of all recorded systems in Europe is approximately 4900 GWh, which is equivalent to 0.14% of the overall requirements for hot water and space heating across the European Union (EU) countries [3]. The use of solar collectors for water heating is also noticeable in the developing nations such as India, South Africa, Nigeria and other sub-Saharan countries of Africa. Some few research works in this field include that of Garg and Prakash [4], Van Niekerk and Scheffler [5], Bhandari and Bamsal [6], Sumathy et al. [7], Danshehu et al. [8] and Danshehu and Atiku [9].

The tropical climates, south of the Sahara and especially in the Sahel region, are characterized by a short seasonal period locally known as harmattan during which, the available solar radiation is significantly low as a result of suspended dust particles in the lower part of the atmosphere. The harmattan dust particles are brought to this region by a north-easterly trade wind prevailing at an elevation of about 3000m, from November to March [10]. The harmattan brings cold, dry and stable air masses from the Sahara desert where it originates. These dust particles seriously affect the performance of any solar equipment and limit the usefulness of concentrating solar collectors. Investigation on concentrating solar collectors' thermal performance, taking due consideration of the effect of harmattan dust particles, is a prerequisite step in improving their adaptability in the tropical sub-region.

The harmattan dust particles suspended in the atmosphere and those deposited on the collector's aperture area represent optical inhomogeneity to the propagation of solar rays by scattering and partly absorbing the solar radiation throughout the electromagnetic spectrum. The scattering phenomenon by these particles causes a redistribution of solar radiation, including losses.

The results of the mineralogical analysis showed that quartz, kaolinite, halloysite, microcline, and mica are the constituent minerals of harmattan dust [10]. Similar analysis carried out in Sudan indicated that harmattan dust is an inhomogeneous mixture of SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, K_2O, SO_4^{2-}, and traces of MnO and Na_2O [11].

The study of solar collectors' thermal performance in the presence of dust particles is very significant for the tropical region of Africa, since this will lead to collector's improved design and adaptability for effective utilization of solar energy. It is for this motive, in this paper, that the performance of a compound parabolic concentrating solar water heater is assessed in the presence of harmattan dust particles.

2. DESIGN OF THE COLLECTOR

2.1 Geometry of the Concentrator

The compound parabolic concentrator is schematically represented in Fig. 1. In a rectangular system of coordinates (x, y), the equations describing the compound parabolic shape of the concentrating collector with tubular receiver of radius r, may be defined by the following relations [12]:

For $0 \leq \varphi \leq 90 + \theta_{max}$

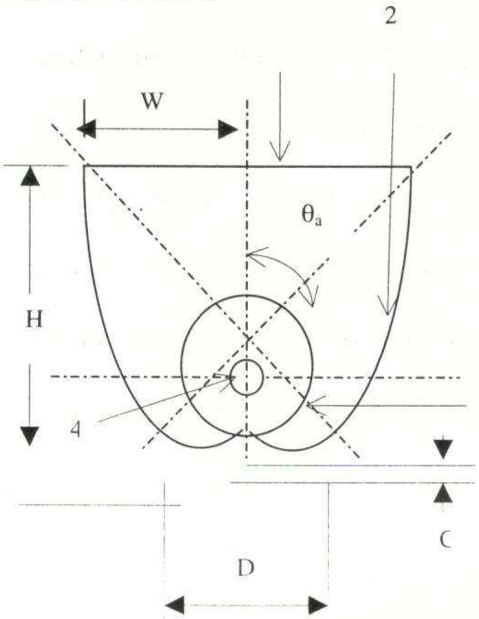
$$\left.\begin{aligned} x &= r(\sin\varphi - \varphi\cos\varphi) \\ y &= -r(\varphi\sin\varphi + \cos\varphi) \end{aligned}\right\} \quad (1)$$

For $90 + \theta_{max} \leq \varphi \leq 270 - \theta_{max}$

$$\left.\begin{aligned} x &= r(\sin\varphi - A\cos\varphi) \\ y &= -r(A\sin\varphi + \cos\varphi) \end{aligned}\right\} \quad (2)$$

Where: $A = \dfrac{\pi/2 + \theta_{max} + \varphi - \cos(\varphi - \theta_{max})}{1 + \sin(\varphi - \theta_{max})}$ (3)

φ is the involute angle of the involute portion of the concentrator and θ_{max} is half acceptance angle of the concentrator.



