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Performance of a zeolite – water adsorption refrigerator

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ABSTRACT

The design and production of a solar powered Zeolite-water adsorption refrigerator using concentrating parabolic collector (CPC) was done. An array of two CPCs with a total collector area of 1.029m^2, concentration ratio of 1.8, height – aperture ratio of 1.19 with diameter 42mm cylindrical adsorber was designed, constructed and performance tested using commercial pelletised Zeolite 4A as adsorbent and water as refrigerant. The experimental results are presented in terms of values of system temperature and cooling performance coefficient. Measured hourly instantaneous COP ranges from 0.2 to 2.5 while the hourly insolation ranges from 34W/m^2 to 345W/m^2. Evaporator temperature of 11^{o}C and maximum adsorber temperature of 110^{o}C was recorded. The minimum daily – hourly mean COP of 0.838 with the corresponding maximum COP value of 1.48 was achieved. Meteorological condition was also recorded with an average total daily-hourly insolation of 170W/m^2.

Keywords: Refrigeration, Adsorption, Performance, Zeolite, Water.

INTRODUCTION

Towards meeting the cooling demand, the conventional mechanical vapour compression systems areoften used [5]. This conventional system is popular and advantageous due to its high coefficient of performance, small size and low weight. However the system is not without disadvantage such as contributing to global warming, ozone layer depletion coupled with high energy consumption. Reduction of primary energy consumption is strongly required to reduce global warming caused by fossil fuel consumption used in producing the electricity. But its main disadvantage is in the refrigerant used, such as chlorofluorocarbon (CFC), Hydrochlorofluorocarbon (CHFC) which has high global warming and Ozone depletion potential. The criticality in the main disadvantage of conventional cooling system lead to the regulatory decision reached at the [11 & 14] convention towards reducing the ozone layer depletion and green house gas emission by the participating countries respectively. The discovery that solar radiation and cooling load reach maximum level in the same season gave impetus to research for solar energy powered refrigeration and air conditioning. That is, demand for cooling (cooling load) is at peak when the solar intensity is optimum.

Thermally activated sorption technology is one of the possible alternatives to electricity driven vapour compression refrigerator. Adsorption cycles has distinct advantage over other heat driven refrigerating cycles in their ability to be driven by heat at relatively low, near environmental temperatures, [12]. A way of decreasing dependence on electricity for cooling is to use environmentally benign, thermally –powered cooling system such as physical adsorption systems. Basically in an adsorption cooling cycle the mechanical compressor of conventional vapour compression system powered by electricity is replaced with a thermal compressor driven by low grade thermal energy like solar energy [18].

The main attraction to the solar adsorption refrigeration is that its working fluids satisfy the Montreal protocol on ozone layer depletion and the Kyoto protocol on global warming. Choosing the most appropriate adsorbent –

adsorbate pair is one of the important factors determining the efficiency of the adsorption refrigerator [16]. Since the desirable lowest adsorption temperature for the adsorption refrigerator is room temperature, the boiling point should be preferentially higher than 20^{o}C. Zeolite – water, Zeolite – methanol, Activated carbon- methanol etc might be mentioned among the adsorbent - adsorbate combinations that have been tested, [3]. Zeolite – water pair is very suitable to be used in adsorption refrigeration owing to the extremely non-linear pressure dependence of its adsorption isotherms [7]. The isotherms saturate at low partial pressure, after which the amount adsorbed becomes almost independent of pressure. At ambient temperature, zeolite can adsorb most of the vapour even at high partial pressure, corresponding to high condenser temperature. This unique property of the zeolite is especially important in the case where a high condenser temperature and only a moderate regeneration temperature might be employed. Since water has a high latent heat of vaporization and a convenient boiling point, the zeolite water pair is one of the most preferred adsorbent – adsorbate pairs. However, water has been shown, in literature to be a potentially excellent working fluid (available in abundance, non-toxic, corrosion free, low cost, ease of handling it, high latent heat and convenient boiling point for adsorption – desorption cycle) for cooling system, [19]. Moreover, its main drawback is the phenomenological volume it presents in the evaporator of the cooling system compared with the volume in the liquid state in the condenser of the system [10, 13]. Also its extremely low saturation pressure makes it impossible to produce evaporator temperature below 0^{o}C. Powering the system directly with Solar energy is advantageous with the provision of energy grade (renewable, abundant, cheap, pollution free and environmentally friendly) in form of heat. It enhanced the system efficiency with the direct conversion of the solar heat with minimal losses in the system.

