Transient Simulation of a Flat Plate Solar Collector Powered Adsorption Refrigeration System

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Abstract- The modeling and simulation of a solar powered adsorption refrigeration system using flat plate solar collector, with activated carbon/methanol as the adsorbent/adsorbate pair has been undertaken in this study. A study of the adsorption bed was carried out to determine the effects of generation, evaporation and condensation temperatures on the performance of the cooling system. This was then used in the optimization of the solar thermal system in the sizing of the collector area and hot water storage tank volume. A transient simulation of the cooling system with an evaporator temperature of 0^oC and condenser temperature of 25^oC was subsequently carried out with the TRNSYS 16 software over a period of a typical year for Kano, Nigeria.The Flat plate collector powered adsorption refrigeration system gave average values of refrigeration effect as 4814.83 kJ, solar coefficient of performance (COPs) of 0.024, a cooling coefficient of performance (COP) of 0.608 and a heating efficiency of 0.46. The system was able to achieve a cold room temperature of about 1^oC.

Keywords- Transient simulation, Flat plate solar collector, Adsorption, Refrigeration, Simulation.

1. Introduction

Refrigeration plays an important role in our world, primarily for the preservation of food, healthcare materials (storage of vaccines, blood and medicine), and human thermal comfort (air conditioning and temperature regulation).

Cooling in industrial countries depends heavily on grid electricity which is supplied continuously and reliably to every part of the country. In contrast, refrigeration is required in developing countries to boost agricultural production and commerce, in large areas without reliable source of electricity supply; hence an alternative method of powering refrigeration is necessary.

Alternatives to hydrofluorocarbons as refrigerants are naturally occurring substances like ammonia, carbon dioxide, methanol, water and air. These can be used in sorption processes to produce refrigeration and have been studied for the last twenty years as a technological alternative to vapor compression systems. Sorption cooling systems have the advantage of being environmentally friendly as they employ safe and non polluting refrigerants.

Adsorption is a surface phenomenon occurring at the interface of two phases, in which cohesive forces act between the molecules of all substances irrespective of their state of aggregation. The solid and the fluid adsorbed in the solid surface are referred to as the adsorbent and the adsorbate respectively. Adsorption however may be due to a physical process (physisorption) or a chemical process (chemisorption) with the heat of adsorption small in physisorption and large in chemisorption. Adsorbent substances are usually restored to their original state by a desorption process involving the application of heat though some chemisorption process maybe irreversible.

From the literature review, various combinations of adsorbate/adsorbent pairs and configurations have been reported as designed, constructed and tested. At the moment absorption refrigeration cycles are most promising technologies, however, the adsorption cycles have the distinct advantage over the other heat driven refrigeration cycles in their ability to be driven by heat of relatively low temperature [1-6]. For food storage and freezing the adsorption system still remains the most viable for solar powered refrigeration though the COP theoretically possible (0.3-0.8) is yet to be achieved in systems so far developed [7-19]. Two adsorbent/adsorbate pairs are however for now predominant in refrigeration systems - Zeolite/water and activated carbon/methanol. Zeolite/water is usually used for cooling systems while activated carbon/methanol is used in ice making systems.

The objective of the present research is to model a solar powered refrigeration system powered by a flat plate solar collector using activated carbon-methanol pair with Kano (latitude 12.05^{o}N, longitude 8.31^{o}E), Nigeria as its location of operation. The simulation is carried out to determine the optimal parameters of the system its performance studied.

2. System Description

The solar powered adsorption system proposed is a hybrid system capable of heating and cooling to achieve higher efficiency and better usefulness in practice. The system is to operate on an activated carbon-methanol adsorption pair. The system consisting of the following components as shown schematically in Figure 1 below: solar collector, water tank, adsorbers, hot water storage tank, condenser, an evaporator and valves for control of flow can be grouped into two subsystems - the solar collector subsystem (heating) and the refrigeration subsystem.