1. Glass cover 3. Enveloping glass tube

2. Reflecting surface 4. Absorber tube

Fig. 1: Schematic representation of the concentrator

2.2 The Widths of the Collector

The geometric concentration ratio, $C_{g,2-D}$ of the concentrator in a 2-D representation as shown in Fig. 1, is expressed as:

$$C_{g,2-D} = \frac{1}{\sin\theta_a} = \frac{2W}{D} \qquad (4)$$

Where θ_a is half acceptance angle of the concentrator. A half acceptance angle of 45° is specified here in order to take advantage of low cost of construction of the concentrator and for the collector to accept high proportion of the diffuse component of solar radiation.

2.3 The Height of the Collector

Geometrically, from Fig.1, the height of the collector, H, can be shown to be [13]:

$$H = \frac{(2W + D)}{2}\cot(\theta_a) \qquad (5)$$

2.4 The Required Surface Area of the Concentrator

The ratio of the concentrator's surface area, A_{con}, and the aperture area, A_a, is given by the relation [4]:

$$\frac{A_{con}}{A_a} = \sin\theta_a(1+\sin\theta_a)\left[\frac{\cos\theta_a}{\sin^2\theta_a} + \ln A - B\right] \qquad (6)$$

Where: $A = \dfrac{(1+\sin\theta_a)(1+\cos\theta_a)}{\sin\theta_a\left(\cos\theta_a + (2+2\sin\theta_a)^{1/2}\right)}$

$$B = \frac{\sqrt{2}\cos\theta_a}{(1+\sin\theta_a)^{3/2}}$$

2.5 The Thermal Efficiency of the Heater

The thermal efficiency of the water heater, η_{th}, may be determined based on the useful heat as follows:

$$\eta_{th} = \frac{q_u}{q_s} \qquad (7)$$

Where q_u is the useful energy or the amount of energy carried by the flowing water through the receiver tube, and q_s is the total energy supplied to the collector. These quantities may be respectively defined as follows:

$$q_u = \dot{m} C_P (T_o - T_i) \quad (8)$$

Where m is the mass flow rate of the circulating water; T_i, T_o are the inlet and outlet temperatures of the water respectively.

And $$q_s = A_a I_T \quad (9)$$

Where A_a is the aperture area of the collector and I_T is the total solar flux reaching the collector's surface.

3. DESCRIPTION OF THE CPC SOLAR WATER HEATER SYSTEM

The solar water heater system under investigation is represented in Figure 2. It consists of a compound parabolic trough concentrator 1.04m long made of wood material with aluminum foil forming its reflecting surface. A receiver tube, 26 mm diameter made of copper is placed along the line focus of the CPC. The absorber tube was coated with commercial black paint in order to enhance high absorption of solar energy, but low thermal emission from its surface. An evacuated enveloping tube made of soda lime glass, 40mm outside diameter and 4mm thick, was placed around the absorber tube in order to eliminate convective heat losses and enhance better radiant energy transfer to the absorber tube. A plain rectangular glass sheet, 4mm thick, was provided to cover the collector's aperture area in order to protect the reflecting surface from dust and at the same time to trap the solar energy and prevent it from escaping, hence providing a greenhouse effect. A 50 litres capacity storage tank was connected to the collector in order to store the hot water. The storage tank consists of a cylindrical container made of galvanized steel sheet (16 gauge) lagged with fine saw dust and a wooden box forming its outer wall. A water flow meter was fitted into the system for measuring the flow rate of the circulating water through the collector.

4. EXPERIMENTAL

The CPC – solar water heater was tested during harmattan dust spell, when the atmospheric condition was very turbid ($0.202 \leq \beta \leq 0.53$). The heater was placed in the sun and positioned in a north – south orientation with a slope of 10.3^o towards the south. This angle is Bauchi town latitude. Its position is adjustable about the axis of orientation (north – south) direction and it was frequently adjusted in order to track the sun for maximum solar energy reception. The temperature of all the components of the heater as well as the ambient temperature were monitored using 1.6mm mineral insulated grounded junction thermocouples. The thermocouples were connected to a Kane-May hand-held digital temperature output meter model KM340. The meter has an in-built electronic compensation network to correct for the thermocouples' reference temperature and has an accuracy of better than ± 0.2%.