This paper presents performance investigation of a designed and constructed solar adsorption refrigeration (Zeolite4A-Water) system [15] as a possible alternative to the vapour compression refrigeration because of its eco-friendliness, solar energy availability and low cost. The main purpose of the refrigerator is for vaccine and food preservation. Using high temperature solar CPC collector, the adsorber bed (Copper pipe) arranged in form of concentric tubes, finned with stainless sheet metal, with is annulus packed with pelletised Zeolite 4A. The system was designed, constructed and tested for its performance in the Mechanical engineering Department of Ahmadu Bello University Nigeria.

2.0 SOLAR ADSORPTION REFRIGERATION SYSTEM

The solar powered adsorption refrigerator was designed to achieve cooling by operating on adsorption – desorption principle. The system has no moving parts. Water is used as working fluid and synthesized highly porous silicon compound (Zeolite 4A) is used as adsorbent.

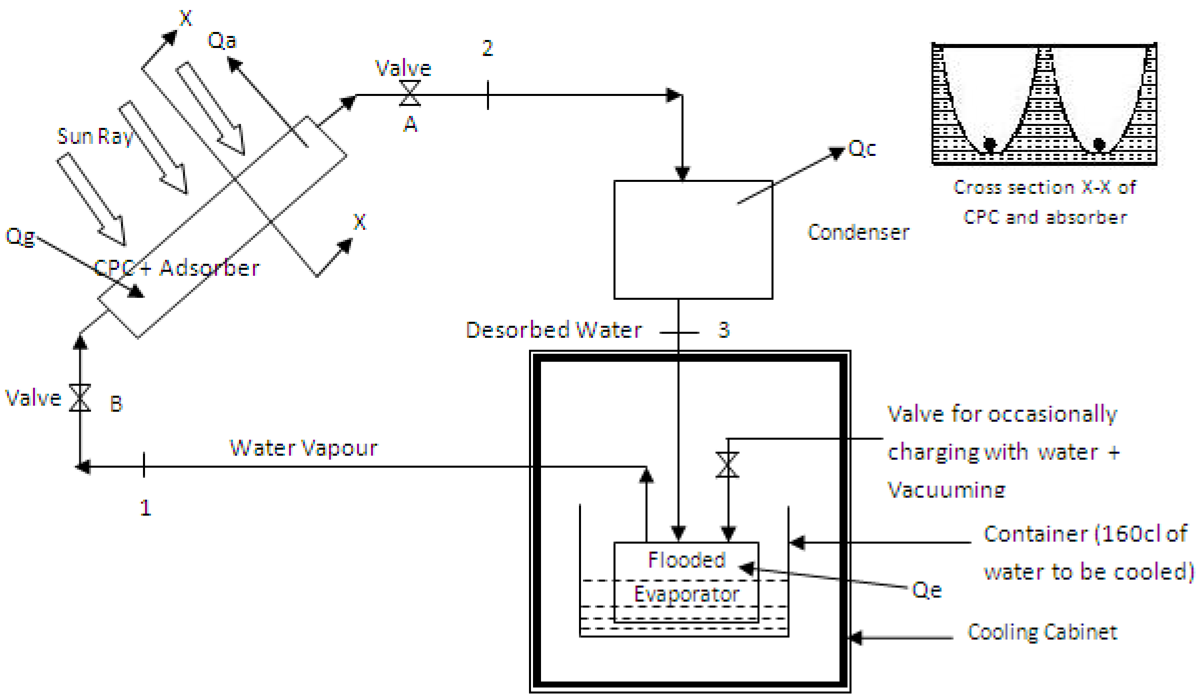

Figure 1; Adsorption Refrigerator Design flow diagrams

The system consist of the following components as shown in Figure 1; The 2-solar compound parabolic concentrating collectors (CPC), the condenser, the flood evaporator, airtight cap (valve) and control valve. The operation concept is based on the fact that when cool (at night) the Zeolite acts like a sponge soaking up or adsorbing the water vapour and when heated during the sunning day the water vapour is desorbed or released. The system operates under a partial vacuum, the water vapour moves with high efficiency under low pressure. At the desorption temperature of water, water vapour begins to desorb from the Zeolite. Thus the receiver act as a boiler and the water vapour leaves through the perforated holes on the duct to the condenser. This water vapour is condensed into water droplet as heat is given off by the heat exchanger (condenser) as depicted in the flow diagram (Figure 1). The resulting water runs down due to gravity into a sealed storage tank inside the refrigerator compartment. During the night, Zeolite is cooled close to ambient temperature and start adsorbing water vapour. The liquid water in the storage tank (an evaporator) adsorbs heat from the space to be cooled and is converted into water vapour. Since the system is sealed under very low pressure the remaining water in the storage tank freeze's into ice. This ice will melt slowly during the next day thus providing sustained cooling at reasonable constant temperature.