In the solar heating subsystem, solar energy gained through the solar collector during daylight hours is transferred to the water in the pipes below it and accumulated in the water tank. As the solar irradiance increases, the temperature of the water tank rises, and consequently the temperature of the adsorbent bed which is immersed in the water tank also rise with an attendant rise in pressure from the evaporator. The temperature of the adsorbent bed is assumed to reach a level very close to the water temperature in the tank (an ideal process). When the temperature of the adsorbent bed reaches the desorption temperature (condenser temperature), desorption of the refrigerant from the adsorption bed is started in the refrigeration subsystem. As the heating of the adsorbent bed progresses, the refrigerant continues to desorb at constant pressure until the adsorbent bed reaches its maximum temperature. The desorption ceases at this temperature and the refrigerant vapor will be condensed into liquid in the condenser. The liquid adsorbate is then transferred and stored in a liquid receiver from where it is passed to the evaporator. At the end of desorption, the circulation through the collector is stopped with a gate valve then the hot water in the first water tank is drained and stored in the hot water storage tank for domestic use. The water tank is then filled with cold water which rapidly cools down the adsorber; this initiates the cooling-adsorption-evaporation process. The adsorbent bed temperature drops with a reduction in system pressure to Pe, the evaporator pressure. When the adsorbent bed reaches the evaporating pressure, the bed will begin to adsorb the refrigerant from the evaporator. The liquid refrigerant in the evaporator vaporizes by absorbing heat energy from the water stored in the evaporator, thereby cooling the water and producing ice.

The resulting sensible heat of the adsorber and heat of adsorption preheats the cold water in the tank (heat recovery), thus making more efficient use of the solar energy gained from the collector.

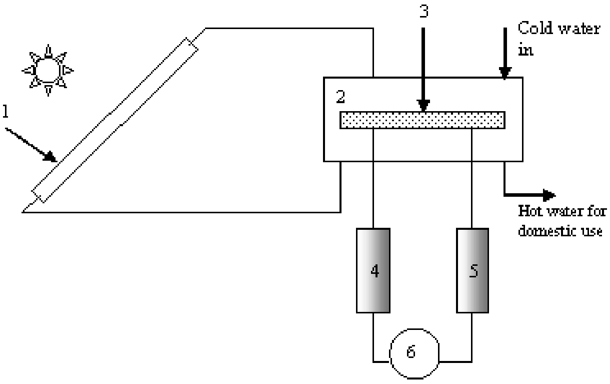

Fig. 1. Schematic view of the solar water heating and cooling system: 1. Solar collector; 2. Hot water storage; 3. Adsorbent bed; 4. Evaporator; 5. Condenser; 6. Methanol liquid receiver.

The adsorbent bed is the heart of the adsorption cooling system and thus, its characteristics are the most influential factors in the efficient operation of such systems. An efficient adsorption system requires that the adsorber have good heat collecting and heat releasing properties. The arrangement of the adsorbers in the adsorbent bed is in the manifold arrangement. This arrangement increases the contact area between adsorbent bed and water as well as obtaining uniform heating. Activated carbon is packed in the annular space between the two co-axial pipes of the bed. The inner pipe is perforated to allow for the flow of desorbed methanol. The vapor is collected from the individual inner pipes into a header pipe on one end which leads to the condenser with the outer pipe sealed. At the other end, the inner pipe ends are sealed while the outer pipe ends are connected to a header pipe which supplies methanol vapor from the evaporator to the adsorbent bed.

3. Mathematical Model

3.1. *Combined Heat and Mass Transfer Equation in the Adsorbent Bed*

The following assumptions are made in the development of the model:

(i) The pressure is uniform in the adsorbent bed.

(ii) The adsorbent bed is considered as a continuous medium whose conduction heat transfer can be characterized by an equivalent thermal conductivity.

(iii) Headers provide uniform flow to and from the adsorber tubes.

(iv) The adsorption/desorption process is an isobaric process.