The wind speed and the atmospheric pressure were measured using a Funk-Wetterstation equipment of type WS-2200-11.

The solar insolations were measured using two pyranometers, one type CM6B/TB which gives the instantaneous values of the global radiation and the other type CM11/121 fitted with shadow ring, measures the diffuse solar radiation.

The dust particles were analyzed through visual examination using a petrological microscope, fitted with graduated lenses in order to determine the size and number of particles.

5. RESULTS AND DISCUSSIONS

Table 1 presents the experimental results when the heater was tested on the 4th February 2004, at an average number density of 1.176×10^{11} m^{-3}, average particles size of 3.41μm and average wind speed of 1.72 m/s. From the values of solar radiations, it could be seen that the values of the diffuse component of solar radiation was much higher than the beam radiation values at any instant of the day. This is a clear indication of much particles presence, whose effect was to scatter and partially absorb the incident beam radiation before it reached the absorber's surface. The maximum temperatures reached by the absorber tube, water, enveloping glass tube and glass cover were 355K, 342K, 345K and 311K respectively despite the highly turbid atmospheric condition (average value of $\beta = 0.387$) that had prevailed.

Figure 3 shows the temperatures' variation with testing time for all the components of the heater. It could be seen from the graphs that the absorber tube temperature, T_{r1}, is by far greater than either T_o, T_e,

$T_{air\text{-}gap}$ or T_{a1} at any hour of the day.

Figure 4 shows the temperature variations with beam radiation. Although the temperature values are expected to be continuously increasing with increase in beam radiation, the slight fall in temperatures at some points is attributable to variations in the sizes of the dust particles present. This could be the same reason for the decrease in temperatures from some maximum values as shown in the plots of temperatures versus beam to diffuse ratio (Fig. 5).

The effect of number density of particles on the performances of the heater is shown in Fig. 6. The pattern of the graph gives a clear indication of continuous decrease in temperature values with increase in number density except for the portion where larger particles sizes were encountered. These large sizes are attributable to large concentration of the small particles at isolated positions. These areas are indicated by the high deeps in the figure.

Figure 7 shows the effect of particles sizes on the temperatures of all the components of the heater. The drastic change in temperatures encountered at about the same particles' size is an indication of a decrease in the incident solar flux value. And the graphs clearly indicated that smaller size particles have greater attenuation ability than the larger ones.

The performance of the heater decreases drastically with increase in the turbidity coefficient as shown in Fig. 8. A large value of the turbidity coefficient is an indication of much dust particles present and consequently, greater attenuation effect of the solar beam radiation intensity.

The values of the instantaneous thermal efficiency of the heater are shown in Table 2. The thermal efficiency of the heater did not exceed 44.85% while the lowest value found throughout the test period was in the vicinity of 3.9%. These extreme values of the heater's thermal efficiency occurred at the early and late hours of the testing period.

6. CONCLUSIONS

From the foregoing, the following conclusions can be drawn:

(1) The effect of harmattan dust particles on the thermal performance of the CPC solar water heater is more pronounced when the particles are of smaller sizes than larger ones.

(2) The highest thermal efficiency of the heater is 44.85% late in the day.

(3) The results on the average demonstrate that CPC type of concentrating collector can be used throughout the year in the tropical region of Africa. Thus the objective of exclusively using solar energy especially for domestic purposes could be highly enhanced with this equipment.

