VOL. 11, NO. 20, OCTOBER 2016 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

THERMODYNAMIC ANALYSIS OF ADSORPTION COOLING CYCLE USING CONSOLIDATED COMPOSITE ADSORBENTS - ETHANOL PAIRS

Animesh Pal[1,2,5], Ibrahim I. El-Sharkawy[2,3,4], Bidyut Baran Saha[1,2,] , Khairul Habib[6], Takahiko Miyazaki[2,4] and Shigeru Koyama[2,4,5]
[1]Kyushu University Program for Leading Graduate School, Green Asia Education Center, Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, Fukuoka, Japan
[2]International Institute for Carbon-Neutral Energy Research, Kyushu University, Fukuoka, Japan
[3]Mechanical Power Engineering Department, Faculty of Engineering, Mansoura University, El-Mansoura, Egypt
[4]Faculty of Engineering Sciences, Kyushu University, Fukuoka, Japan
[5]Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, Fukuoka, Japan
[6]Department of Mechanical Engineering, Universiti Teknologi Petronas, Perak Darul Ridzuan, Malaysia
E-Mail: saha.baran.bidyut.213@m.kyushu-u.ac.jp

ABSTRACT

This study deals with the thermodynamic analysis of adsorption cooling cycle using consolidated composite adsorbents-ethanol pairs. The studied composites are named as composite A (50% Maxsorb III, 40% expanded graphite (EG), 10% binder) and composite C (70% Maxsorb III, 20% expanded graphite (EG), 10% binder). The Dubinin-Radushkevich (D-R) and Dubinin Astakhov (D-A) equation are used to draw pressure-temperature-concentration (P-T-W) diagrams of the assorted pairs. The specific cooling effect (SCE) and coefficient of performance (COP) of both pairs have been simulated for desorption temperatures ranging from 40 to 90 ºC at different evaporator temperatures along with a heat sink at 30 ºC by considering a time independent thermodynamic model. The maximum COPs of composite A-ethanol and composite C-ethanol based cooling systems are found to be 0.69 and 0.765, respectively.

Keywords: consolidated composite adsorbent, adsorption cooling system, ethanol, performance evaluation.

INTRODUCTION

Adsorption cooling systems have attracted much attention in the last two decades as it can be driven by low temperature waste heat and can utilize environmentally friendly adsorbents-refrigerants pairs such as silica gel-water, activated carbon (AC) fibers-ethanol, and AC powder-ethanol [1-8]. However, the main difficulty for spreading this technology is the poor system performance and bulkiness that is due to the limitation of sorption capacity and low heat transfer rate inside the adsorber/desorber reactors.

Enhancement of heat and mass transfer rate inside absorber bed could be one of the possible methods to enhance the system performance and size reduction. Recently, several notable researchers have been focused on composite material in order to improve the system performance. Following are some representative examples; El-Sharkawy *et al*. [9] prepared consolidated composite adsorbents and experimentally investigated the adsorption uptake and thermal conductivities. Authors reported the thermal conductivity of composite adsorbents showed up to 11 times than that of Maxsorb III. Cacciola *et al*. [10] developed adsorbent materials as a block using polytetrafluorethylene binder and AC. Results showed effective thermal conductivity ranging between 0.13 and 0.20 W m^{-1} K^{-1}. Jin *et al*. [11] studied consolidated AC with chemical binder, and consolidated AC with expanded natural graphite. The thermal conductivity of granular AC with different sizes almost maintains a constant at 0.36 Wm^{-1} K^{-1}, while the value modestly increases to 0.40 Wm^{-1} K^{-1} for the consolidated AC with chemical binder. Zhao *et al*. [12] used granular AC with thermal conductivity is 0.16 Wm^{-1} K^{-1}. Results showed that with the addition of ENG-TSA, the thermal conductivity of composite AC is increased significantly.

This study aims to evaluate the performance of an ideal adsorption cooling cycle in terms of SCE and COP using consolidated composite adsorbents-ethanol pairs for further improvement of adsorption cooling cycle.