(v) All phases are continuously in thermal and chemical equilibrium.

(vi)The thermophysical properties of the adsorbate are those of the bulk liquid and the gaseous phase behaves as an ideal gas.

(vii)The condenser and evaporator processes are ideal processes; Tcon and Tev are constant during the isobaric phases.

(viii)The heat transfer in the adsorbent is radial and the convection heat transfer due to radial mass transfer is neglected.

Assuming negligible heat losses from the tank due to insulation, the useful heat from the collector Q_u is supplied as input heat required to heat up (i) the water in the tank (Q_1), (ii) the metallic storage tank (Q_2), (iii) adsorber tubes and adsorbent mass (Q_3), (iv) the adsorbate mass before desorption (Q_4) i.e. sensible heat of adsorbate, (v) desorb a differential amount of adsorbate (Q_5), (vi) the adsorbate mass as desorption starts (Q_6), i.e. sensible heat of the adsorbate left in the adsorbent.

$$Q_u = Q_1 + Q_2 + Q_3 + Q_4 + Q_5 + Q_6 \quad (1)$$

But

$$Q_1 = \int_{T_1}^{T_3} m_w c_{p_w}\, dT \quad (2)$$

m_w is mass of water in tank (kg), cpw is the specific heat capacity of water (kJ/kgK)

$$Q_2 = \int_{T_1}^{T_3} m_{wt} c_{p_{wt}} dT \quad (3)$$

m_{wt} is mass of water tank (kg), cpwt is the specific heat capacity of water tank (kJ/kgK)

$$Q_3 = \int_{T_1}^{T_3} \left(m_{ad} c_{p_{ad}} + m_{ac} c_{p_{ac}} \right) dT \quad (4)$$

m_{ad} is the mass of adsorber tube (kg), mac is the mass of activated carbon in adsorber tube (kg), cpad is the specific heat of adsorber tube (kJ/kgK),and cpac is the specific heat capacity of activated carbon (kg).

$$Q_4 = \int_{T_1}^{T_2} x_{\max} m_{ac} c_{v_m}\, dT \quad (5)$$

x_{max} is maximum quantity of methanol adsorbed (kg) per kg of activated carbon and cvm is the specific heat at constant volume of methanol (kJ/kgK).

$$Q_5 = \int_{T_2}^{T_3} m_{ac} h_d \frac{dx}{dT} dT \quad (6)$$

h_d is heat of sorption (kJ/kgK) for activated carbon-methanol pair is calculated from the Clausius-Clapeyron equation as

$$H = R\,A \frac{T}{T_s} \quad (7)$$

where R is the gas constant for methanol with a value of 260 J/kgK, T is the sample temperature K, Ts is the saturation temperature corresponding to the gas pressure P. A is a constant corresponding to the slope of the saturation curve on a plot of lnP vs. (-1/Ts) and for methanol A = 4666 [20].

$$Q_6 = \int_{T_2}^{T_3} x(T, P_c) m_{ac} c_{p_{mv}}\, dT \quad (8)$$

c_{pmv} is the specific heat of methanol vapor (kJ/kgK).

$$\Rightarrow Q_u = \int_{T_1}^{T_3} m_w c_{p_w} dT + \int_{T_1}^{T_3} m_{wt} c_{p_{wt}} dT + \int_{T_1}^{T_3} \left(m_{ad} c_{p_{ad}} + m_{ac} c_{p_{ac}} \right) dT + \int_{T_1}^{T_2} x_{\max} m_{ac} c_{v_m} dT + \int_{T_2}^{T_3} m_{ac} h_d \frac{dx}{dT} dT + \int_{T_2}^{T_3} x(T, P_c) m_{ac} c_{p_{mv}} dT \quad (9)$$