3.0INSTRUMENTATION FOR TEST

The instrumentation was located appropriately on respective system component where readings are to be taken as shown in Figure 2 and Plate 1. One end of the six thermocouple wire were each glued to the surface of adsorber tube, condenser pipe, evaporator box, glass cover, cooling box interior wall while the last wire hang freely in the air (ambient). The other ends were soldered to the input point on a switch with its output connected to the voltmeter.

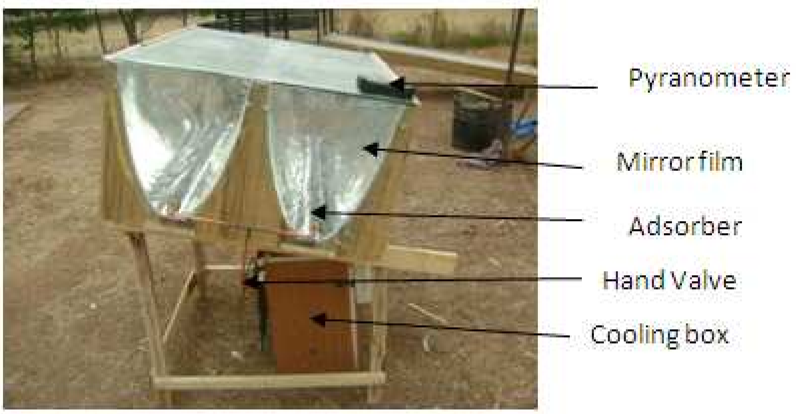

Plate 1; System assembly (Side view)

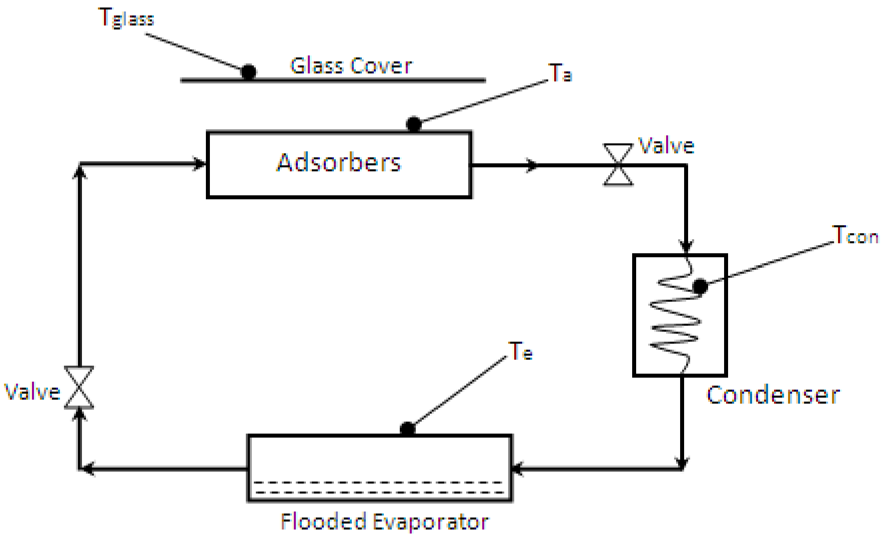

Figure 2: Flow diagram and Instrumentation

While testing the refrigerator design, the following equipment was employed for temperature, volume, Electric vacuum pump for vacuuming and solar radiation measurement [10];

Thermocouple

System component surface temperature was sensed with calibrated copper-constantan thermocouple wire (0.5mm diameter) in conjunction with digital voltmeter which can take readings from below Zero degrees and above in unit of Fahrenheit and Celsius degree. The meter is used to obtain readings at respective point s of contact as each point is connected through a switch.

Switch
For ease of taking instantaneous reading, the entire six thermocouple wires free end were soldier to the switch input terminal while its output is connected to the meter. It is a mechanical device for breaking or making of electrical circuits. The instrument has input and output terminals with rotary leverage.
Measuring cylinder
A transparent measuring cylinder of capacity 250ml was used in measuring the volume of distilled water charged into the system and for loading water into the cooling box.

