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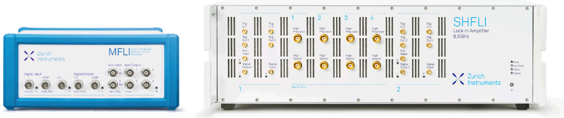

Experimental Study on the Effect of Adsorbent Height on Adsorption Dynamics

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Abstract. This study experimentally investigated the effect of adsorbent height on adsorption dynamics for carbon dioxide gas (CO_2) adsorption onto commercially available highly porous activated carbon powder, named as Maxsorb III. The experiments were conducted using a magnetic suspension adsorption measurement unit. Three different heights of the Maxsorb III adsorbent were used in the experiments. Experimental data were reported for adsorption temperatures of 30 ºC and 70 ºC and for 2 different pressure steps. It had been observed that the adsorption rate strongly depended on the height of the adsorbent. This signifies that the kinetic parameters obtained by the similar experimental measurements may not be directly applicable in designing an adsorption heat exchanger. The lower height of the adsorbent provided faster adsorption kinetics. Key performance parameter, such as the specific cooling capacity for an adsorption refrigeration system was also calculated from the experimental data. The results of the present study suggested that the adsorbent height needs to be considered while using kinetics parameters in designing adsorption heat exchanger. .

NOMENCLATURE

E	Characteristic energy for D-A equation (J/mol)
P	Pressure (kPa)
P_S	Saturation pressure (kPa)
R	Universal gas constant (J/mol K)
T	Temperature (ºC or K)
W	Instantaneous uptake (kg/kg)
W_0	Saturation adsorption capacity (kg/kg)
W_{eq}	Equilibrium uptake (kg/kg)
W_N	Normalized uptake (kg/kg)
SCE	Specific cooling effect (kJ/kg)
SCC	Specific cooling capacity (W/kg)
t	Time (s)
τ	Time constant (s)

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INTRODUCTION

According to the estimation of International Institute of Refrigeration (IIR), approximately 15% of the total electricity produced in the world are used for refrigeration and air-conditioning [1]. Conventional vapor compression refrigeration system uses HFC and HCFC based refrigerants which cause increase in global temperature due to their high global warming potential (GWP) when they are released in the atmosphere. Accordingly, researches have been carried out to utilize natural and alternative refrigerants having low or no GWP. Adsorption refrigeration systems are gaining considerable attention from the scientists due to its environment friendly nature and ability to utilize low grade heat which would otherwise go as waste [2,3,4].

Among all natural refrigerants, CO_2 offers a number of advantages such as,

- it is non-toxic, non-flammable;
- it has zero ODP and minimal GWP, as low as 1;
- excellent thermophysical properties, high volumetric capacity;
- its application is not limited to cooling and air-conditioning above 0 ºC. It can be used for freezing and ice making applications.

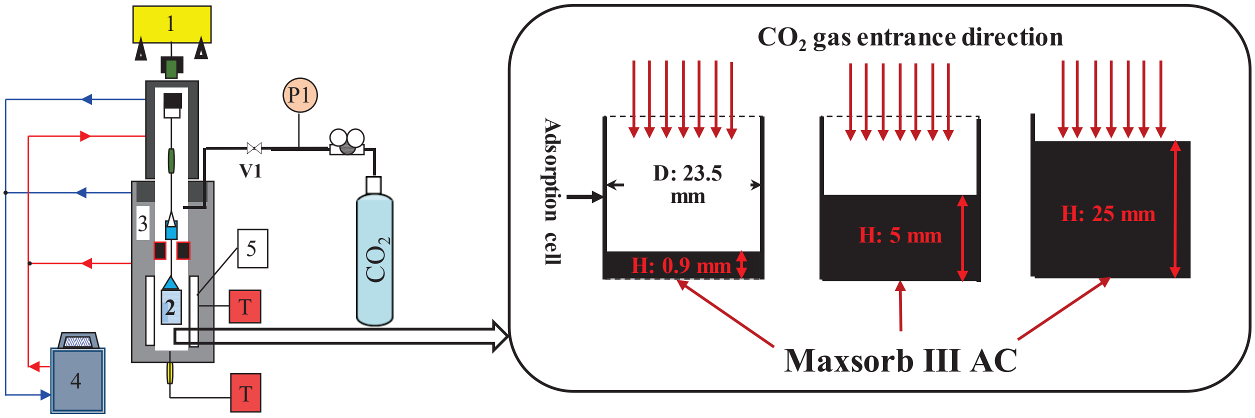
Characterization of promising adsorption pairs is hugely important in developing high performance adsorption cooling systems. Adsorption isotherm and adsorption kinetics are two important parameters that estimate the performance of an adsorption refrigeration system. Several researchers measured the adsorption isotherm [5,6,7] and kinetics [6,8,9] of different adsorption pairs. Saha et al. [10] measured the adsorption isotherm of CO_2 onto activated carbon fiber and activated carbon powder. Jribi et al. [11] measured the adsorption kinetics of CO_2 onto highly porous activated carbon, commercially named as Maxsorb III. Mitra et al. [12] numerically investigated the effect of heat exchanger aspect ratio on the adsorption kinetics. Alam et al. [13] and Niazmand et al. [14] numerically investigated the effect of heat exchanger design on the performance of adsorption refrigeration system. Pal et al. [15] investigated the adsorption of CO_2 onto carbon based consolidated composite adsorbent for adsorption cooling application. They analyzed the performance of a refrigeration system for evaporation temperature of 5, 10 and 15 °C and condensation temperature of 25 °C (corresponding saturation pressure is 6434.2 kPa). For adsorption and evaporation temperature of 25 °C and 5 °C respectively, the minimum temperature required for regeneration is found to be 46.4 °C [16,17]. Singh and Kumar [18] explained the dependence of specific cooling effect of Maxsorb III/CO_2 based cooling system on the regeneration temperature. The objective of the current study is to experimentally investigate the effect of adsorbent height on the adsorption kinetics for adsorption of CO_2 on Maxsorb III powder. At the same time, the present study analyzes the performance of adsorption refrigeration systems having different heat exchanger fin heights.