The adsorption equation of activated carbon-methanol is calculated from the Dubnin-Astakhov equation as in [21]

$$x = x_o \exp\left[-k \left(\frac{T}{T_s} - 1 \right)^n \right] \quad (10)$$

The useful energy in equation (1) can also be expressed as

$$\left(m_w c_{p_w} + m_{wt} c_{p_{wt}} \right) \frac{dT}{dt} = Q_u - h_{c_{w-ad}} \left(T_w - T_{ad} \right) A_{ad} \quad (11)$$

where $h_{c_{w-ad}}$ is the heat transfer coefficient between water and adsorber tubes of diameter d, and can be evaluated using the following correlation given by Deaver [22] as

$$h_{c_{w-ad}} = Nu_d \frac{k_1}{d} \quad (12)$$

And $Nu_d = 0.48 Ra_d^{0.23} \quad for\ 10^4 \langle Ra_d \langle 10^7$ (13)

The Raleigh number $Ra_d = \dfrac{g \beta' d^3 \left(T_w - T_{ad} \right) \mu c_p}{\nu^2 k_1}$ (14)

Then the energy balance between the hot water in the tank, adsorber tubes and content is

$$\left(m_{ad} c_{p_{ad}} + m_{ac} c_{p_{ac}} + x_{\max} m_{ac} c_{v_m} \right) \frac{dT_{ad}}{dt} = h_{c_{w-ad}} \left(T_w - T_{ad} \right) A_{ad} - m_{ac} h_d \frac{dx}{dt} \quad (15)$$

In the evening, the hot water is drained and replaced with cold which cools the adsorber. The sensible heat of the adsorber and heat of adsorption rejected from the adsorbent bed will cause the temperature of the water in the tank to rise by a few degrees.

Heat rejected from the adsorbent bed into the water tank and heat recovered by the water can be expressed with the following heat balance equation:

$$Q_{ct} = \int_{T_0}^{T_1} m_w c_{p_w}$$
$$= \int_{T_1}^{T_3} \left(m_{ad} c_{p_{ad}} + m_{ac} c_{p_{ac}} \right) dT + \int_{T_4}^{T_3} x_{\min} m_{ac} c_{v_m} dT \quad (16)$$
$$+ \int_{T_1}^{T_4} m_{ac} h_a \frac{dx}{dT} dT + \int_{T_1}^{T_4} x\left(T, P_e\right) m_{ac} c_{p_m} dT$$

x_{min} is the adsorption capacity after desorption(kg/kg) and ha is the heat of sorption.

The cold water to fill the tank in the evening enters at a temperature T_0, which can be expressed as

$$T_1 = T_0 + \frac{Q_{ct}}{\dot{m}_w c_{p_w}} \quad (17)$$

3.2. Refrigeration Effect and System Efficiency

The desorbed refrigerant collects and is condensed in the condenser from where it flows into the evaporator. At night, with the introduction of cold water into the water tank, the temperature and subsequently the pressure of the adsorbent bed drops to below the evaporation pressure, causing the refrigerant liquid in the evaporator to vaporize resulting in the refrigeration effect. The refrigeration effect is measured by the system performance efficiency. It is described by the coefficient of performance (COP) as

$$COP = \frac{Q_{ref} - Q_{cc}}{Q_g} \quad (18)$$

The amount of refrigeration is calculated as

$$Q_{ref} = \Delta x m_{ac} L_e \quad (19)$$

Le is the latent heat of vaporization of the adsorbate.

Q_{cc} is the amount of energy assumed to be utilized in cooling the refrigerant liquid from the condensing temperature T_c to the evaporation temperature Te. Q_{cc} is estimated as

$$Q_{ref} = \Delta x m_{ac} L_e \quad . \quad (20)$$

Qg is the heat required for the regeneration of the adsorption bed and it is calculated the equation below.

