

Thermodynamic Analysis of Activated Carbon-CO₂ based Adsorption Cooling Cycles

Skander Jribi, Anutosh Chakraborty, Ibrahim I. El-Sharkawy, Bidyut Baran Saha*, Shigeru Koyama

Abstract—Heat powered solid sorption is a feasible alternative to electrical vapor compression refrigeration systems. In this paper, activated carbon (powder type Maxsorb and fiber type ACF-A10)-CO₂ based adsorption cooling cycles are studied using the pressure-temperature-concentration (*P-T-W*) diagram. The specific cooling effect (SCE) and the coefficient of performance (COP) of these two cooling systems are simulated for the driving heat source temperatures ranging from 30 °C to 90 °C in terms of different cooling load temperatures with a cooling source temperature of 25 °C. It is found from the present analysis that Maxsorb-CO₂ couple shows higher cooling capacity and COP. The maximum COPs of Maxsorb-CO₂ and ACF(A10)-CO₂ based cooling systems are found to be 0.15 and 0.083, respectively. The main innovative feature of this cooling cycle is the ability to utilize low temperature waste heat or solar energy using CO₂ as the refrigerant, which is one of the best alternative for applications where flammability and toxicity are not allowed.

Keywords—Activated carbon, Adsorption cooling system, Carbon dioxide, Performance evaluation.

I. INTRODUCTION

IN the present context, where vapor compression cycles are questioned due to environmental concerns and restrictions, solid-gas sorption heat powered cycles appear to be an attractive alternative for cooling or air conditioning applications. Solid-gas systems present the advantage of being absolutely benign for the environment: zero ODP (Ozone Depletion Potential) as well as zero GWP (Global Warming Potential). The solid sorption system utilizing carbon dioxide as adsorbate not only possesses the advantage of no ODP and negligible GWP for refrigeration and air conditioning but also possesses the advantages of operating with solar thermal energy or waste heat. Many authors investigated the performances of adsorption cooling cycles for various adsorbent-refrigerant pairs experimentally as well as theoretically, and these are (i) silica gel-water [1]-[2], (ii) zeolite-water [3]-[4], (iii) activated carbon-ammonia [5]-[6]-[7], (iv) activated carbon-methanol [8]-[9], etc. Multi-stage adsorption cooling cycles have also been developed and analyzed [10]-[11] for utilizing waste heat as low as near

room temperature, and in this context, two-bed adsorption chillers using silica gel-water pair have already been commercialized [12].

Carbon dioxide has been used as a refrigerant in vapor compression systems for over a century, but it is only in the last decade that inventive minds and modern techniques have found new ways to exploit the uniquely beneficial properties of this remarkable substance. CO₂ is a non-toxic and non-flammable natural refrigerant with a zero ODP and a negligible GWP. The use of CO₂ for solid sorption system is attractive and interesting. The aims of this paper are to describe the working principles of CO₂ based adsorption cooling cycles and calculate their performances in terms of cooling capacity and COP, which are developed from the rigor of classical thermodynamics and experimentally measured adsorption isotherms data [13].

II. ADSORPTION COOLING CYCLE

The adsorption cooling process utilizes the adsorbent-adsorbate characteristics and produces cooling at the evaporator by the combination of “adsorption-triggered-evaporation” and “desorption-resulted-condensation”. Fig. 1 shows the schematic layout of the adsorption cooling system that comprises the evaporator, the reactor or bed for thermal compression and the condenser. In this system, pitch-based activated carbon (Maxsorb) and activated carbon fiber (type A10), and CO₂ are used as adsorbents and refrigerant. For continuous cooling operation, firstly a low-pressure refrigerant (hence CO₂) is evaporated at the evaporator due to external cooling load and is adsorbed into the solid adsorbent located in the adsorber at evaporator pressure (P_e). The process of adsorption results in the liberation of heat of adsorption at the adsorber providing a useful heat energy output and a cooling effect in the condenser/evaporator heat exchanger. Secondly, the adsorbed bed is heated by the external heat source and the refrigerant is desorbed from the adsorbent and goes to the condenser at condenser pressure (P_c) for condensation by pumping heat through the environment. The condensate (refrigerant) is refluxed back to the evaporator via a pressure reducing valve for maintaining the pressure difference between the condenser and the evaporator. Pool boiling is affected in the evaporator by the vapor uptake at the adsorber, and thus completing the refrigeration close loop or cycle.