NOMENCLATURE

Cp	specific heat (kJ kg^{-1} K^{-1})
COP	coefficient of performance (-)
E	adsorption characteristics (kJ kg^{-1} K^{-1})
LH	latent heat (kJ kg^{-1} K^{-1})
n	exponent of D-A equation
P	equilibrium pressure (kPa)
P_s	saturation pressure (kPa)
R_g	gas constant (kJ kg^{-1} K^{-1})
T	temperature (K or °C)
Q_h	heat added (kJ kg^{-1})
Q_{st}	heat of adsorption (kJ kg^{-1})
SCE	specific cooling effect (kJ kg^{-1})
Ts,a	temperature at the starting of adsorption (°C)
Te,a	temperature at the end of adsorption (°C)
Ts,d	temperature at the starting of desorption (°C)
Te,d	temperature at the end of desorption (°C)
W	adsorption uptake at equilibrium (kg kg^{-1})
W_0	maximum adsorption uptake (kg kg^{-1})

Subscripts

ad	adsorbent
c	condenser
e	evaporator

ref	refrigerant
s	saturation
sens	sensible
max	maximum
min	minimum

ADSORPTION COOLING CYCLE

The schematic diagram of adsorption cooling system and the thermodynamic processes of a basic adsorption cycle are shown in Figures-1(a) and 1(b), respectively. It consists of an evaporator, a condenser, an adsorber/desorber, and a throttling valve or a bending capillary tube, which is used to connect the condenser and the evaporator. As can be seen from Figure-1(b) the ideal cycle consists of four steps, which are pre-heating, desorption process, pre-cooling, and adsorption process. In the first step, the adsorber is disconnected from both the evaporator and the condenser. It is then heated by external heat source at constant refrigerant concentration, which results in the temperature increase of refrigerant from Te,a to Ts,d. The adsorber pressure increases from the evaporating pressure up to the condensing pressure. In the second step, adsorber is connected to the condenser and the heat added from external source continues in this process. The refrigerant vapor is desorbed at constant pressure, Pc, while the temperature increases until it reaches the desorption temperature, Te,d. The desorbed refrigerant vapour is liquefied in the condenser and the condensing heat is removed by coolant of temperature Tc that flows inside the condenser heat transfer tubes. In the pre-cooling process, the adsorber is isolated from both the evaporator and the condenser. It is then cooled down at constant refrigerant concentration from Te,d to Ts,a by coolant. The pressure of the adsorber decreases from condenser pressure down to the evaporator pressure. In the last step, the adsorber is connected to the evaporator and adsorb the refrigerant vapour from the evaporator. During the adsorption process the adsorber is cooled from Ts,a to Te,a. Adsorption heat is removed by coolant that flows inside the adsorber.

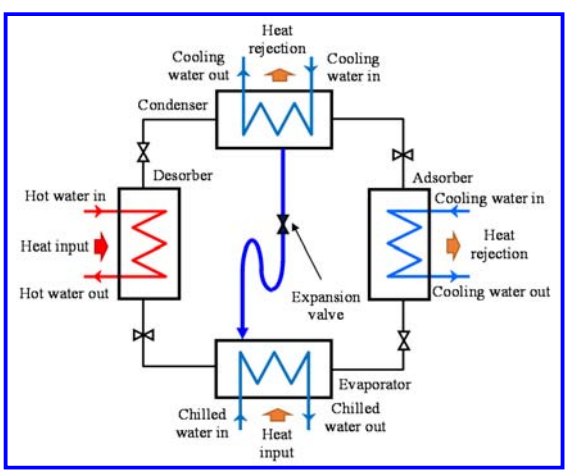

Figure-1(a). Schematic diagram of basic adsorption cooling system.

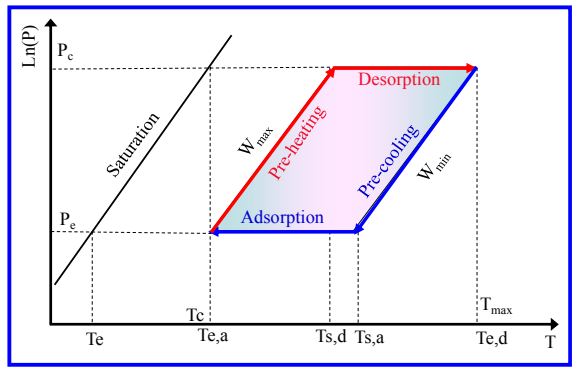

Figure-1(b). Thermodynamic process of the basic adsorption cooling cycle.