$$Q_g = Q_u - \left(Q_1 + Q_2 \right) \quad (21)$$
$$\Rightarrow Q_g = Q_3 + Q_4 + Q_5 + Q_6$$
$$Q_g = \int_{T_1}^{T_3} \left(m_{ad} c_{p_{ad}} + m_{ac} c_{p_{ac}} \right) dT + \int_{T_1}^{T_2} x_{\max} m_{ac} c_{v_m} dT +$$
$$\int_{T_2}^{T_3} m_{ac} h_d \frac{dx}{dT} dT + \int_{T_2}^{T_3} x\left(T, P_c\right) m_{ac} c_{p_{mv}} dT$$

The specific cooling power

$$SCP = \frac{Q_{ref} - Q_{cc}}{t_{cycle} . m_{ac}} \quad (22)$$

The gross solar coefficient of performance is

$$COP_s = \frac{Q_{ref} - Q_{cc}}{\int A_c I(t) \partial t} \quad (23)$$

4. Adsorption Refrigeration System Simulation

The simulation of the adsorption refrigeration system was carried out in TRNSYS, with the TYPE 155 component used to model the adsorption unit. This TRNSYS type implements a link with Matlab. The modeling equations for the adsorption unit developed in chapter four are written in Matlab code that can be read by the TRNSYS software. The connection with the Matlab engine using Type 155 is launched as a separate process, the FORTRAN routine communicates with the Matlab engine through a Component Object Model (COM) interface.

Table 1 below gives the specification of the flat plate collector used in the simulation.

Table 1. Parameters for the flat plate single glazing collector

Parameter	Value
Gross Area	2m^2
Frame	Anodized Aluminum
Outer cover	Low iron tempered glass
Absorber plate	Copper fin
Absorber tube	Copper
Absorber coating	Moderately selective black paint
Insulation	Polyisocyanurate
Intercept Efficiency	0.80
First order loss coefficient	5 W/m^2 K^{-1}
Second order loss coefficient	0.014 W/m^2 K^{-2}
Tested Flow rate	0.0111 kg/m^2 s
Specific heat of working fluid	4.190 kJ/kg K

Table 2 below shows some of the parameters used in the simulation of the adsorption unit. The thermodynamic properties of methanol are as obtained from Methanex Corporation information guide [23].

The maximum quantity of methanol adsorbed by the activated carbon at 25oC (starting temperature) given the above conditions is 0.311kg/kg [24]; Xmin gives the quantity of methanol left in the adsorbent as the generation temperature increases. The change in Xmin and generation temperature as well as the COPsolar and COP attained by the system for four months of the year are presented in Figures 2 – 9

Table 2. Parameters Used in the Simulation of Adsorption Unit

Symbol	Parameter	Value	Unit
Activated Carbon			
c_{pac}	Specific heat of activated carbon	0.711	kJ/kgK
ρ_{ac}	Density of activated carbon	2000	kg/m^3
m_{ac}	Mass of activated carbon	26.07	kg
Methanol			
c_{pml}	Specific heat of liquid methanol	2.534	kJ/kgK
c_{pm}	Specific heat of methanol vapor at constant pressure	1.820	kJ/kgK
c_{vm}	Specific heat of methanol vapor at constant pressure	1.560	kJ/kgK
Stainless Steel Adsorber tubes			
c_{pad}	Specific heat of adsorber tube material	0.480	kJ/kgK
ρ_{ad}	Density of adsorber tube material	8055	kg/m^3
m_{ad}	Mass of adsorber tubes	12.4	kg
D_o	Diameter of each of the outer co-axial Adsorber tubes	0.0508	m
D_i	Diameter of each of the inner co-axial Adsorber tubes	0.0254	m
l_{ad}	Length of Adsorber tubes	1	m
N	Number of Adsorber tubes	10	-
Evaporator Temperature		0°C	
CondenserTemperature		25°C	