Manuscript received June 30, 2008.

Authors are with the Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, Kasuga-koen 6-1, Kasuga-shi, Fukuoka 816-8580, Japan (*Corresponding author: +81-92-583-7382; fax: +81-92-583-7833; e-mail: bidyutb@cm.kyushu-u.ac.jp).

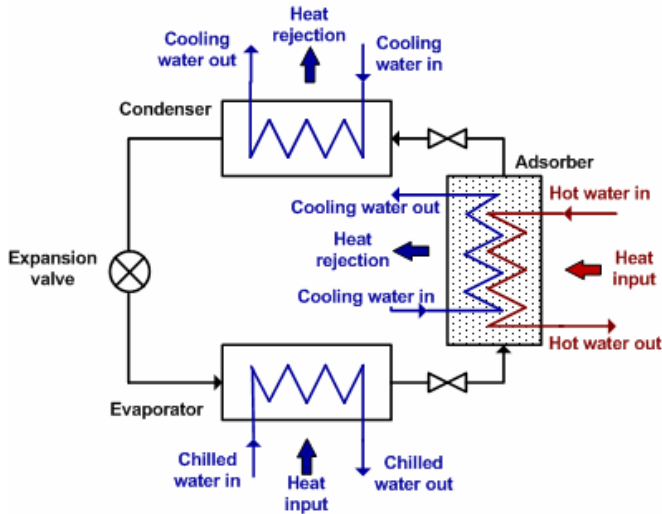


Fig. 1 Schematic diagram of the basic adsorption cooling cycle

III. THERMODYNAMIC FRAMEWORK

As the adsorption cooling system is based on the energetic performances of adsorbant-refrigerant pairs, the adsorption isotherms are used to evaluate the amount of adsorbate uptake and offtake during adsorption/desorption processes. In the present analysis, we have used Tóth isotherm equation to calculate the amount of CO₂ adsorbed on to Maxsorb and ACF-A10 as a function of pressure and temperature, and this is given by:

$$W = \frac{W_0 b P}{(1 + (bP)^t)^{1/t}}, \quad (1)$$

where W is the amount adsorbed, P is the equilibrium pressure, T indicates the temperature, W_0 represents the saturated amount adsorbed, b the affinity that depends on temperature, and t the heterogeneity factor. It is found from the present analysis that Maxsorb contains about 3 times higher CO₂ uptake comparing to A10.

The performances analyses of an ideal adsorption cooling system as time independent are as follows:

The specific cooling effect (SCE) is given by:

$$SCE = (W_{\max} - W_{\min}) \left[LH_{Te} - \int_{Te}^{Tc} Cp_{ref} dT \right], \quad (2)$$

where W_{\max} indicates the amount of adsorbate uptake as a function of adsorption temperature and evaporation pressure, W_{\min} defines the amount of adsorbate during desorption at the desorption temperature and condenser pressure, LH_{Te} represents the latent heat of evaporation at the cooling load temperature and Cp_{ref} shows the specific heat capacity of liquid CO₂. The coefficient of performance (COP) can be defined as:

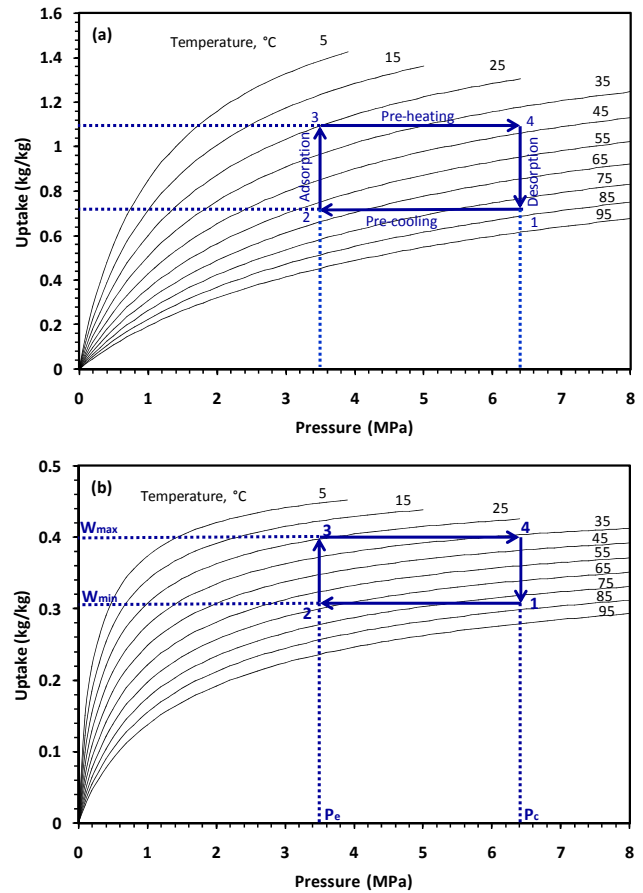


Fig. 2 Adsorption isotherms of CO₂ in (a) Maxsorb and (b) ACF-A10

$$COP = \frac{SCE}{Q_h}, \quad (3)$$

Where Q_h is the heat added from sensible and latent heats and expressed as:

$$Q_h = Q_{sens} + Q_{Latent}, \quad (4)$$

Q_{sens} is the sensible heat added to the (i) adsorbent resulting from the increase of its temperature from $T_{e,a}$ to $T_{e,d}$, and (ii) refrigerant per kilogram of adsorbent during the pre-heating and the desorption phases.

$$Q_{sens} = \int_{T_{e,a}}^{T_{e,d}} Cp_{ad} dT + W_{\max} \int_{T_{e,a}}^{T_{s,d}} Cp_{ref} dT + \int_{T_{s,d}}^{T_{e,d}} W Cp_{ref} dT, \quad (5)$$

In the present analysis, the specific heat capacity of adsorbent (Cp_{ad}) was taken a constant for the range of temperature utilized. A value of 1.375 for Maxsorb [14] and 1.05 kJ.kg⁻¹.K⁻¹ for the ACF-A10 [15] had been used. The specific heat capacity of refrigerant (Cp_{ref}) of CO₂ is taken function of temperature and the full integration is carried.

Q_{Latent} is the latent heat of the adsorption cooling cycle given by:

$$Q_{Latent} = q_{st} \int_{W_{max}}^{W_{min}} dW, \quad (6)$$

Where q_{st} is the Clausius-Clapeyron heat of adsorption expressed by:

$$q_{st(W)} = \frac{-R\partial(\ln P)}{\partial\left(\frac{1}{T}\right)}, \quad (7)$$

An average value of the isosteric heat of adsorption is taken 522.7 kJ.kg^{-1} and 697.7 kJ.kg^{-1} for the Maxsorb-CO₂ pair and A10-CO₂ pair, respectively.

per unit mass of adsorbent generated from adsorption isotherm equation (1). This diagram provides a simple prediction of the performances of the ideal adsorption cooling cycle. The Maxsorb-CO₂ diagram and A10-CO₂ diagram are presented in Figs. 3 (a) and (b), and the adsorption cooling cycle processes are super-imposed therein.