THERMODYNAMIC FRAMEWORK

In this study two types of consolidated composite adsorbents have been used, namely composite A, and composite C for investigating the performance of ideal adsorption cooling cycle. Composite A comprises of 50% Maxsorb III, 40% EG, 10% binder whilst composite C contains 70% Maxsorb III, 20% EG, 10% binder. The preparation process; porous properties; adsorption uptake measurement procedure; and thermal conductivities of these adsorbents can be found in El-Sharkawy *et al*. [9]. Dubinin Radushkevich (D-R) and Dubinin Astakhov (D-A) equations are used, respectively, to fit adsorption uptakes of composite A and composite C as written by Equation. (1) and Equation. (2) below. The estimated fitting parameters reported by El-Sharkawy *et al*. [9] are furnished in Table-1.

$$W = W_0 \exp\left[-\left(\frac{R_g T}{E}\ln\left(\frac{P_s}{P}\right)\right)^2\right] \tag{1}$$

$$W = W_0 \exp\left[-\left(\frac{R_g T}{E}\ln\left(\frac{P_s}{P}\right)\right)^n\right] \tag{2}$$

Specific cooling effect (SCE) can be defined as the following equation:

$$SCE = \left(W_{\max} - W_{\min}\right)\left[LH - \int_{Te}^{Tc} Cp_{ref}\, dT\right] \tag{3}$$

The coefficient of performance (COP) can be written as: $COP = \dfrac{SCE}{Q_{sens} + Q_{latent}}$ (4)

where,

$$Q_{sens} = \int_{Te,a}^{Te,d} Cp_{ad}\, dT + W_{\max}\int_{Te,a}^{Ts,d} Cp_{ref}\, dT + \int_{Ts,d}^{Te,d} WCp_{ref}\, dT \tag{5}$$

and, $Q_{latent} = Q_{st}\int_{W_{\max}}^{W_{\min}} dW$ (6)

VOL. 11, NO. 20, OCTOBER 2016 ISSN 1819-6608
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Table-1. Fitting parameters of D-R and D-A equation of studied composite adsorbents-ethanol pairs [9].

Composite	W_0 [kg kg^{-1}]	E [kJ kg^{-1}]	n [-]
A: 50% Maxsorb III, 40% EG, 10% binder	0.61	125	2
C: 70% Maxsorb III, 20% EG, 10% binder	0.89	119	1.8

In Equation (5), the first term defines the sensible heat added to the adsorbent consequently its temperature increases from Te,a to Te,d whilst the second and third terms are represented sensible heat added to the refrigerant during pre-heating and the desorption process, respectively. The specific heat capacity of adsorbent (Cp_{ad}) is calculated according to El-Sharkawy *et al.* [9] and has been taken constant for the range of temperature utilized. Q_{st} is the heat of adsorption in Equation. (6). Clausius–Clapeyron equation (Equation. 7) is used to compute the average value of heat of adsorption. It is found that value of the average heat of adsorption (Q_{st}) for the composite A and composite C are 995 kJ kg^{-1} and 960 kJ kg^{-1}, respectively.

$$Q_{st(W=\text{constant})} = \frac{-R_g \partial \ln P}{\partial\left(\frac{1}{T}\right)} \quad (7)$$

