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DEVELOPMENT AND PRELIMINARY PERFORMANCE EVALUATION OF A SOLAR COLLECTOR FOR ADSORPTION REFRIGERATOR

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Abstract : The design and construction of a flat plate solar collector is presented in this paper. The solar collector was designed to power adsorption refrigerator using activated carbon/methanol pair. Design was such as to provide simplicity and yet ruggedness for harsh operating environment in the tropical climate of Nigeria. For methanol desorption, the collector must reach a maximum temperature of at least 100°C. Performance results showed that the maximum temperature of 108°C attained in the solar collector was adequate for methanol generation, while maximum received insolation of 1000 kW/m² was sufficient for methanol desorption.

1. Introduction

A major part of solar cooling system is the collector that converts solar radiation into heat at a temperature suitable for powering the cooling device. The collectors vary in type from the common, low temperature flat-plate to the more sophisticated high, temperature evaluated tubes or concentrators. The technical feasibility of solar energy for domestic water heating and space heating has been well established. While economic feasibility is the major barrier restricting its widespread usage, solar heating may be economically competitive with conventional heating fuels, depending on the individual circumstances of the user [1].

Characteristics curves of a photovoltaic module have been studied and compared with the standard characteristics curves. Energy conservation efficiency of the same module was studied using Ampere-Hour Meter. The efficiency obtained is 10.2% which is normal for the type of silicon solar cells used in the module [2].

The 'heart' of a solar refrigerator is the collector and so the choice of a particular collector for use in solar adsorption refrigeration is a key parameter that needs careful and thoughtful selection. This is largely with regard to the design configuration and economic considerations of the materials so that high efficiencies and overall cost-effectiveness of the system will be attained [3]. Non-tracking solar collectors are usually oriented towards the equator in order to maximise their exposure to direct and diffuse solar radiation. This implies that the surface azimuth angle for the collectors is zero. In addition to the orientation, non-tracking solar collectors are tilted at recommended angles to the horizontal in order to maximise the average total direct and diffuse radiation over a specified period, such as daily, monthly or annually [4-6].

Keywords : Solar, collectors, refrigeration, adsorption, performance

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Thermal performance of solar air heaters : mathematical model and solution procedure was presented by Ong [1]. In the mathematical model, the surface temperatures of the walls surrounding the air streams were assumed uniform whereas the air temperatures were assumed to vary linearly along the collector. In the mathematical model, the solar collector was assumed sufficiently short for which the assumptions were valid. Using the developed procedure, predictions of mean wall and air streams temperatures for a collector of any length could be obtained. Others authors [8-15] have made significant contributions towards the development of solar collectors for engineering applications.

This paper presents the design, construction and performance of a solar collector tested in the city of Ibadan, Nigeria.

2. Materials and Methods

2.1 Flat plate solar collector

The combined collector/absorber/generator is the heart of the solar refrigerator. A solar collector is a device that converts solar radiant energy to useful heat energy. Thus, this is the basic source of heat for the generation of methanol from the adsorbent bed.

The performance of the solar refrigerator depends largely on the effectiveness of the solar collector, hence the need for proper design. Generally, a good adsorbent bed must have good heat and mass transfer capabilities. The adsorbent bed will be made of flat plate stainless steel box; having surface area 1m^2. Selective coating was used on the top surface of the steel plate box.

Finally, the steel plate box was placed behind a sheet of window glass in a thermally insulated case. In order to guarantee good heat transfer between the front side and the adsorbent, fins made of stainless steel were placed inside the adsorbent bed box in contact with the front side and the activated carbon. The thickness of the adsorbent layer is 0.04m while the distance between the fins is approximately 0.1m[15].

The photograph designed solar collector is shown in fig. 1.0. Temperatures measurements were mounted at four different locations to monitor its performance. The equipment used for data acquisition are : Multimeter with thermocouple and Solar radiometer. The whole collector was mounted on a stand with the aim of achieving an angle of tilt of 7.5°. The main components of the designed collector are :

(i) A transparent cover (single sheet of glass, 3mm thick).