The effects of regeneration temperatures, $T_{e,d}$, on the SCE at four different evaporator temperatures, namely 0, 5, 10, and 15 °C are presented in Figs. 4 (a) and (b) for Maxsorb-CO₂ and A10-CO₂ based cooling cycles, respectively. The SCE increases linearly with the increase of regeneration temperatures as $W_{max}-W_{min}$, i.e. the difference between minimum and maximum concentrations, increases. As a result, the higher SCE is obtained. In fact, $W_{max}-W_{min}$ for Maxsorb is greater than that of A10 and thus SCE of Maxsorb is about 4 times higher than A10 as can be seen from Figs. 4 (a) and (b).

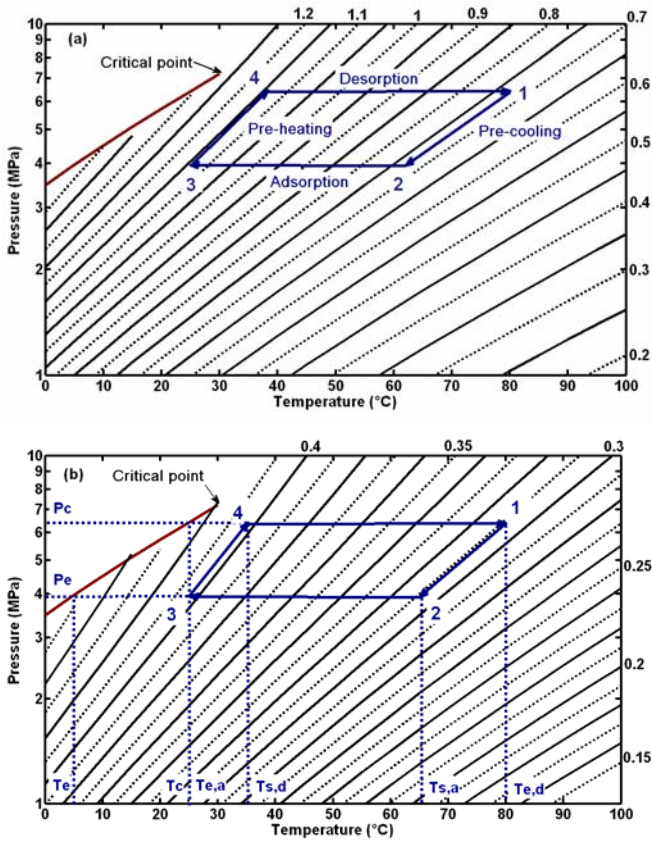


Fig. 3 P-T-W diagram of (a) Maxsorb-CO₂ pair and (b) A10-CO₂ pair

IV. RESULTS AND DISCUSSION

The adsorption isotherms as shown in Figs. 2 (a) and (b) for CO₂ on Maxsorb and A10 are predicted from the experimental data [13] where the adsorption equilibrium at three different temperatures 0, 25 and 50°C, and at pressures ranging from 0 to 5 MPa have been measured. The Tóth isotherm equation is used to correlate these data. The P-T-W diagram shows the thermodynamic relation between the equilibrium pressure, adsorption temperature and amount of refrigerant adsorbed