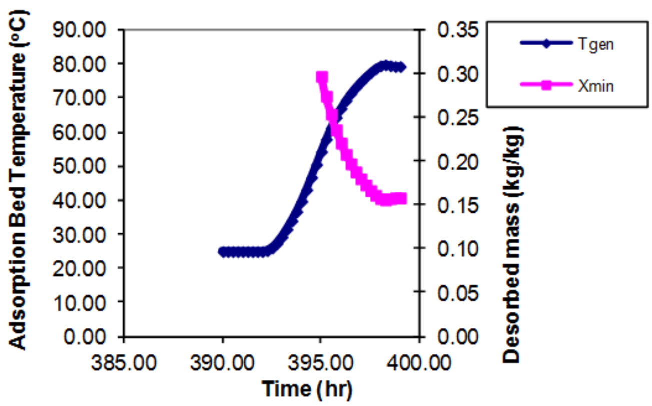

Fig. 2. Variation of Adsorption bed Temperature and Desorbed mass with Time (FPC Jan)

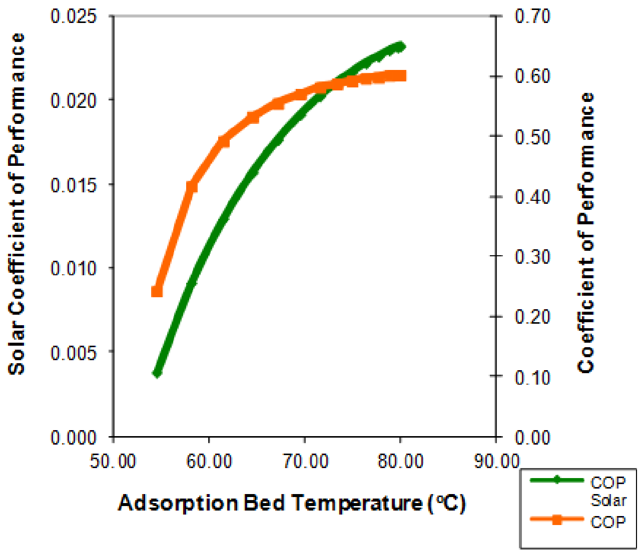

Fig. 3. Effect of Adsorption Bed Temperature on Coefficient of Performance (FPC Jan)

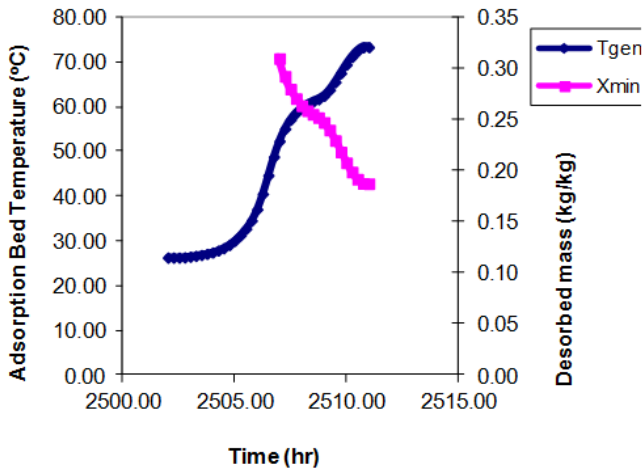

Fig. 4. Variation of Adsorption Bed Temperature and Desorbed Mass with Time (FPC Apr)

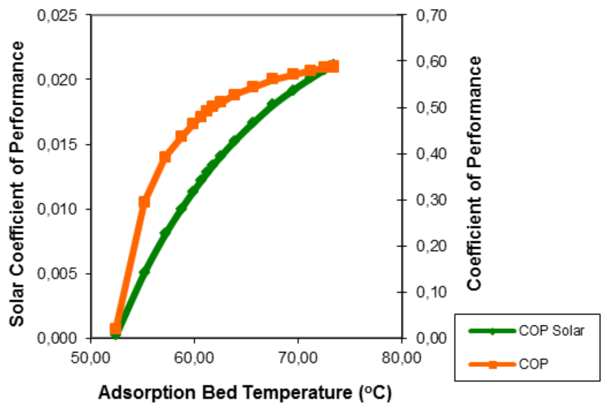

Fig. 5. Effect of Adsorption Bed Temperature on Coefficient of Performance (FPC Apr)

