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Research Paper

Experimental investigation of CO_2 adsorption onto a carbon based consolidated composite adsorbent for adsorption cooling application

Animesh Pal [a,b,e], Ibrahim I. El-Sharkawy [b,c], Bidyut Baran Saha [a,b,d,*], Skander Jribi [b,e], Takahiko Miyazaki [b,e], Shigeru Koyama [b,e]

[a] Kyushu University Program for Leading Graduate School, Green Asia Education Center, Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, Kasuga-koen 6-1, Kasuga-shi, Fukuoka 816-8580, Japan
[b] International Institute for Carbon-Neutral Energy Research (WPI-I2CNER), Kyushu University, 744 Motooka, Nishi-ku, Fukuoka 819-0395, Japan
[c] Mechanical Power Engineering Department, Faculty of Engineering, Mansoura University, El-Mansoura 35516, Egypt
[d] Mechanical Engineering Department, Kyushu University, 744 Motooka, Nishi-ku, Fukuoka 819-0395, Japan
[e] Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, Kasuga-koen 6-1, Kasuga-shi, Fukuoka 816-8580, Japan

HIGHLIGHTS

- Adsorption of CO_2 onto consolidated composite adsorbent has been experimentally investigated.
- Experiments have been conducted at temperatures 30, 50 and 70 °C and pressures up to 7 MPa.
- This study presents original data of CO_2 adsorption uptake onto consolidated composite adsorbent.
- Three isotherm models have been used to correlate the measured isotherms data.
- Estimated thermodynamic parameters are important for further development of CO_2 based adsorption cooling systems.

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ABSTRACT

Adsorption of carbon dioxide onto highly porous activated carbon based consolidated composite adsorbent has been experimentally investigated. Experiments have been conducted at temperatures of 30, 50, 70 °C and pressures up to 7 MPa using magnetic suspension adsorption measurement unit. The innovative adsorption isotherms data have been correlated using three isotherm models namely, Langmuir, Tóth, and modified Dubinin-Astakhov (D-A). The studied models successfully fitted with the experimental data and Tóth isotherm model shows a better fitting. Results showed that the volumetric adsorption capacity of CO_2 onto the studied consolidated composite is higher than that of CO_2 onto parent activated carbon powder (Maxsorb III). The isosteric heat of adsorption of the studied pairs has been calculated from isotherm data. The performance of ideal adsorption cooling cycle, employing consolidated composite adsorbent/CO_2 pair, has also been simulated at three different evaporator temperatures, namely 5, 10 and 15 °C along with a coolant temperature of 25 °C and heat source temperatures ranging from 45 to 90 °C. The estimated thermodynamic parameters and isotherm data are important for further development of CO_2 based adsorption cooling systems.

1. Introduction

Utilization of HCFCs and HFCs in heat pump systems leads to an increase in environmental temperature as these have high global warming potential (GWP). According to the Paris agreement in December 2015, the goal is to hold the increase in the global average temperature to well below 2 °C [1]. Accordingly, research and development on the utilization of natural and/or alternative refrigerants in heat pump systems has been intensified. Studies showed that adsorption heat pump system can utilize natural or alternative refrigerants and it can be driven by waste heat or solar heat of temperature below 100 °C [2–15]. Among all natural refrigerants, carbon dioxide (CO_2) offers a number of advantages including excellent thermo-physical properties, high volumetric capacity. Moreover, it is a non-toxic, nonflammable refrigerant having zero ODP and GWP as low as 1. Therefore, it is suitable for adsorption cooling applications where the flammability and toxicity of ammo-

* Corresponding author at: International Institute for Carbon-Neutral Energy Research (WPI-I2CNER), Kyushu University, 744 Motooka, Nishi-ku, Fukuoka 819-0395, Japan.
E-mail address: saha.baran.bidyut.213@m.kyushu-u.ac.jp (B.B. Saha).

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Nomenclature

A	adsorption potential [kJ mol^{-1}]
b_o	equilibrium constant [–]
C	adsorption uptake [kg kg^{-1}]
C_o	saturated amount adsorbed [kg kg^{-1}]
c_p	specific heat capacity [kJ kg^{-1} k^{-1}]
CE_v	cooling effect per unit volume [MJ m^{-3}]
COP	coefficient of performance [–]
E	adsorption characteristic energy [kJ mole^{-1}]
k	fitting parameter of modified D-A equation [–]
n	exponential parameter of D-A equation [–]
P	equilibrium pressure [MPa]
P_s	saturated pressure [MPa]
Pc	pressure at critical point [MPa]
q	heat input [kJ kg^{-1}]
Q	isosteric heat of adsorption [kJ mol^{-1}]
R	universal gas constant [J mol^{-1} K^{-1}]
SCE	specific cooling effect [kJ kg^{-1}]
T	temperature [K]
T_C	temperature at critical point [K]
t	heterogeneity factor [–]
V_m	molar volume [cm^3 g^{-1}]
V_t	specific volume of liquid carbon dioxide [cm^3 g^{-1}]
W	volumetric adsorption uptake [cm^3 g^{-1}]
W_o	maximum volumetric adsorption capacity [cm^3 g^{-1}]
ΔH	vaporization enthalpy [kJ mol^{-1}]