Solarimeter
Calibrated Day Star Pyranometer was used in measuring instant solar irradiation (sun's power). The instrument measured the power (insolation) in W/m^2. The meter provides accurate reading from 50-1200W/m^2. The instrument consists of silicon Photovoltaic (PV) cell mounted on the front of the meter using a 9V battery.

Electric vacuum pump.
A motor driven Edward vacuum pump (horse power of 2.85 and 0.3Amperes) was used to mechanically extract air from the system turning it to 0bar. The pressure gauge measures pressure ranging from 0bar to 40bar.

3.1 TESTS PROCEDURE

The tests were carried out in the months of April 2011 at Mechanical Engineering Department ABU Samaru Zaria. The objective of the April 2011 measurement was to obtain the continuous measurement of the system performance in the peak month of solar radiation and be able to determine the performance of the designed and constructed solar adsorption system. In doing this a procedure was followed. The System design was setup as shown in Figure 2 and Plate 1. Charging of the system commences by 4.00pm with the filling of the evaporator tank with 75cm^3 of distilled water. After which the evaporator tank valve was connected to an electrically control Edward vacuum pump from UK London while the two hand valves were open. On starting the pump, the machine sucked all the air in the system. This was immediately followed with the valve lock replacement and tightening simultaneously with the removal of the vacuum pump. With the aid of thermocouple wire, and a switch connected to the voltmeter, the readings from the system glued surfaces were taken from the voltmeter. The tube surface temperature of the adsorber/generator (T_a/T_g), the condenser (T_c), the evaporator (T_e) the ambient air temperature (T_{amb}), cooling box interior wall (T_w) and the glass cover surface (T_s) were measured. The global solar radiation (I_r) [9] in the plane of the collector was measured using the Daystar pyranometer. The thermocouple meter and the solarimeter were placed in the plane of the collector, side by side since simultaneous reading is required. Moreso, that each temperature reading required turning the switch. The loading was achieved by placing some quantity of water (160cl) in the container containing the evaporator. This was followed with the locking of valve A (valve connecting adsorber to condenser) and opening of valve B (valve connecting the evaporator to adsorber). This is repeated everyday at 8.00am and 4.00pm alternately. The readings were taken for a period of 2weeks (1-14 April 2011).

4.0 REFRIGERATOR COEFFICIENT OF PERFORMANCE (COP)

Cycle COP
For a batch refrigeration process as in this case which operate as an intermittent adsorption cycle, the assessment parameter is the coefficient of performance (COP) defined as the ratio of the cooling effect to the total energy required for the desired cooling effect.

$$C.O.P_{ref} = \frac{Cooling \quad effect}{Total \quad energy \quad input}$$

$$C.O.P_1 = \frac{Q_e}{Q_g} = \frac{T_e(T_g - T_a)}{T_g(T_c - T_e)} \quad \text{----------- (1)}$$

$$COP_2 = \frac{Q_e}{Q_g} \approx \frac{T_e}{T_g} ---------------------- (2)$$

Where Q_e and Q_g are the heat transfer during refrigeration and the heat used to generate refrigerant during generation respectively.

Solar COP

Being an intermittent system cycle, the solar powered adsorption machine solar COP is usually defined as

$$C.O.P_s = \frac{Q_e}{Q_I} = \frac{\Delta m.\left[L - c_p\left(T_c - T_e\right)\right]}{A.\int_{sunrise}^{sunset} I(t)dt} \text{------------------} (4)$$

Where c_p is the specific heat of the liquid refrigerant, L is its vapourisation latent heat, Δm is the evaporated refrigerant mass, A is the collector area and I is the irradiance. The denominator account for the solar thermal supply $Q_I$while the numerator take care of the portion of gross cold productionQ_e, Δm.L must be spent to cool the liquid refrigerant from the condensation temperature T_c to the evaporation temperature T_e.