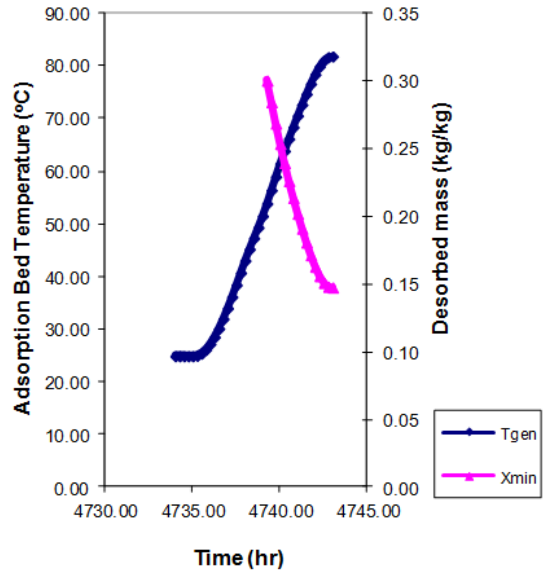

Fig. 6. Variation of Adsorption Bed Temperature and Desorbed mass with Time (FPC Jul)

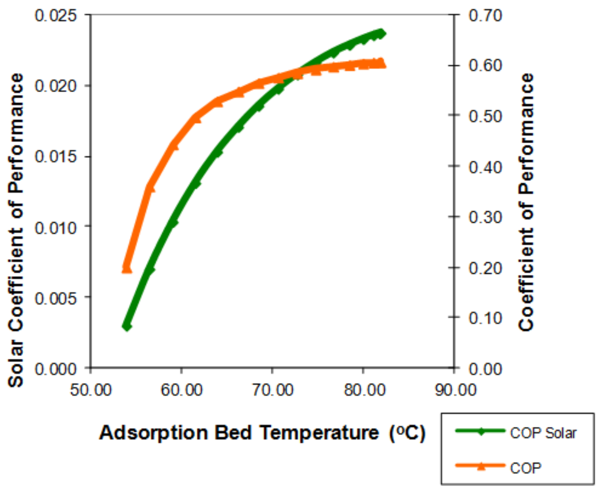

Fig. 7. Effect of Adsorption Bed Temperature on Coefficient of Performance (FPC Jul)

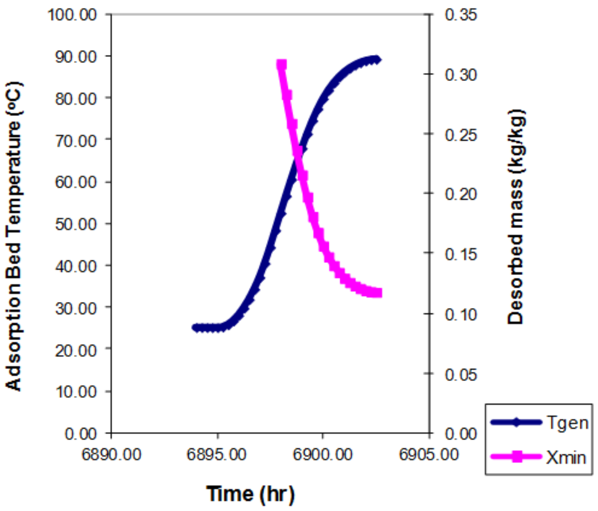

Fig. 8. Variation of Adsorption Bed Temperature and Desorbed mass with Time (FPC Oct)