Subscripts

ad	adsorbent
cond	condenser
evap	evaporator
max	maximum
min	minimum
ref	refrigerant
reg	regeneration
s	saturation
sens	sensible

Greek symbol

α	thermal expansion of the adsorbed gas [K^{-1}]

nia and hydrocarbons refrigerants for example, may be a problem. Besides, adsorption cooling systems using CO_2 as refrigerant are not limited only to cooling and air-conditioning applications above 0 °C like those using water, but can be applied for freezing and ice-making applications.

Adsorption isotherm and isosteric heat of adsorption are important in order to investigate the performance of CO_2 based adsorption cooling systems. Saha et al. [10] studied adsorption isotherms of CO_2 onto highly porous activated carbon (AC) fiber of type A-20 and AC powder of type Maxsorb III. The authors found that the Tóth and modified Dubinin-Astakhov (D-A) isotherms well matched with the experimental data within ±5% root-mean-square deviation. Guo et al. [16] investigated adsorption of CO_2 on raw AC and three modified AC samples at temperatures ranging from 303 to 333 K. They found that Dubinin-Radushkevich (D-R) and Freundlich adsorption models were the best fitted models with the adsorption data on carbon samples. Singh and Kumar [17] measured adsorption isotherms in the pressure range of 0–45 bar at various temperatures using Sievert's type experimental setup. Experimental data of CO_2 adsorption isotherms were modelled using Langmuir and D–A isotherm models and found that D–A model was well matched with the experimental data. Himeno et al. [18] experimentally conducted adsorption of CO_2 onto five microporous ACs at different temperatures and pressure ranges using a static volumetric apparatus. The experimental data were associated using the Tóth model and the D-A model. Shen et al. [19] measured CO_2 adsorption gravimetrically at different temperatures and pressures ranges on pitch-based AC beads. They showed that experimental data were best fitted with the Virial isotherm model at low and high pressures, whereas the multisite Langmuir model only fits well with at low pressures. However, activated carbon of type powder and fiber suffers are prone to low thermal conductivity.

Recently, several researchers have reported that consolidated composites adsorbents can enhance the heat transfer inside the adsorber unit [20–26]. From the above perspective, the present authors have been experimentally investigated the adsorption of carbon dioxide onto highly porous activated carbon based consolidated composite adsorbent. Notable contributions presented in this article are:

(1) Consolidated composite has been synthesized by the authors.
(2) Carbon dioxide (CO_2) is used as a refrigerant.
(3) Adsorption isotherm data of CO_2 onto the developed composite adsorbent are original.
(4) Isosteric heat of adsorption data are calculated from the isotherm data.
(5) Ideal cooling cycle performance and effect of packing density of composite adsorbent on volumetric cooling capacity have been discussed.

2. Experiments

2.1. Materials

The material used in the present study is consolidated composite adsorbent. It has been prepared by mixing a highly porous activated carbon powder (ACP) namely Maxsorb III, binder, water, and expanded graphite (EG) with certain ratios. The binder used in this study is Polyvinyl alcohol (PVA) supplied by Kanto Chemical Co., Inc., Japan. Maxsorb III is supplied by Kansai Coke & Chemicals Co. Ltd., Japan whilst expanded graphite (EG) type EC500 is provided by Ito Graphite Industries Co., Ltd., Japan. Synthetization of consolidated composite adsorbents can be elucidated as follows; Maxsorb III and EC500 are dried in the oven at a temperature of 120 °C for 6 h to remove the moisture content. Secondly, PVA has been mixed with water to make it solvent. Maxsorb III and EC500 powder mixture are then added to the water-binder solvent. After that the mixer of Maxsorb III, binder, water and EC500 is compressed using a pressing machine at pressure of 34 MPa. Lastly, the consolidated sample is dried in the oven at the temperature of 120 °C about 10 h to remove water. Adsorbent used in this study is comprised of 70% Maxsorb III, 20% EC500, and 10% binder. The dry sample mass is 208 mg, height is 1.9 mm, and 17 mm diameter with 480 kg m^{-3} packing density. The photograph of prepared consolidated composite is shown in Fig. 1. The total surface area and micropore volume of a sample with similar composition (70% Maxsorb III, 20% EC500, and 10% binder) are 2000 m^2 g^{-1} and 1.094 cm^3 g^{-1}, respectively [20].