RESULTS AND DISCUSSION

Figure 3 shows the variation of solar insolation and corresponding system temperature with time on an experimental day (first of April 2011). In the figure, the curves of the solar insolation, adsorber temperature, condenser temperature, evaporator temperature, ambient and the cooling box wall temperature were shown. From the graph, at about 7:00am, the temperature of the adsorber is a little above the ambient temperature which is above 20^{o}C. Beyond 7:00am on the same day, the adsorber temperature increases due to increase in insolation. This corresponds with isosteric heating and the system operates on constant amount of adsorbate in the adsorber. On this day, the adsorber temperature increased to a maximum between 8:00am and 13:00pm (as shown in Figure 3). Before this peak temperature, desorption of the adsorbate had commenced. This is the isobaric desorption stage which resulted in the condensation of the adsorbate. During the period of attaining the peak temperature, similar temperature profile were recorded in the case of Condenser and Glass cover due to increase in insolation with corresponding increase in ambient temperature. The evaporator unit recorded a relatively small increase in temperature. Subsequent period (13:00pm - 17:00pm) experienced a decrease in the temperature of adsorber, condenser, glass cover and ambient temperature. With the absorption of heat by the evaporator unit from the interior (products) of the cooling cabinet at saturation temperature lead to the formation of water vapour in the evaporator unit thus creating cooling effect, hence isosteric cooling.

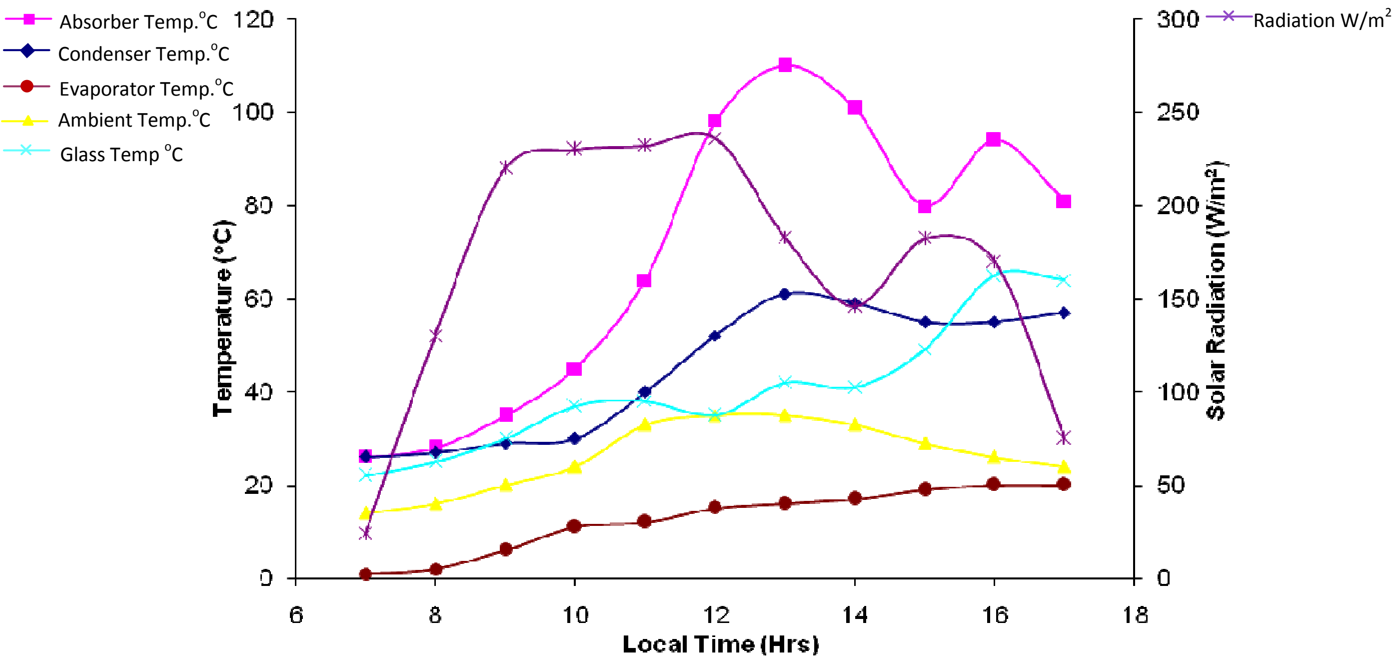

Figure 3: Day 1(1stApril 2011) Hourly variation of Solar Radiation and system temperature in a day