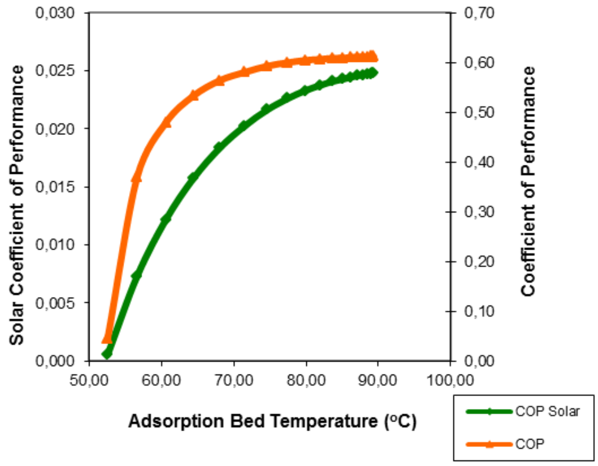

Fig. 9. Effect of Adsorption Bed Temperature on Coefficient of Performance (FPC Oct)

5. Discussions

In the flat plate collector powered system (figs. 2 - 9), heating of the adsorbent bed started on the average at about 8am with desorption starting about 11am and reaching a maximum generation temperature between the hours of 2-3pm. The period between 8 - 11am represents the isosteric heating phase, where the adsorbent bed continuously absorbs heat from the hot water tank. This results in a rapid increase in the adsorption bed temperature (as shown in the figures) from about 25^{o}C to about 55^{o}C in a time period of about 3 hours after which methanol starts to desorb from the activated carbon and flows to the condenser. The rate of heating and its associated adsorbent bed temperature rise is however lower for the isobaric desorption phase. Table 3 shows the highest generation temperature recorded for this system as 94.4^{o}C in the month of February (high insolation month) with the lowest peak temperature of 73.37^{o}C recorded in the month of April (low insolation month). This system also recorded appreciable desorption of methanol (0.123 - 0.211 kg/kg of activated carbon) resulting in a refrigeration effect ranging from 3329.27 kJ to 5704 kJ within an average desorption time of 234mins (3hr 54mins).

Table 3. Simulation Parameters of the Adsorption Refrigeration System

Month	T_{gen}(^{o}C)	Δx (kg/kg)	DesorptionTime (min)
January	79.89	0.155	195
February	94.40	0.211	240
March	90.38	0.197	255
April	73.37	0.123	225
May	81.72	0.163	240
June	88.97	0.192	255
July	81.86	0.163	210
August	84.48	0.174	210
September	94.06	0.210	270
October	89.34	0.193	270
November	85.67	0.179	225
December	85.09	0.177	210

The system achieved an average cooling process COP of 0.608, COP_{solar} of 0.024 and efficiency for the heating process of 0.47 as shown in Table 4.

Table 4. Simulated Performance Parameters of the Adsorption Refrigeration System

Month	Q_e (kJ)	COP	COP_s	Efficiency
Jan	4177.96	0.603	0.023	0.42
Feb	5704.82	0.613	0.025	0.47
Mar	5328.60	0.613	0.025	0.50
Apr	3329.27	0.589	0.021	0.51
May	4398.02	0.606	0.024	0.49
Jun	5189.30	0.612	0.025	0.46
Jul	4413.64	0.607	0.024	0.44
Aug	4713.57	0.610	0.024	0.45
Sep	5670.69	0.613	0.025	0.47
Oct	5226.20	0.612	0.025	0.49
Nov	4844.88	0.611	0.024	0.47
Dec	4780.96	0.610	0.024	0.43
Average	4814.83	0.608	0.024	0.46

6. Conclusion

The study showed that for appreciable desorption of methanol from activated carbon in a cooling system with 0^oC and 25^oC evaporator and condenser temperatures respectively, a temperature of at least 80^oC is required by the adsorbent bed. These parameters were then used in the transient simulation of the cooling system over a period of a typical year.

The FPC system gave average values of refrigeration effect of 4814.83 kJ, solar coefficient of performance (COPs) of 0.024, a cooling COP of 0.608 and a heating efficiency of 0.46.

This study shows that solar powered adsorption refrigeration can be effective, economic, practicable and an eco-friendly option for Kano in the northern region of Nigeria with abundant sunshine.

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