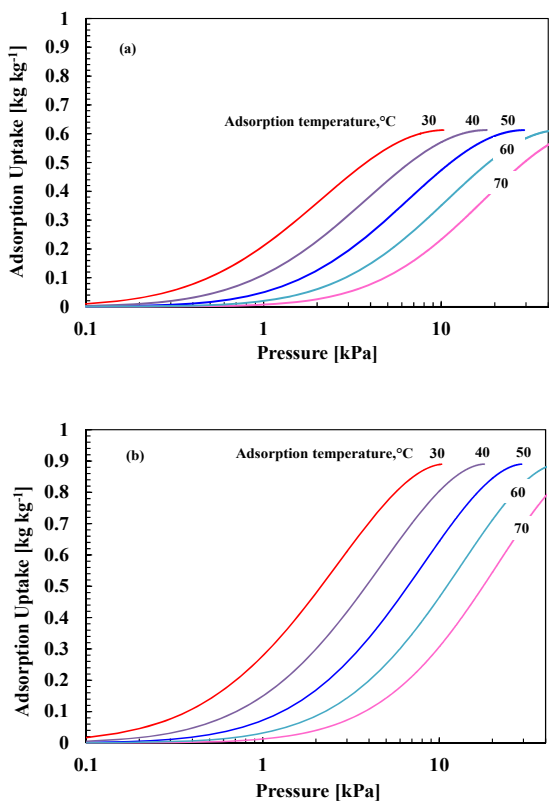

Figure-2. Predicted adsorption isotherms of (a) composite A-ethanol pair, and (b) composite C-ethanol pair.

RESULTS AND DISCUSSIONS

The adsorption isotherms as shown in Figures-2. a-2.b for composite A-ethanol pair and composite C-ethanol pair are predicted from measured data, where experiments have been conducted at three evaporator temperatures of 5, 10, and 15°C whilst changing the adsorption temperature from 20 to 70 °C [9]. The pressure-temperature-concentration (P-T-W) diagram is used to analysis the performance of an ideal adsorption cooling cycle. It shows the thermodynamic relation between the equilibrium pressure, adsorbent temperature and adsorption capacity at equilibrium conditions. The D-R equation has been used to draw the P-T-W diagram of composite A-ethanol pair, whilst D-A equation is used to draw the P-T-W diagram of composite C-ethanol pair, which are shown in Figure-3.a and Figure-3.b, respectively. Figures-4.a-4.b show the effect of desorption temperature on the SCE of composite A-ethanol and composite C-ethanol pair, respectively, at different evaporator temperatures, namely 3, 7, 10 and 15 °C. It is seen that the SCE increases linearly with the increases of desorption temperature. This is due to the increases of concentration difference with the increases of desorption temperature at constant adsorption and evaporator temperatures.

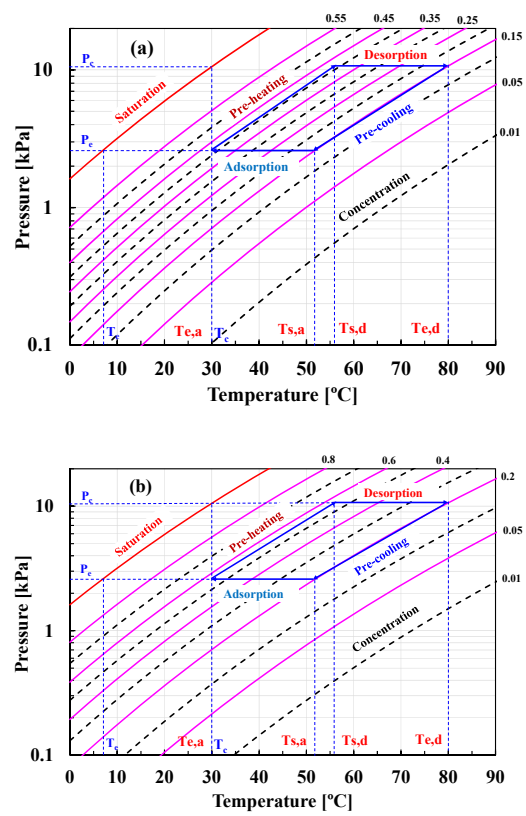

Figure-3. P-T-W diagram of (a) composite A-ethanol pair, and (b) composite C-ethanol pair.

