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Full Length Research Article

Performance Evaluation of Date-Seed Activated Carbon as Adsorbent in Adsorption Refrigeration System

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ABSTRACT
Vapour compression refrigeration systems are characterised by relative high energy requirement in addition to environmental pollution tendencies. Adsorption refrigeration system could be a better option in terms of huge energy savings and carbon emission reduction. This study is aimed at evaluating the performance and characteristics of date-seed activated carbon (DSAC) for use as adsorbent in adsorption refrigeration. Using isoster-based adsorbent/adsorbate equilibrium test rig, pressure, temperature and concentration (P-T-X) data were obtained. The isosteric heat of adsorption for conventional activated (CAC) and DSAC are estimated to a first approximation to be 16.058 and 16.650 kJ/Kg respectively. The results showed that date-seed activated carbon has relatively good adsorptive characteristics.
Keywords: Activated Carbon, Adsorption Refrigeration, Date-seed, Equilibrium test

INTRODUCTION
Energy consumption to air-conditioning systems has been estimated to constitute 45% of the whole households and commercial buildings demands (Wolak, 2017). It is forecasted that by the year 2100, air conditioning power consumption will expand to 33-fold worldwide (Norhayati *et al*., 2021). Increase in population and hence increased demand for human comfort, coupled with relative high energy requirement of vapour compression refrigeration necessitated the increasing need for more reliable, flexible and cost-efficient cooling system alternatives (Abdulkadir *et al*., 2015). Adsorption refrigeration and air conditioning systems could be a better option in terms of huge energy saving potential, carbon emission reduction and waste heat utilisation. Adsorption system could be seen as an opportunity to reduce the consumption of non-renewable primary energy and carbon footprint (Boruta *et al*., 2021).
Adsorption capacity (or “loading”) is the most important characteristic of an adsorbent. Simply stated, it is the amount of adsorbate taken up by adsorbent, per unit mass (or volume) of the adsorbent (Kent, 2015). Adsorption can therefore be defined as adhesion of atoms, ions, or molecules from a gas, liquid, or dissolved solid to a solid surface. This process creates a film of the adsorbate on the surface of the adsorbent. This process differs from absorption, in which a fluid (the absorbate) permeates or is dissolved by a liquid or solid (the absorbent). Adsorption is a surface-based process while absorption involves the whole volume of the material (Eric and Björn, 2005). The pore structure of adsorptive solids can be divided into three approximate groups: micro pores (radii <15 Å), transitional (15 Å ≤ radii ≤ 200 Å) and macro pores (radii > 200 Å). The solid pore structure of interest for solar refrigeration is the microspore (Anyawu and Ogueke, 2001). The performance of adsorbent is important for the efficient operation of an adsorption refrigeration cycle system (Zhang *et al*., 2020).

Commercially available solid adsorbent includes: Silica-Gel, Zeolite, Activated Alumina, Activated-Carbon, Calcium chloride, Metal oxides, Porous Metal hydrides (PMH) and Composite adsorbent (Alghoul *et al*., 2007). Activated carbon appeared to have strike the best compromise in terms of availability, relative high surface area and suitable porosity characteristics, as well as high heat conductivity to ensure energy transfer (Abdulkadir *et al*., 2015). Adsorption refrigeration system is thermal driven refrigeration which uses solid adsorbent beds to adsorb and desorb a refrigerant to obtain the cooling effect. These solid adsorbent beds adsorb and desorb a refrigerant vapour in response to changes in the temperature of the adsorbent (Li and Ruzhu, 2007). Adsorption refrigeration systems have higher reliability because there are no moving parts (Ahmed and Shehata, 2011).

The most common adsorbate used in adsorption refrigeration systems Include: ammonia, water, methanol and ethanol. Methanol appears to be the most favoured adsorbate for pairing with stable adsorbent (Alghoul *et al*., 2007). Methanol is environmentally friendly, non-toxic and has the added advantage of a freezing point temperature of -97.7ºC and boiling point temperature of 64.6 ºC (Knaebil, 2004), which makes it easy to drive adsorption systems with low temperature heat source (Alghoul *et al*., 2007; Anyanwu and Ogueke, 2001). According to Yongling (2011), adsorption refrigeration cycle consists of four thermodynamic processes as shown in Figure1 (Clapeyron diagram).