(ii) Absorber plate, metallic net and false bottom.

(iii) Insulation, which should be provided at the back and sides to minimize the heat losses.

2.2 Collector Materials and Corrosion

All components and materials used in this solar energy collector were designed to operate satisfactorily under the worst conditions that could be expected in any particular installation. Materials used were capable of withstanding both the high temperatures that would be encountered during periods of maximum radiation with no flow through the collector and the low temperature which could occur in the night. Problems which could arise from cyclic variations in temperature or large temperature differences within the collector were taken into consideration in materials selection and design.

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2.3 Solar Irradiation

Since the energy for this solar collector is to be derived from sun, there is need to study the nature of radiation in some detail. Solar radiation incident on a body is partially absorbed, partially reflected and partially transmitted if the body is transparent. The mathematical relationship between the absorbed, reflected and transmitted energy is given as :

$a_s + r_s + t_s = 1$ .... (1)

where :

a_s = absorptivity or part of the total energy absorbed
r_s = reflectivity or part of the total energy reflected
t_s = transmisivity or part of the total energy transmitted

The amount of energy received by a unit area of a surface placed perpendicular to the sun rays in near earth space at the earth's mean distance from the sun is called solar constant (I_{sc}). Its value has been estimated to be 1.353kW/m^2 and represents the total energy in the solar spectrum [6].

However, solar radiation incident on the earth's surface depends on the following parameters : Latitude, L; declination, d, hour angle of the sun, h; solar altitude, a; solar azimuth z; angle of tilt, c and diffuse radiation.

Solar irradiation on a horizontal surface is proportional to the sine of the angle of solar altitude, a given as :

Sin a = Sin L Sind + CosLCosdCosh .... (2)

d is derived from

d = 23.45 Sin [360/365(284+N)] = 23.45Sin .... (3)

where :

N is the day of the year.

N = 45

d = 23.45 Sin 360/365(284 + 45)

d = 14.59°

Ibadan is on Latitude of 7.45°N and a longitude of 8°E. The hour angle is calculated from Hour angle, h = (LST – 12.00hr) 15°

Where LST = Local solar Time and is derived from local clock time from this expression :

LST= (Local clock time) – (number to time zone) + (correction for longitude in mins) + (time correction)

For local time of 15.00hr

LST = 15.00hr – 1hr + 32mins – 6.2mins = 14.00hr + 25.8mins

Therefore, h = (2hrs + 25.8mins) 15° = 36.45°

When this is substituted in equation (3.2) yields :

Sin a = (Sin 7.45 + Sin 14.59) + (Cos 7.45 Cos 14.59 × Cos 36.45)

= 0.05151 + 0.73193 = 0.7834

a = 51.57°

The solar azimuth is derived from :

$$\text{Sin}z = \frac{\text{Sin}h\ \text{Cos}\partial}{\text{Cos}\alpha} \quad .... (4)$$

$$= \frac{\text{Sin } 36.45 \text{ Cos } 14.9}{\text{Cos } 51.57} = 0.91387$$

z = 66.04°

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2.4 Radiation reaching the Collector Surface

Radiation impinges on a tilted surface consists of the following : beam, diffuse and reflected radiation. For a tilted surface, the total radiation was determined from the equation :

$$H_T = H_bR_b + H_d\left(\frac{1+\text{Cos}\beta}{2}\right) \qquad \text{.........} \ (5)$$

The reflected component has been neglected and b is the collector inclination. The ratio of radiation on the tilted surface H_T, to that on the horizontal surface, H, is given in terms of the angles q_Z and q_T and radiation normal to the beam as :

$$R_b = \frac{H_T}{H} = \frac{H_n\text{Cos}\theta_T}{H_n\text{Cos}\theta_Z} = \frac{\text{Cos}\theta_T}{\text{Cos}\theta_Z} \qquad \text{.........} \ (6)$$

$$R_b = \frac{\text{Cos}(L-\beta)\text{Cos}\partial\text{Cosh} + \text{Sin}(l-\beta)\text{Cos}\partial}{\text{CosLCos}\partial\text{Cosh} + \text{SinhSin}\partial} \qquad \text{.........} \ (7)$$

$$= \frac{\text{Cos}\partial x\text{Cosh}}{\text{CosLCos}\partial\text{Cosh} + \text{SinhSin}\partial} \qquad \text{.........} \ (8)$$