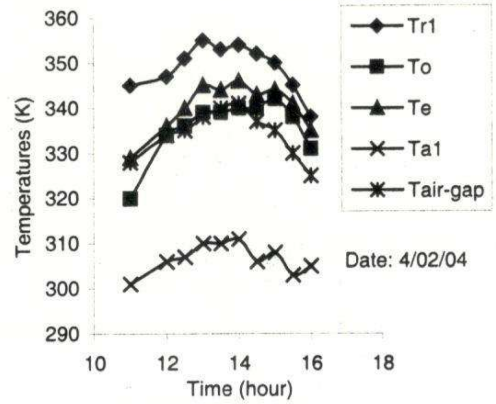


Fig. 3: Temperatures variations with time

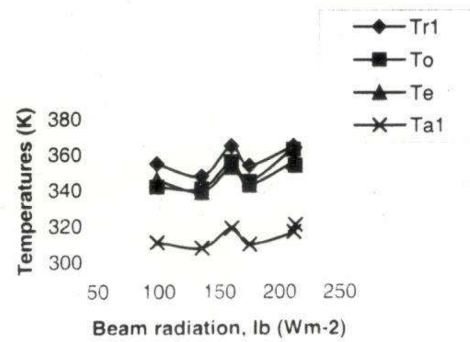


Fig. 4: Temperatures variations with beam radiation

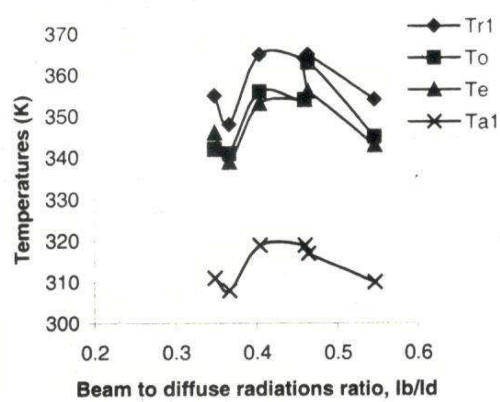


Fig. 5: Temperatures variations with beam to diffuse radiations ratio

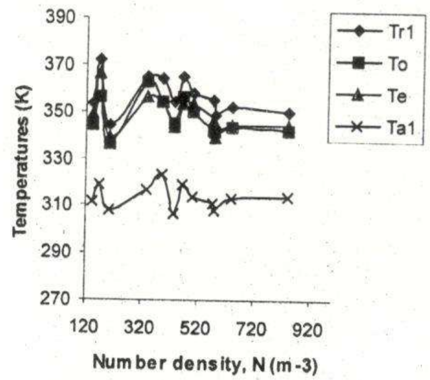


Fig. 6: Temperatures variations with number density of particles

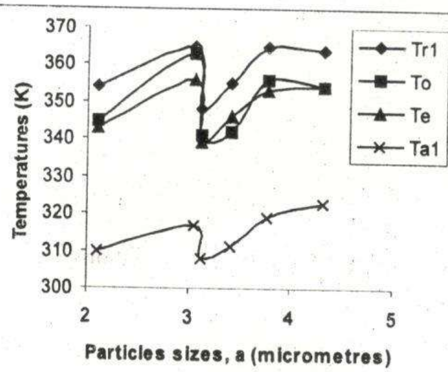


Fig. 7: Temperatures variations with particles sizes (heater)

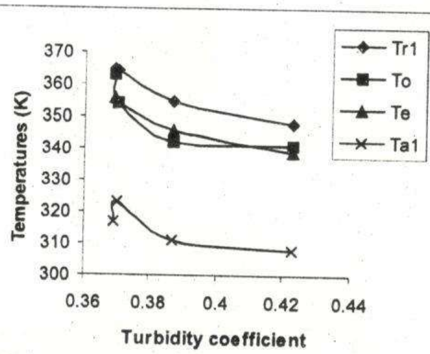


Fig. 8: Temperatures variations with turbidity coefficient

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Table 1: Performance of the CPC solar water heater

Time Rad. (Hour)	Beam Rad. Ib (Wm^{-2})	Diffuse Rad. Id (Wm^{-2})	Global Temp. I_g (Wm^{-2})	Absorber Temp. T_{r1} (K)	Outlet Temp. T_o(K)	Inlet Temp. T_i(K)	Envelope Temp. T_e (K)	Glass Cov Temp. T_{a1}	Air-gap Temp. $T_{air-gap}$ (K)	Ambient T_{sur} (K)	Tilt Angle (deg.)
11:00	82.08	191.52	273.6	345	320	311	329	301	328	301	-15
12:00	253.08	307.8	560.88	347	334	317	336	306	334	303	-10
12:30	-	-	-	351	336	320	340	307	335	300	-5
1:00	82.08	471.96	554.04	355	339	322	345	310	338	307	5
1:30	-	-	-	353	339	323	344	310	340	304	15
2:00	54.72	300.96	355.68	354	340	324	346	311	341	302	15
2:30	-	-	-	352	340	324	343	306	337	301	20
3:00	41.04	191.52	232.56	350	342	323	344	308	335	300	25
3:30	-	-	-	345	338	321	341	303	330	300	25
4:00	82.08	246.92	329	338	331	317	335	305	325	299	25