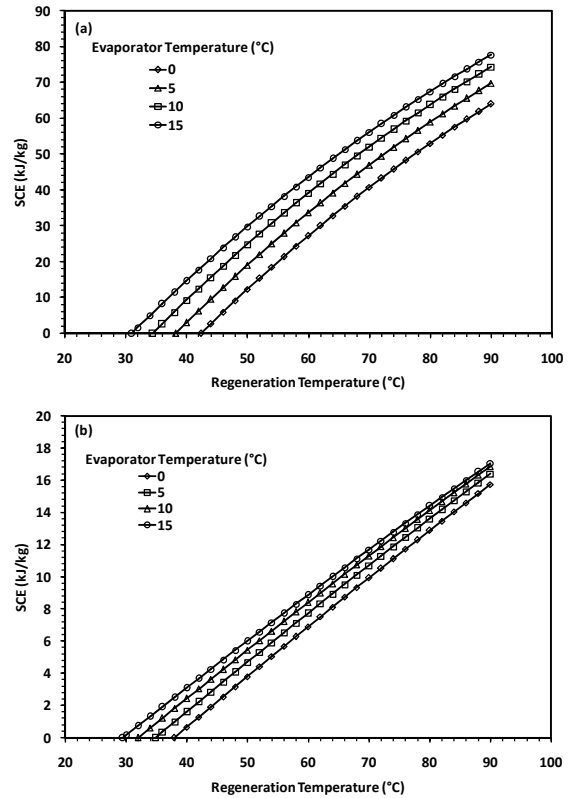


Fig. 4 Specific cooling effect of (a) Maxsorb and (b) ACF-A10 function of regeneration temperature

The effects of regeneration temperatures on COP for Maxsorb-CO₂ and A10-CO₂ systems are shown in Figs. 5(a) and (b), respectively. It is observed that the COP increases sharply at desorption temperatures below 70 °C. At $T_{e,d}$ above 70 °C, the increase in COP is marginal even though the SCE increases, which occur due to the fact that the heat input becomes significantly large for relatively higher temperature difference between the heat source and heat sink. The COP of Maxsorb based adsorption cooling system is about 2 times higher than that of A10 based system.

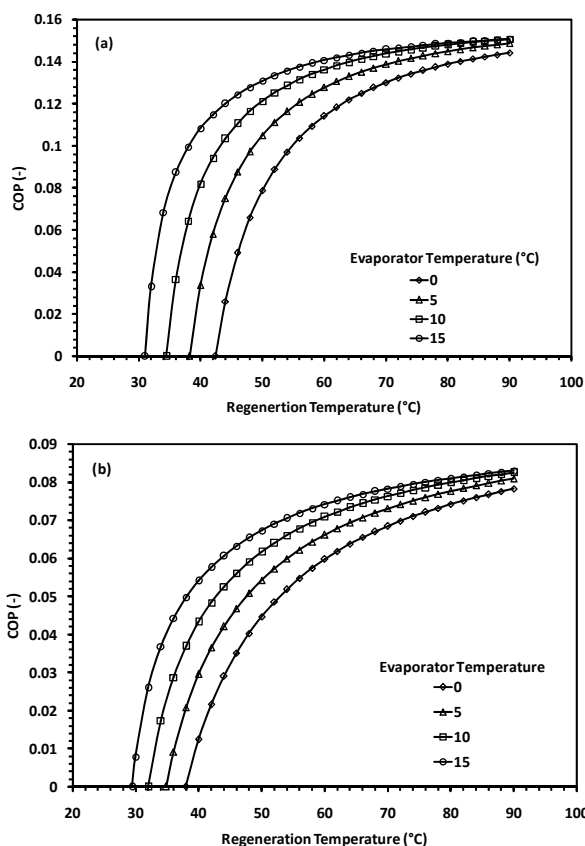


Fig. 5 Effect of regeneration temperature on COP for (a) Maxsorb and (b) ACF-A10

V. CONCLUSION

An innovative CO₂ based adsorption cooling system that amalgamates the behaviors of CO₂ adsorption and desorption on activated carbons has been described. The analysis presented herein is based on the experimentally confirmed adsorption isotherm data and CO₂ properties routines using the first law of thermodynamics. Energy dissipations are not taken into account. The performances of the novel system in terms of SCE and COP for various regeneration and evaporator temperatures are presented. It is found that the performances of adsorption cycle incorporating Maxsorb as adsorbents, in terms of cooling capacity and coefficient of performance, are higher than those of A10 activated carbon based adsorption system. This proposed adsorption system seems to be suitable for automobile air-conditioning and heat pumping applications.