The refrigeration effect caused with the removal of heat from the cooling cabinet further increased with the adsorption of the water vapour by the hydrated zeolite 4A inside the adsorber tube giving rise to isobaric adsorption. However, the general graphical profile of solar radiation and system temperature with local time is like a dome with some exception (where the dome is not growing smoothly, remain flat or with pronounced inclination) [6]. A maximum adsorber temperature of 110^{o}C was recorded at 13:00pm. The maximum Insolation of 345W/m^2 (on 8th April 2011) occurs at 12:00noon while the minimum of 34W/m^2(2nd of April) occurs at 7:00am. While the desorbed vapour flow to the condenser, (Desorption + condensation occur simultaneously) the Condenser temperature increases from 8:00am to 13:00pm to a peak value. Generally, condenser temperatures profile is slightly higher than the ambient temperature and much lower than that of the adsorber. This shows that condensation actually occurs. Condensed Water flows into the evaporator which accommodates the receiver tank. The evaporator temperature of 10^{o}C and 11^{o}C recorded in the early hours of the days is usually due to the volume of desorption as a result of high insolation recorded the previous day. Refrigeration effect and COP depends upon the mass of desorbed refrigerant. However, the daily-hourly mean component temperature readings are plotted in Figure 4. The system performance COP was calculated using temperature readings from experimental results. From the results the maximum desorption temperature of 110^{o}C (Adsorber temperature) attained so far is below the designed optimum temperature of 200^{o}C. This may be due to the inability of the collector profile (mirror surface) to concentrate the radiation on the adsorber and lack of good contact between the metal surface (adsorber tube) and the adsorbent which created a steep thermal gradient at the interface. The inefficient heat exchange is mainly due to the shape of the adsorbent particles, generally spherical or cylindrical which do not allow a good contact between the adsorbent solid surface and the metallic heat exchanger [1].

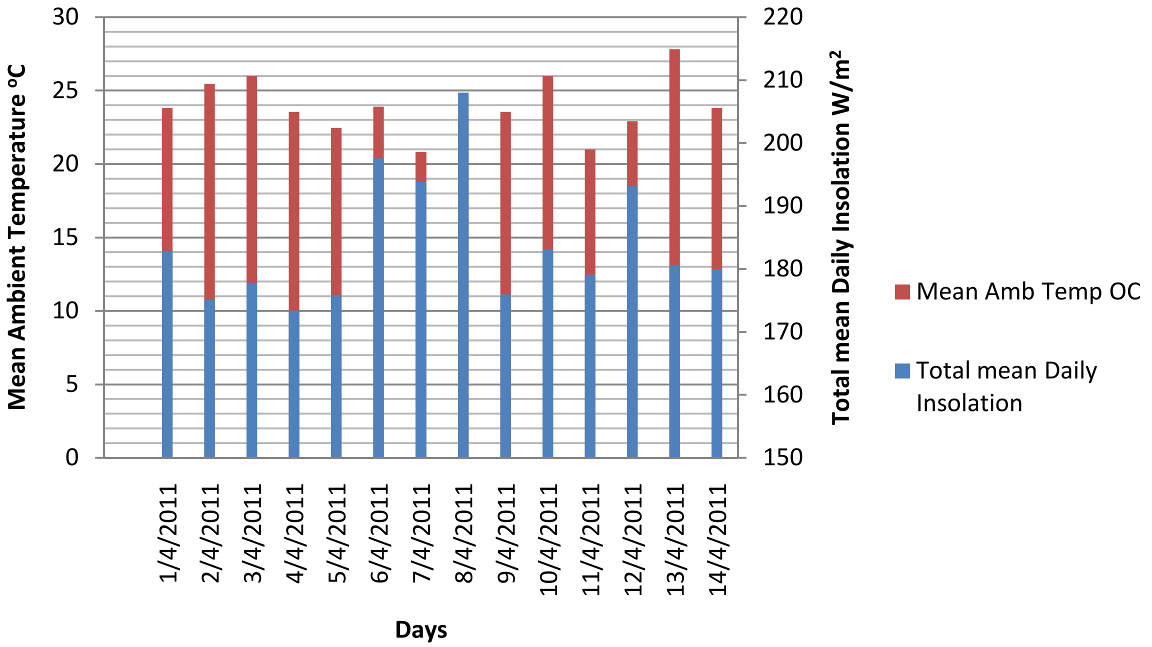

Figure 4: Evolution of Total mean Daily-Hourly Solar Radiation and mean external temperature between (7:00am-17:00pm)for the experiment

During the period of the experiment, the ambient temperature was above 20^{o}C and the total mean irradiation was 170W/m^{2}on the average. However the irradiation varies from one day to another. The Pyranometer results of solar radiation from day to day are difficult to compare with any degree of certainty, [6]. The Sky condition change every day and even for the same day, sudden and unpredictable absence or presence of cloud, dust or haze can upset any basis of comparison. At night, the lower the night time temperature of the adsorber the better the readsorption of water by the zeolite. With high readsorption, so is evaporation and consequently large refrigeration effect. Zeolite – water is suitable for high temperature heat hence the use of double compound parabolic concentrator collector. It is more stable at higher temperatures above 150^{o}C with higher COP. It is suitable for air-conditioning because it is impossible for it to produce evaporation temperature below 0^{o}C, [2].