Since L = b = 7.5°

$$R_b = \frac{\text{Cos}14.59\text{Cos}36.45}{\text{Cos}7.45\text{Cos}14.59\text{Cos}36.45 + \text{Sin}36.45\text{Sin}14.59}$$

$$= 0.8447$$

The average ratio of direct and diffuse radiations to total radiation was given by Fagbenle [6] as 0.222 and 0.732 respectively and this will be used here to obtain the beam and diffuse components of total radiation. The average daily solar radiation at Ibadan for the design period of October to March was 17.44 MJ/m^2. The daily value was estimated to be 605.5 W/m^2.

$H = 605.5$ W/m^2

$H_bR_b = (605.5 \times 0.222) \times 0.732 = 98.396$ W/m^2

$$H_d\frac{(1+\text{Cos}\beta)}{2} = (0.775x605.5\left(\frac{1+\text{Cos}7.5}{2}\right), \text{ where}$$

$R_d = (1 + \text{Cos b})/2 = 0.995$

$$H_d\frac{(1+\text{Cos}\beta)}{2} = .775x605.5x.995 = 466.92\text{W}/\text{m}^2$$

Therefore, the average radiation intensity falling on the tilted surface of the collector for the design period of October to March is :

$H_T = 98.396$ W/m^2 + 466.92 W/m^2 = 565.316 W/m^2

2.5 Energy absorbed by the Collector Absorber Plate

The collector for this machine is made of a window glass cover, blackened steel flat plate absorber, adsorbent bed, with insulation at the back, connecting pipes and the housing box. The glass cover receives heat from the sun as said earlier on but due to the optical properties of the glass, not all the heat is received by the absorber plate.

To determine the energy absorbed by the absorber plate there is the need to determine the transmittance-absorptance product, ta

The glass sheet is assumed to have the following properties [15].

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Iron oxide content = 0.11
Refractive index = 1.52
Transmittance = 0.83
Reflectance = 0.08
Absorptance = 0.09

The absorptivity of the plate is taken to be 0.91. The absorptance-transmittance product is calculated from the equation :

$$(\tau\alpha)_{diff} = \frac{\tau\alpha}{1-(1-\alpha)_4\rho_d} \qquad \text{......... (9)}$$

For a single glazing collector the value of r_d which is the diffuse component is 0.16 for angle of incidence of 60°, [15]

$$(\tau\alpha)_{dir} = \frac{0.83x0.91}{1-(1-0.91)0.16} = 0.766$$

$(ta)_{diff} = (ta)_{dir}$. Evaluated at i = 60°

From [15] :

$a = 0.8615$, $t = 0.83$, $d = 0.16$

$$(\tau\alpha)_{diff} = \frac{0.83x0.8615}{1-(1-0.8615)0.16} = 0.7312$$

The total energy falling on the absorber plate is therefore given by :

$S = 0.766 \times 98.396 + 0.7312 \times 466.92 = 416.783\ W/m^2$

2.6 Determination of Collector Area

The area of the collector is normally determined using the area of the exposed glass cover to the sunlight. The design of the collector is expected to be a model that will give the required output and at the same time be cost effective.

For a single-glass collector, the optimum collector efficiency is assumed to be 20%.

$h_c = 20\%$

$H_T = 565.316\ W/m^2$

For 6 hours of insolation

$H_a = 0.20\ H_T A_c t$

$H_a = 4000kJ$

$A_c = H_a/\ 0.20 \times H_T t = 4000/0.20 \times 0.565316 \times 6 \times 3600 = 1.64m^2$

Collector length = 1m – 1.64m

Collector width = 0.75m – 1m

2.7 Estimation of Heat Losses

The thermal losses of a flat plate collector depend on the operating temperature of the collector. The maximum operating temperature for the generation of methanol is between 90°C – 100°C.The energy falling on the generator/adsorber is distributed to losses through the top, bottom and edges and to useful energy gain.