For process 1 – 2:
The heat input to the adsorber bed (adsorbent together with the adsorbate trapped in its micro-pores) for isosteric heating (1 – 2) can be evaluated as (Yongling, 2011):

$$Q_{1-2} = (M_{ac}Cp_{ac} + M_{m1}Cp_m)(T_2 - T_1) \ldots (1)$$

Q_{1-2}–is the heat supplied to heat up activated carbon and methanol to condenser pressure.

For process 2 – 3:
The heat required for the isobaric desorption (2 – 3) is evaluated as follows (Yongling, 2011):

$$Q_{2-3} = (M_{ac}Cp_{ac} + M_{m.avr}Cp_m)(T_3 - T_2) + \Delta_x M_{ac}H_d \;....(2)$$

Q_{2-3} -is the heat supplied to heat up activated carbon and methanol that lead to desorption. $M_{m.avr}$ is the average mass of the adsorbate while H_d is the heat of desorption.

For process 3 – 4:
The heat removed from the adsorber bed (adsorbent together with the adsorbate trapped in its micro-pores) for isosteric cooling (3 – 4) by external source (ambient air or water from cooling system can be evaluated as (Yongling, 2011):

$$Q_{3-4} = (M_{ac}Cp_{ac} + M_{m3}Cp_m)(T_3 - T_4) \;...(3)$$

For process 4 – 1:
Energy that must be removed from the evaporator, Q_{ev}, is evaluated as the difference between the latent heat of vaporisation of the cycled adsorbate and the sensible heat of the adsorbate entering the evaporator at condensation temperature. This is given as (Yongling, 2011):

$$Q_{ev} = \Delta M_l[L_e - Cp_m(T_3 - T_4)] \;...(4)$$

The overall coefficient of performance (COP) can thus be determined from (Yongling, 2011):

$$C.O.P = \frac{Q_{ev}}{Q_{1-2} + Q_{2-3}} \;......(5)$$

Adsorptive properties of adsorbate/adsorbent pairs are usually determined by their correlation in terms pressure-temperature-concentration (P-T-X) relationship (Halder and Sarkar, 2007). Adsorption equilibrium is usually tested with Isotherm, Isobar (Yongling, 2011) and isosteric (Xia, 2008) methods. Data obtained from the experimental process are fitted in to any of the isotherm, isobar or isosteric equilibrium equations to be able to establish the properties of any adsorbent-adsorbate combination specific to adsorption refrigeration. In particular, the solid-vapour equilibrium is obtained from the Clausius-Clapeyron equation (Anyawu and Ogueke, 2001):

$$\frac{dP}{dT} = \frac{P.DH}{RT^2} \;......(6)$$

Where P is the vapour pressure, T is the absolute temperature and DH is the isosteric heat of adsorption per unit mass of adsorbent for the transition (kJ/kg).
Hence by integrating equation (6):

$$Log\ P = \frac{DH}{RT} + Constant \;....(7)$$

(Clapeyron Equation)
From the plot, we can estimate the isosteric heat of adsorption from the gradient of the equilibrium line (John, 2014).
This study therefore aims to measure and evaluate the performance of date-seed activated carbon as adsorbent in adsorption refrigeration system in comparison with commercial activated-carbon (Maxsorb III) in order to predict their respective relative coefficient of performance (COP) and hence determine the suitability or otherwise of using date-seed activated carbon as adsorbent in adsorption refrigeration systems.

MATERIALS AND METHODS

Methanol (99.8% purity) was obtained from Rembil Nig. Ltd (Kaduna, Nigeria) and was used as the adsorbate while 1 kg date-seed activated carbon, DSAC produced following method described by Abdulkadir *et al*. (2015) was used as adsorbent 1. Similarly, 1 kg of Industrial activated carbon, CAC (Maxsorb III) obtained from Rembil Nig. Ltd (Kaduna, Nigeria) was used as adsorbent 2. Adsorption equilibrium test rig (Figure 2) was used to carry out equilibrium studies as described by Ahmed and Shehata, (2015).