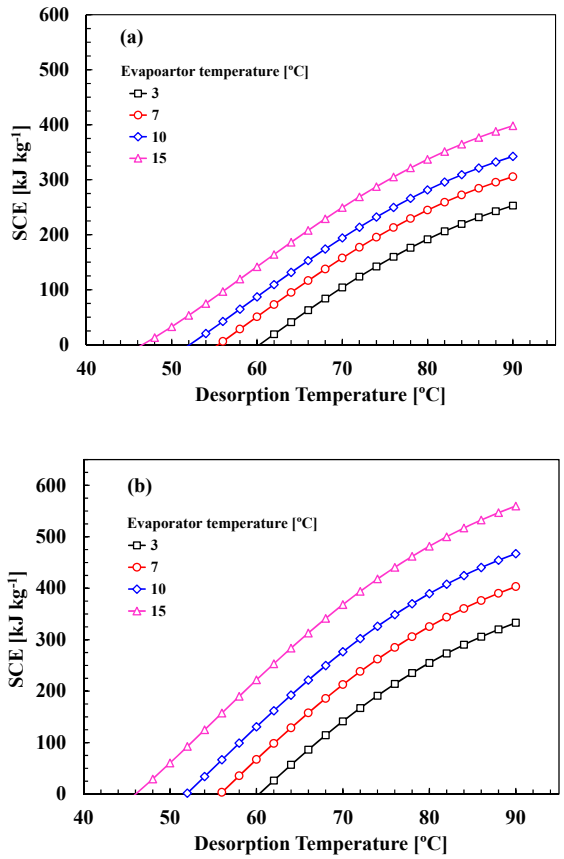

Figure-4. Specific cooling effect (SCE) of (a) composite A, and (b) composite C with function of desorption temperature.

It is observed that consolidated composite A-ethanol adsorption cycle can achieve SCE as about 398 kJ kg^{-1} at evaporation 15 ºC along heat source 90 ºC whilst composite C-ethanol pair gives about 560 kJ kg^{-1}. Figures-5.a-5.b show the effect of desorption temperature on COP of both pairs, respectively. It can be seen that the COP increases sharply only when the desorption temperature is below 70 °C. After that, the increase in COP is marginal even though the SCE increases. This happens due to the requirement of heat input becomes significantly large when the temperature difference between heat source and heat sink is relatively high. The maximum COPs of composite A-ethanol and composite C-ethanol based cooling systems are found to be 0.69 and 0.765, respectively. In addition, both consolidated composite adsorbents show much higher thermal conductivity compared to parent material Maxsorb III, which is reported by El-Sharkawy *et al*. [9].

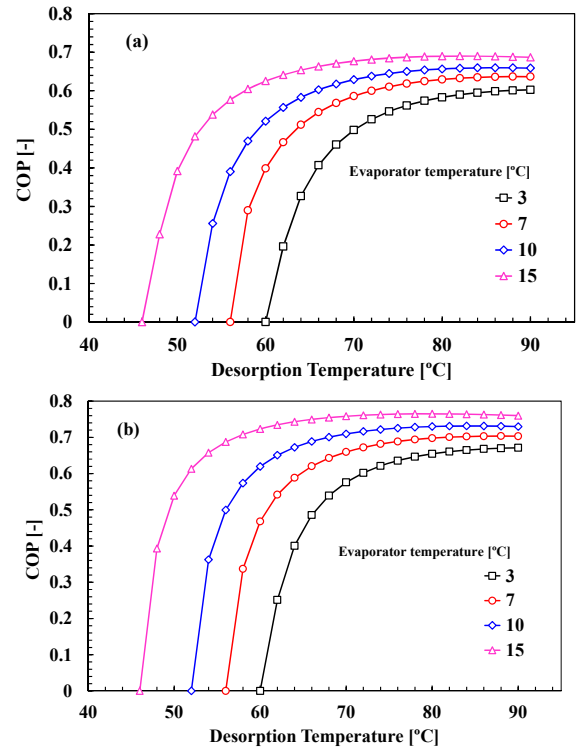

Figure-5. Effect of desorption temperature on COP for (a) composite A, and (b) composite C.

CONCLUSIONS

The ideal adsorption cooling cycle based on consolidated composite, namely, composite A and composite C, adsorbents-ethanol pairs has been investigated. The Dubinin-Radushkevich (D-R) and Dubinin Astakhov (D-A) equations have been used to draw P-T-W diagrams of the assorted pairs. The specific cooling effect (SCE) and coefficient of performance (COP) of both pairs have been estimated for desorption temperatures ranging from 40 to 90 ºC at different evaporator temperatures along with a heat sink at 30 ºC. It is found that consolidated composite A-ethanol adsorption cycle can achieve SCE and COP as about 398 kJ kg^{-1} and 0.69, respectively, at evaporation 15 ºC along heat source 90 ºC whilst composite C-ethanol pair gives about 560 kJ kg^{-1} and 0.765. Both pairs show high SCE and COP with much higher thermal conductivity compared to Maxsorb III, which may lead to compact design of adsorption cooling systems.

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