Average number density, N = 1.176 x $10^{11}m^{-3}$
Average Particles size, a = 3.41 um
Average wind speed, V = 1.72 m/s
Average turbidity coefficient, â = 0.387
Average atmospheric pressure, P_{atm} = 948 mbar
Setting time: 10:22 am
Date: 04/02/04

Table 2: Instantaneous thermal efficiency of the heater

Time (Hour)	q_s W	q_u W	η (%)
9:00	195.36	7.5808	3.8805
10:00	243.99	18.952	7.7677
11:00	337.03	22.743	6.748
12:00	362.32	53.066	14.646
1:00	355.02	30.323	8.5414
2:00	336.18	41.695	12.402
3:00	259.73	37.904	14.594
4:00	193.95	70.123	36.155
4:30	126.77	56.856	44.850

Average number density, N = 1.21 x $10^{11}m^{-3}$
Average Particles size, a = 2.68 um
Average wind speed, V = 2.69 m/s
Average atmospheric pressure, P_{atm} = 937.33 mbar
Setting time: 08:30 am
Date: 29/03/04

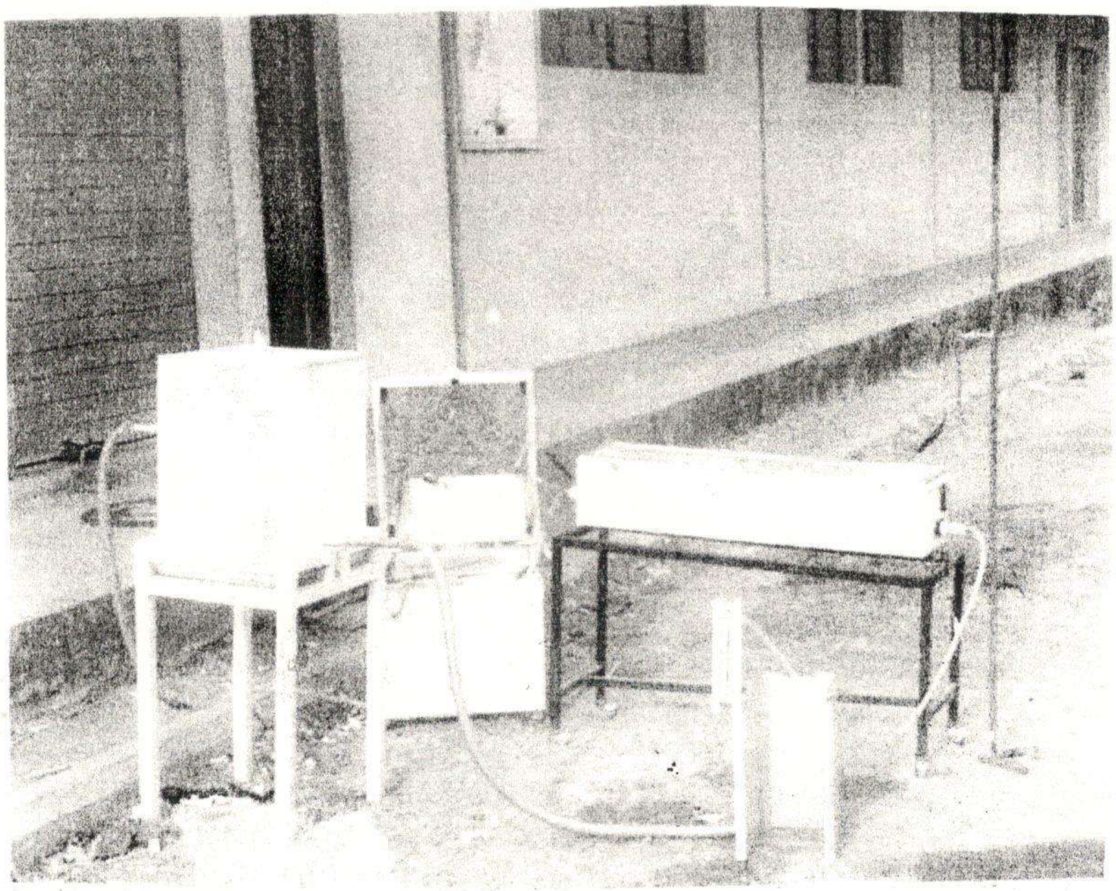

Fig. 2: Experimental set-up