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Research Paper

Adsorption isotherms and kinetics of HFC-404A onto bituminous based granular activated carbon for storage and cooling applications

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HIGHLIGHTS

- Experimental adsorption isotherms of GAC/HFC-404A have been investigated.
- D–A and Tóth models have been fitted with the experimental adsorption isotherms.
- Isosteric heat of adsorption has been presented.
- Adsorption kinetics have been investigated experimentally and theoretically.

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ABSTRACT

Adsorption characteristics of granular activated carbon/HFC-404A has been investigated in terms of adsorption isotherms and kinetics. AquaSorb 2000 which is bituminous based carbon has been used as an adsorbent. Experimentally and theoretical investigations have been conducted within temperature range of 25–75 °C. Experimental results have been fitted with Dubinin–Astakhov (D–A) and Tóth equations for the isotherms and linear driving force and Fickian diffusion models for the kinetics. It has been reported that maximum adsorption capacity is about 0.52 kg/kg. Activation energy and the pre-exponential coefficient were estimated to be 10488.49 J/mol and 1.11 respectively. Isosteric heat of adsorption as a function of relative adsorption capacity with non-ideal consideration has been also estimated using Clausius–Clapeyron equation and is found to vary from 145 to 330 kJ/kg. Pressure–tem perature–concentration diagram of the adsorption pair has been also presented.

1. Introduction

Saving energy using environment friendly applications are turning out to be one of the important research topics in the last years. 10–20% of the produced energy in the world goes to space cooling and heating applications [1,2]. Therefore, any decrease in the used energy in cooling and heating systems leads to a significant effect on the dependence of fossil fuel.

Adsorption phenomena have been improved to be used either in adsorption cooling applications or storing the unwanted gases such as high GWP gases. Adsorption cooling system powered by waste and/or renewable energy sources is one of possible alternatives to traditional mechanical vapor compression cooling systems in terms of environmental issues and energy saving [3,4]. These systems are simple, less moving mechanical parts, noiseless, low maintenance and have the ability to be driven by relatively low temperature heat sources or renewable energy sources, reducing the effects of global warming [5,6].

Over the past several decades, different adsorption cooling systems with different adsorbent–adsorbate pairs have been presented. For example, Exhaust gas-driven adsorption air conditioners [7–9], exhaust gas-driven adsorption ice makers [10,11] solar-powered adsorption air conditioners [12–14], and solar-powered adsorption ice makers [15,16] have been conducted.

Many studies have been carried out to investigate new adsorbent/refrigerant pairs and system designs [17–19]. Studying new

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Nomenclature

A	constant	P_s	saturation pressure, kPa
A_s	surface area, $m^2\ kg^{-1}$	R	universal gas constant, $kJ\ g^{-1}\ K^{-1}$
B	constant	Rp	particle radius of adsorbent, m
b	adsorption affinity, kPa^{-1}	T	temperature, K
b_o	adsorption affinity at infinite temperature, kPa^{-1}	t	micro pore distribution parameter
C	adsorbed amount, $kg\ kg^{-1}$	T_{ads}	adsorption temperature, K
C_o	maximum adsorbed amount, $kg\ kg^{-1}$	V	particle volume, m^3
D_s	surface diffusion, m^2 s	v_a	specific volume of adsorbed phase in $m^3\ kg^{-1}$
D_{so}	pre-exponential coefficient, m^2 s	V_{ads}	volume of the adsorption cell, m^3
E	characteristic energy, $kJ\ kg^{-1}$	v_f	specific volumes at liquid saturation phases in $m^3\ kg^{-1}$
E_a	activation energy, $kJ\ kg^{-1}$	v_g	specific volumes at vapor saturation phases in $m^3\ kg^{-1}$
F	constant	V_{load}	volume of the load cell, m^3
h_{fg}	heat of vaporization, $kJ\ kg^{-1}$	V_{pore}	volume of the micro pores of the adsorbent, m^3
H_{st}	isosteric heat of adsorption, $kJ\ kg^{-1}$	V_{tube}	volume of the connected tubes, m^3
m_{ads}	mass of adsorbent, kg	v_v	gas phase specific volume in $m^3\ kg^{-1}$
m_{load}	mass of refrigerant of load cell, kg	V_{void}	void volume, m^3
m_{void}	mass of refrigerant of void volume, kg	W_o	limiting uptake, $cm^3\ g^{-1}$
n	fitting parameter	α	thermal expansion coefficient, K^{-1}
P	pressure, kPa	ρ_{adsf}	density of refrigerant at final of adsorption, $m^3\ kg^{-1}$
P_f	final pressure, kPa	ρ_{adsi}	density of refrigerant at initial of adsorption, $m^3\ kg^{-1}$
P_i	initial pressure, kPa		