The top loss coefficient from the collector plate inclined at 45° is evaluated from the equation [15].

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$$(U_t)_{45°} = \left[\frac{N_g}{\frac{(344)}{T_p}\left(\frac{T_p - T_g}{N_g + F}\right)^{0.31}} + \frac{1}{h_{wi}}\right]^{-1} + \frac{\sigma(T_p + T_a)(T_p^2 + T_a^2)}{\left[E_p + 0.0425N_g(1 - E_p)\right]^{-1} + \left(\frac{2N_g + F - 1}{E_g}\right)^{-N}} \quad \text{........ (10)}$$

where :

N_g = number of glass cover.

$F = (1.0 + 0.04h_w + 5.0 \times 10^{-4}h_w^{\ 2})\ (1 + 0.058N_g)$

E_g= emittance of glass (0.88)

E_p = emittance of plate (0.970)

T_a = ambient temperature (°K)

T_p = plate temperature (°K)

h_{wi} = wind heat transfer coefficient (W/m²°C)

h_{wi} is evaluated from the equation : [15]

$h_{wi} = 5.7 + 3.8V$, where

V = the speed of wind in m/s = 1.1973m/s (as recorded by IITA)

$h_{wi} = 5.7 + 3.8(1.1973) = 10.25$ W/m²°C

$F = 1.0 - 0.04(10.25) + 5.0 \times 10^{-4}(10.25)^2[1+0.058(1)] = 0.6798$

Assuming

$T_p = 351°K$, $T_a = 300°K$, $s = 5.67 \times 10^{-8} W/m^2K^4$

$$(U_t)_{45°} = \left[\frac{1}{\frac{344}{351}\left(\frac{351 - 300}{1 + 0.675}\right)^{0.31}} + \frac{1}{10.25}\right]^{-1} + \frac{5.67x10^{-8}(351 + 300)(351^2 + 300^2)}{0.97 + 0.0425(1 - 0.97) + \left(\frac{2 + 0.678 - 1}{0.88}\right)^{-1}}$$

$$= (0.3541 + 0.0975)^{-1} + \frac{7.869}{1.877} = 6.404 \text{ W/m}^{2}{}^{\circ}\text{C}$$

For a collector tilt of 7.5° :

$$\frac{(U_t)_{7.5°}}{(U_t)_{45°}} = 1 - (7.5 - 45)(0.00259 - 0.00144x0.97) = 1.0447$$

$(U_t)_{7.5} = 1{\cdot}0447 \times 6.404$ W/m²°C = 6.6902 W/m²°C

The back loss coefficient is given as :

$$U_b = \frac{K}{L} \text{.(11)}$$

where :

K = thermal conductivity of insulation, L = thickness of insulator

Styrofoam of thickness 100mm will be used as the insulator and it has thermal conductivity of 0.043W/m°C.

Therefore,

$U_b = 0.043/0.1 = 0.43$ W/m°C

It is assumed that the edge loss coefficient is of the same magnitude as the back loss. The overall loss coefficient, U_L, is determined by adding together all the loss coefficients :

$U_L = 6.092 + 0.43 + 0.43 = 6.695$ W/m²°C

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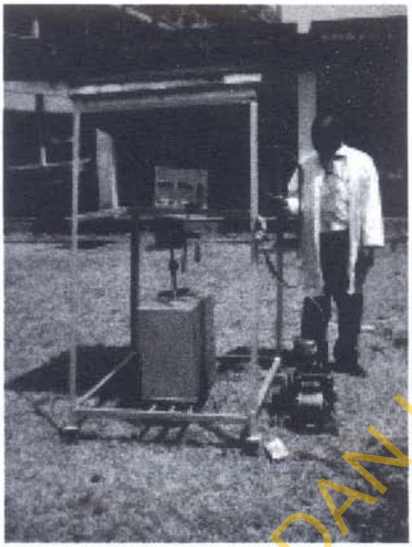

Fig-1.0 : Photograph of the designed solar collector on site.