NOMENCLATURE

b	Affinity (MPa ⁻¹)
C _p	Specific heat capacity (kJ/(kg.K))
COP	Coefficient of performance (-)
LH	Latent heat (kJ/kg)
P	Pressure (MPa)
q _{st}	Isosteric heat of adsorption (kJ/kg)
Q	Heat added or rejected (kJ/kg)
SCE	Specific cooling effect (kJ/kg)

t	Heterogeneity factor (-)
T	Temperature (K)
W	Equilibrium uptake (kg/kg)
W ₀	Saturated amount adsorbed (kg/kg)

SUBSCRIPTS

ad	Adsorbent
ads	Adsorption
c	Condenser
des	Desorption
e	Evaporator
h	Heat added
latent	Latent heat
max	Maximum
min	Minimum
ref	Refrigerant
sens	Sensible heat

REFERENCES

- [1] E. Boelman, B.B. Saha and T. Kashiwagi, "Experimental investigation of a silica gel-water adsorption refrigeration cycle—the influence of operating conditions on cooling output and COP", *ASHRAE Trans.*, vol. 101, pp. 358–366, 1995.
- [2] B.B. Saha, E. Boelman and T. Kashiwagi, "Computer simulation of a silica gel-water adsorption refrigeration cycle—the influence of operating conditions on cooling output and COP", *ASHRAE Trans.*, vol. 101, pp. 348–357, 1995.
- [3] M. Tatlier and A. Erdem-Senatalar, "Effects of thermal gradients in a solar adsorption heat pump utilizing the zeolite-water pair", *Appl. Therm. Eng.*, vol. 19, pp. 1157–1172, 1999.
- [4] D.C. Wang, Z.Z. Xia, and J.Y. Wu, "Design and performance prediction of a novel zeolite-water adsorption air conditioner", *Energy Conv. Mang.*, vol. 47, pp. 590–610, 2006.
- [5] R.E. Critoph, "Forced convection enhancement of adsorption cycles", *Heat Recovery Syst. CHP*, vol. 14, pp. 343–350, 1994.
- [6] R.E. Critoph, "Forced convection adsorption cycles", *Appl. Therm. Eng.*, vol. 18, pp. 799–807, 1998.
- [7] D.J. Miles and S.V. Shelton, "Design and testing of a solid-sorption heat-pump system", *Appl. Therm. Eng.*, vol. 16, pp. 389–394, 1996.
- [8] M. Pons and J.J. Guillemot, "Design of an experimental solar powered, solid adsorption ice maker", *J. Solar Energy Eng., Trans. ASME*, vol. 103, pp. 332–337, 1986.
- [9] F. Meunier, "Solid sorption heat powered cycles for cooling and heat pumping applications", *Appl. Therm. Eng.*, vol. 18, pp. 715–729, 1989.
- [10] B.B. Saha, A. Akisawa and T. Kashiwagi, "Silica gel water advanced adsorption refrigeration cycle", *Energy*, vol. 22, pp. 437–447, 1997.
- [11] B.B. Saha, S. Koyama, J.B. Lee, K. Kuwahara, K.C.A. Alam, Y. Hamamoto, A. Akisawa and T. Kashiwagi, "Performance evaluation of a low temperature waste heat driven multi-bed adsorption chiller", *Int. J. Multiph. Flow*, vol.29, pp. 1249–1263, 2003.
- [12] R.Z. Wang, R.G. Oliveira, "Adsorption refrigeration-An efficient way to make good use of waste heat and solar energy". *Prog. Energy Comb. Sci.*, vol. 32, pp. 424–458, 2006.
- [13] S. Himeno, T. Komatsu, and S. Fujita, "High-pressure adsorption equilibria of methane and carbon dioxide on several activated carbons", *J. Chem. and Eng. Data*, vol. 50 (2), pp. 369–376, 2005.
- [14] Biloe, S., Goetz, V., Mauran, S., "Dynamic discharge and performance of a new adsorbent for natural gas storage, *AIChE J.* 47 (12), pp. 2819–2830, 2001.
- [15] K. J. Chang and O. Talu, "Behavior and performance of adsorptive natural gas storage cylinders during discharge", *App. Therm. Eng.*, vol. 16 (5 SPEC. ISS.), pp. 359–374, 1996.