adsorption pairs are still needed to be should be investigated, and their characteristics in adsorption cooling should be defined accurately. A activated carbon particle either in a granular or powder forms has a porous structure of interconnected macrospores, mesopores, and micropores that makes it a good due to its high surface area [20]. Some studies of granular activated carbon have already been performed [21,22].

Forane 404A (HFC-404A) is a blend refrigerant developed as a substitute for HFC-22 and HFC-502 (HCFC/CFC blend refrigerant). It is a mixture of HFC-143a (44%), HFC-125 (44%) and HFC-134a (4%), and is a pseudo-azeotropic refrigerant. It has zero ODP, non-toxic, non-flammable (A_1) according to ASHRAE 2007. HFC-404A has been approved by many cooling systems manufacturers for using it in new refrigeration equipment, such as food display and storage cases.

Accurate information about thermo-physical properties and adsorption characteristics of activated carbon/HFC-404A are essential in designing either adsorption cooling system or a storage system for it [17]. These characteristics are isotherms, kinetics and isosteric heat of adsorption at different temperatures and pressures [23,24].

It is essential to estimate the adsorption kinetics in designing an adsorption system. Adsorption kinetics has also been studied by a respected number of researchers [25–28].

Linear driving force (LDF) and Fickian diffusion (FD) are famous models model in evaluating the kinetics parameters.

The present study presents an experimental investigation of adsorption isotherms and kinetics of HFC-404A onto granular activated carbon for cooling applications. Experiments have been conducted in a temperature range that could be useful for adsorption cooling applications.

2. Experimental section

2.1. Materials

AquaSorb 2000 granular activated carbon (supplied by Jacobi Company) has been used as adsorbent and HFC-404A used as adsorbate in adsorption isotherms and kinetics experiments. AquaSorb 2000 properties are summarized in Table 1. REFPROP9 software [29] has been used to provide properties of HFC-404A.

2.2. Experimental setup and description

Fig. 1 shows the schematic diagram of the experimental apparatus which comprises mainly of (i) an adsorber, (ii) an evaporator, (iii) constant temperature water bath, (iv) vacuumed pump, (v) water circulator, (vi) valves and (vii) data acquisition system connected to a personal computer. The adsorber is made of stainless steel tube of inner diameter 20 mm and 50 mm height. The evaporator is also made of stainless steel tube of inner diameter 30 mm and 100 mm height and functions as a liquid refrigerant reservoir. The adsorber contains 10 g of AquaSorb 2000, while the evaporator acts as a reservoir for HFC-404A. The adsorber and evaporator are installed inside a stainless steel water tank of 0.02 m^3 volume. To achieve a certain homogenous temperature ranging from 25 °C to 75 °C, a water circulator has been connected to the tank. A vacuum pump has been used in evacuating the whole apparatus before the beginning of each test.

2.3. Instrumentations

Temperatures of the adsorber and the evaporator are controlled by a water bath and a water circulator with ±0.5 °C accuracy. Temperatures of and the evaporator, adsorber, water tank, and connecting tubes are measured using a set of type K thermocouples. Thermocouples are calibrated by standard platinum resistance thermometer with ±0.1 °C accuracy. Pressure transducers

Table 1
Physical properties of AquaSorb 2000.

Parameter	Value
Pore volume ($cm^3\ g^{-1}$)	1.04
Surface area ($m^2\ g^{-1}$)	1050
Mean pore diameter (nm)	280
Amount in adsorption cell (g)	10
Density ($g\ cm^{-3}$)	0.48
Mass reduction during preparation from carbon (%)	8–11