3. Results and Discussion

The performance results of the solar collector are presented in tables 1-3. The maximum temperature attained was 108°C. The regeneration temperature (T_{g2}), which is T_1 in tables 1,2

Table-1.0 : Insolation and Temperature distribution obtained (19/10/2005).

Am/Pm	INSOLATION Btu/ ft²h	INSOLATION W/m²	T_2 °C	T_1 °C	T_3 °C	T_4 °C
9.30	35	110.425	37	26	25	24
10.00	65	205.075	47	69	29	25
10.30	70	220.85	57	100	37	28
11.00	95	299.725	59	101	36	28
12.00	280	883.40	99	108	58	34
12.30	100	315.5	80	104	49	33
1.00	110	347.05	68	104	42	31
1.30	265	836.075	70	104	42	33
2.00	220	694.10	89	105	55	35
2.15	205	646.775	91	108	59	36
2.25	200	631	92	108	55	34
2.35	180	567.90	91	106	68	36
2.45	145	457.475	85	99	62	31
2.55	50	157.75	79	91	52	33
3.05	110	347.05	80	92	40	33
3.25	100	315.50	78	89	39	34
3.35	70	220.85	74	85	39	32
4.05	55	173.525	62	70	33	30

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Table-2.0 : Insolation and Temperature distribution obtained (20/10/2005).

Am/Pm	INSOLATION Btu/ft²h	INSOLATION W/m²	T_1 °C	T_1 °C	T_3 °C	T_4 °C
9.00	15	47.325	31	31	31	23
9.30	50	157.75	42	42	50	24
10.00	60	189.30	51	50	36	25
10.30	30	94.65	46	45	35	25
11.00	65	205.075	52	51	30	25
11.30	70	220.85	64	61	31	26
12.00	60	189.30	59	57	32	26
12.30	90	283.95	64	62	32	27
1.00	180	567.90	93	89	29	28
1.30	60	189.30	63	61	28	27
2.00	60	189.30	64	61	40	27
2.30	95	299.725	71	69	29	28
3.00	55	173.525	59	57	27	28
315	60	189.30	59	58	27	28

Table-3.0 : Insolation and Temperature distribution obtained (21/10/2005)

Am/Pm	INSOLATION Btu/ft²h	INSOLATION W/m²	T_1 °C	T_2 °C	T_3 °C	T_4 °C
8.30	90	283.95	42	05	85	24
9.00	40	126.2	55	62	64	24
9.30	60	189.3	61	65	41	25
10.00	50	157.75	77	67	32	26
10.30	320	1009.6	85	60	72	27
11.00	170	536.35	82	61	73	27
11.30	80	252.4	94	62	70	28
12.00	50	157.75	82	64	62	27
12.30	70	220.85	87	63	56	28
1.00	210	662.55	97	54	64	29
1.30	65	205.075	87	61	43	31
2.00	45	141.975	67	55	56	30
2.30	200	631	72	49	87	29
3.00	165	520.575	72	46	83	29
3.30	125	394.375	81	49	83	29

Keys :

T_1 = absorber plate temperature (middle)
T_2 = absorber plate temperature (front)
T_3 = collector plate temperature
T_4 = ambient temperature

and 3 is : 70°C < T_{g2} < 140°C. For ice making (moderate ambient temperature, 25°C) the regeneration temperature is 65°C while for hot ambient temperature (45°C) the regeneration temperature is 112°C. The activated carbon can adsorb a large amount of methanol vapour in ambient temperature and desorbs it at a higher temperature (about 80°C)[15].

It can be rightly concluded that the designed flat plate collector that was tested in Ibadan was found suitable to power the designed solar adsorption refrigerator.

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4. Conclusion

A solar collector to power adsorption refrigerator using activated carbon/methanol pair has been designed, fabricated and tested in Ibadan city using locally available materials. During the clear day the maximum temperature attained was 108°C. This was sufficient for the desorption of methanol (adsorbate) from the activated carbon (adsorbent). Work is in progress on the whole arrangement to improve its effectiveness in the area of heat transfer.

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