The refrigerant (Methanol) cylinder was first weighed. The pressure vessel containing 1 kg of the absorbent (Activated-Carbon) was immersed in oil contained in a temperature bath set at 30 ºC. The adsorbent samples were heated by heating the oil bath through an electrical heating element. Valve one (V_1) was open while valve two (V_2) was closed and the pressure vessel was first evacuated at 120 ºC using a vacuum pump. The pressure vessel was later allowed to cool. Valve one (V_1) was closed and a known mass (32.0×10^{-3} Kg/mole) of adsorbate (Methanol) was administered by opening valve two (V_2). The temperature of the vessel was raised in stages from 30 ºC to 160 ºC at an interval of 10 ºC and the corresponding pressure measured at each stage.
From standard table of properties:
Universal gas constant, $\boldsymbol{R_{universal}}$= 8.3144598 J / (mol.K)
Methanol (CH_4OH) Molecular Mass, $\mathbf{M_{methanol}}$ = 32.0×10^{-3}Kg/mole
Specific gas constant for Methanol, $\mathbf{R_{methanol}}$=8.3145/32.0 × 10^{-3}= 259.83 J/Kg.K.

Statistical Analysis

The Data obtained on pressure, temperature, and mass (P-T-X data) during the experiment for each of the adsorbent samples (DSAC and CAC) were used to predict operational performance of the adsorption cooling system using Clapeyron Equation (Equation 7).The plot of the relationship between P and T were presented graphically using excel spread sheet, Microsoft Office 2016. Two-Sample assuming equal variances T-test was used to analyse and determine whether there is significant deference between the variables.

RESULTS AND DISCUSSION

Table 1 presents comparison of DCAC and CAC pressure values. The p value p = 0.912 indicate that there is no significant difference between DSAC and CAC Pressure values.

Table 1: Comparison DCAC and CAC pressure values using T-Test

SAMPLES	PRESSURE (bar)	
	Mean	**Variance**
DCAC	2.54881	4.266365
CAC	2.636666667	4.424511111
***p*-value**	0.912069	
Significance Level (α)	0.05	

Figure 3 shows corresponding pressure and mass readings recorded at temperature interval of 10 ºC from 30 ºC to 160 ºC.

Figures 3 show a linear plot of **Log (P)** Vs **1/T** for both conventional activated carbon (CAC) and Date-seed activated carbon (DSAC), respectively.

Plot of the linear relationship between $logP$ and I/T were used to obtain the gradient of the equilibrium line and hence the isosteric heat of adsorption (ΔH) of the system is in line with findings of John(2013). Isosteric heat of adsorption has an inverse relationship with the Coefficient of performance (COP) (Anyanwu and Ogueke, 2005). The gradient of the linear plot for CAC and DSAC were found to be -61.8and -64.3respectively. Clapeyron equation assumes that the vapour phase behaves like perfect (ideal) gas and that the molar volume of the liquid phase is much smaller than the molar volume of the gas phase (Anyawu and Ogueke, 2005). Therefore, the Isosteric heat of adsorption for CAC (ΔH_{cac}) and DSAC(ΔH_{dsac}) are estimated to a first approximation to be 1605.8 and1665.0kJ/Kg respectively.

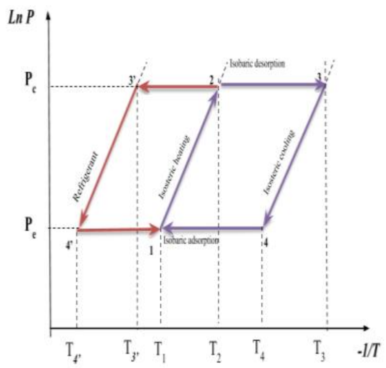

Figure 1: Clapeyron diagram of the ideal adsorption cycle (Abdulkadir *et al.*, 2015)