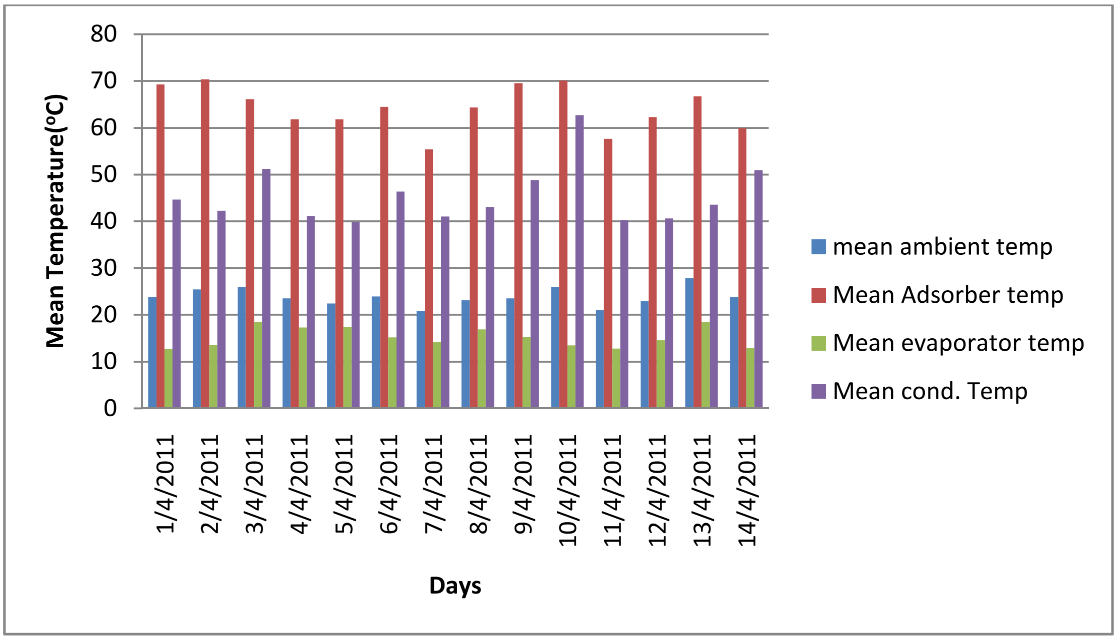

Figure 5: Mean system temperature against Days

Moreso that the system operates in a vacuum condition hence leak proof machine is essential to maintain the performance of the system.