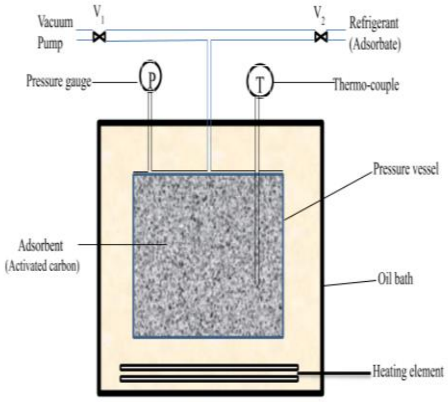

Figure 2: Adsorbent/adsorbate equilibrium test rig

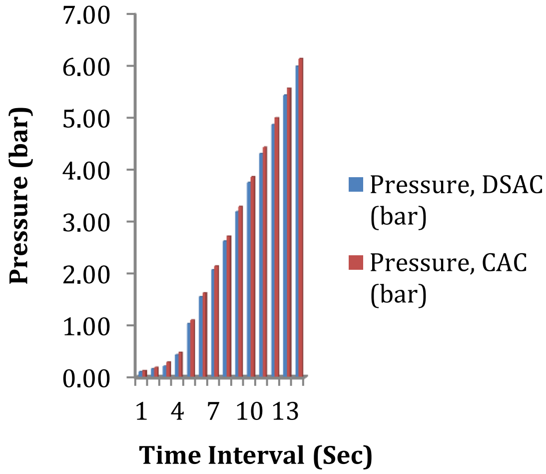

Figure 3: Pressure obtained with DSAC and CAC at the same methanol temperature and concentration level

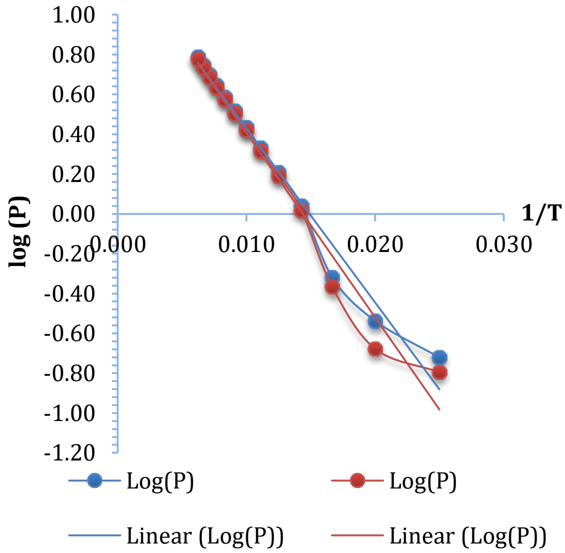

Figure 4: Gradients of linear plots between log (P) and 1/T for both CAC and DSAC

Ahmed and Shehata (2011) obtained DH_{ad} of 2800.0 kJ/Kg while Zeng *et al*. (2017) in obtained DH_{ad} of 1922.0 kJ/Kg. The DH_{ad} obtained from DSAC (1665.0 kJ/Kg) appeared to be lower than those obtained previously (Ahmed and Shehata, 2011; Zeng *et al*., 2017), suggesting possibility of DSAC/Methanol pair yielding a better COP.

Conventional activated Carbon (CAC) appears to require lower value of Isosteric heat of adsorption than the Date-seed activated carbon (DSAC). This is shown in figure 4 with the CAC having the lowest gradient (slope) of about 61.8. From the two linear plots for CAC and DSAC (having closed trend), it was observed that at pressure above atmospheric, the plot is perfectly linear obeying the Clapeyron-Clausius equation. This corresponds to temperatures above melting point of methanol. However, below this point (1 atm and 64.85 ^{o}C) the plots tend to slightly disobey the linearity (Clapeyron-Clausius equation). This is because of the presence of partial vacuum created initially before raising the temperature of both adsorbate/adsorbent pair. This is further indicated with the occurrence of negative values of log (P) below atmospheric pressure (partial vacuum). At one atmospheric (1 atm), log (P) becomes zero and gradually positively increases with further addition of heat.

Also, from Figure 4, at the initial stage (at lower temperatures) and the same working condition, CAC appear to require slightly lower energy to induce desorption of the adsorbate (Methanol) from the solid carbon (adsorbent). However, at higher temperatures close to the atmospheric boiling point of Methanol (65 ºC), the two adsorbents (CAC and DSAC) appear to have almost the same energy requirements to sustain desorption of the adsorbate (refrigerant). Also at the same working parameters, DSAC appear to have adsorbed 0.238 kg of Methanol per kg of activated carbon while CAC appear to have adsorbed 0.253kg of Methanol per kg of activated carbon. This by implication indicates that CAC tends to have a higher adsorption capacity than DSAC.

CONCLUSION

From the results obtained, the two adsorbents (CAC and DSAC) appear to have close and favourable energy requirements (16.058 and 16.650 kJ/Kg respectively) to sustain desorption of the adsorbate (refrigerant). Therefore, with its relative low cost and availability, date-seed activated carbon was found to have relatively good adsorptive properties/characteristics that could be used in adsorption refrigeration system.

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