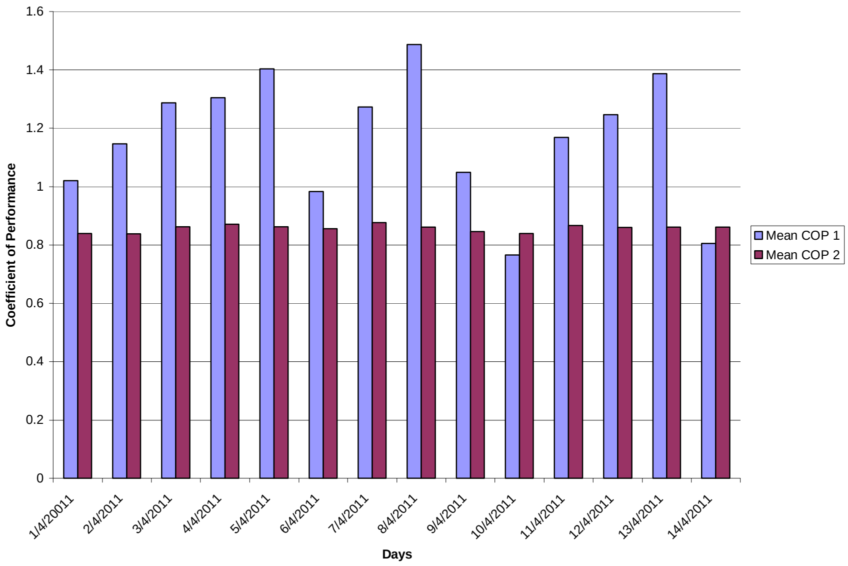

Figure 6: Mean Coefficient of Performance against Days

The total mean hourly insolation recorded daily is plotted in Figure 4. Also the daily – hourly mean system temperature plotted against corresponding days and the daily mean COP against days are presented in the Figure 5 and 6 respectively. In comparison, a solar thermal system where the collectors probably dominate the capital cost, and the fuel cost is zero, COP of the system according to [4] can range from 0.2 to 0.5 for intermittent sorption systems and up to 0.7 for intermittent regenerative cycles. Vapour compression machines with an electricity input would have typical COPs of 1.0 to 1.5. Using equations 1 and 2, the COP of the system was evaluated. The hourly instantaneous COP ranges from 0.2 to 2.5 while the hourly insolation ranges from $34W/m^2$ to $345W/m^2$. Evaporator temperature of 11^oC and maximum adsorber temperature of 110^oC was recorded. The minimum daily – hourly mean COP_2 of 0.838 with the corresponding maximum COP value of 1.48 was achieved as depicted in Figure 6. Meteorological condition was also recorded with a total mean daily-hourly insolation of $170W/m^2$on an average. The difference in the values of COP_1 and COP_2 is as a result of the assumptions made in the derivation of the equations. That is the properties of the adsorbent material and the adsorber tube material was not accounted for in the equation. Scattered in the literature are varying values of COP for different collector type, system design and geometry, and the operating principle which include the available solar radiation during the experimental period. Each of the zeolite – water system design and their operations are aimed at achieving specific objective while operating in an area with varying weather situation, sunny, hazy etc. The measuring tools are of different quality and are design for a specific environment. However, US standardized Daystar Pyranometer was used. The tests were performed in the Department of Mechanical Engineering ABU Zaria. The above stated COP was recorded based on prevailing weather situation within the experimental period and with the corresponding evaporator and desorption temperature.

CONCLUSION

The entire system was designed, constructed and tested which shows that;
(1) The design used an array of two CPCs with 1.029m^2 collector areas and 1.8 concentration ratio truncated to height/aperture ratio of 1.19. The system was constructed and tested in April 2011 in the Department of Mechanical Engineering ABU Zaria.
(2) The design hourly instantaneous COP ranges from 0.2 to 2.5 while the hourly insolation ranges from 34W/m^2 to 345W/m^2. Evaporator temperature of 11^{o}C and maximum adsorber temperature of 110^{o}C was recorded. The minimum daily – hourly mean COP of 0.838 with the corresponding maximum COP value of 1.48 was achieved as depicted in Figure 11. Meteorological condition was also recorded with a total mean daily-hourly insolation of 170W/m^2 on an average.

Acknowledgement
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NOMENCLATURE

m	quantity of adsorbent/adsorbate (kg)
C.O.P	Coefficient of performance
SCP	Specific cooling power(W/s-kg)
EES	Engineering equation solver
AutoCAD	Computer aided drafting
h_{fg}	latent heat of water vapour (2500kJ/kg commonly used)
C_p	Specific heat (kJ/kg-K)
Te	Evaporator Temperature (^{o}C)
Tc	Condenser Temperature (^{o}C)
Tg	Generator Temperature (^{o}C)
P	Pressure (Nm^2)
V	Volume (m^3)
A	Area through which heat is transferred (collector area (m^2)
U	Overall heat transfer coefficient.(kJ/h-rm^{2}K)
I_T	Solar radiation intense incident on the aperture (kJ/h-rm^2)
D	diameter of adsorber tube (m)
L	length of CPC trough (m)
f	focal length (m)
m_{rg}	Mass of refrigerant (kg)
Qe	Heat evaporator (kJ)
Qg	Heat of generator (kJ)
k	Heat transfer coefficient (W/m-^{o}C)
t_{cycle}	adsorption cycle time(s)

Subscripts

amb	ambient
ref	refrigeration
r	refrigerant
Δ	Incremental change
c	condenser
E, e	evaporator
G, g	generator
d	desorber
a	adsorber
W,w	water, adsorbate concentration (kg/kg)
i	initial
z	zeolite
f	final

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