EXPERIMENT

The measurement of adsorption dynamics is conducted gravimetrically using magnetic suspension adsorption measurement unit (MSB-GS-100-10M) supplied by Bel Japan. A schematic of the experimental setup is depicted in Figure 1. The setup consists of a magnetic suspension balance; a sample cell to hold the sample; a circulation oil bath to control the adsorption temperature; a series of vacuum pumps, pressure sensors and thermocouples. The magnetic suspension unit contains a permanent magnet, sensor code and electronic control unit. The sample cell is surrounded by a circulation jacket so that the isothermal condition is maintained.

A CO_2 gas cylinder supplies the gas to be adsorbed by the sample at the adsorption cell. The adsorbed amount is measured as weight by the magnetic suspension balance having a resolution of ±10μg. It needs mentioning that the buoyancy effect in the adsorbed quantity measurement is automatically considered by the software. The weight measurement repeatability of the balance is ±30μg with a relative error of ±0.002% of the reading. A pressure gauge of type Keller PAA-35X can measure pressure up to 10,000 kPa absolute with an uncertainty of ±0.1 of full scale.

To measure the adsorption isotherm, the adsorbent sample is placed in the sample basket which is connected to the measuring unit of the system. First the sample is heated at a temperature of 130 °C for several hours to remove any previously adsorbed gas; the process is called regeneration. To measure the adsorption isotherm at a particular pressure, the CO_2 gas is charged into a tube from the CO_2 cylinder which is then directed to the magnetic suspension balance unit.



1) Magnetic suspension balance; 2) adsorption cell; 3) Circulation oil jacket; 4) Isothermal circulation oil bath; 5) Sheathed heater and the refrigerant (CO_2) charging cell.

FIGURE 1. Schematic of the magnetic suspension adsorption measurement unit.

The pressure of the CO_2 cylinder is the saturation pressure of CO_2 at ambient temperature and the pressure in the connecting tube is controlled by a control valve. This technique allows to measure adsorption isotherm at low to medium pressure. The maximum allowable pressure of the system can be 7 MPa. The detail experimental procedure can be found in reference [11,15].

MATHEMATICAL EQUATIONS

In the present study, normalized uptake is used to analyze the effect of adsorbent height on the adsorption dynamics. For the normalization, the following equation is used,

$$W_N = \frac{W - W_{in}}{W_{eq} - W_{in}} \tag{1}$$

where, W_N, W, W_{in} and W_{eq} are normalized uptake, instantaneous uptake, initial uptake and equilibrium uptake, respectively.

The adsorption rate can be estimated using the Linear Driving Force (LDF) equation,

$$\frac{\partial W}{\partial t} = \frac{W_{eq} - W}{\tau} \tag{2}$$

where, τ is the diffusion time constant which governs the rate of adsorption. This time constant provides an estimate of the intra-particle mass transfer resistance.

For an adsorption refrigeration system, specific cooling effect (SCE) can be defined by the refrigerating effect produced by unit quantity of refrigerant. Since the refrigerating effect is determined by the amount of refrigerant adsorbed, SCE can by expressed by,

$$\mathrm{SCE} = 0.8 W_{eq} \times h_{fg} \tag{3}$$

where, h_{fg} is the latent heat of vaporization for CO_2 gas at the evaporation temperature. In the current investigation, optimum cycle time is determined as the time required ($t_{0.8}$) by the adsorbent to adsorb 80% of the maximum adsorption capacity. Hence, specific cooling capacity (SCC) can be determined from the below equation,

$$\mathrm{SCC} = \mathrm{SCE}/t_{0.8} \tag{4}$$

Dubinin-Astakhov (D-A) equation is used to determine the equilibrium adsorbed quantity,

$$W_{eq} = W_0 \exp\left[-\left\{ \frac{RT}{E} \ln\left(\frac{P_S}{P} \right) \right\}^n \right] \tag{5}$$

where, W_0 is the saturation adsorption capacity, R is the molar gas constant, T is the adsorption temperature, E is the characteristic energy for D-A equation, P_S is the saturation pressure at adsorption temperature and P is the adsorption pressure.

RESULTS AND DISCUSSION

Adsorption uptake of CO_2 gas is measured at temperatures of 30 °C and 70 °C. For each temperature 2 different pressure levels are considered in the current study. The density of loosely packed Maxsorb III is measured as 170 kg/m^3. The adsorbents are placed in an adsorption cell having an inner diameter of 23.5 mm. Three different quantities of adsorbent are used in the investigation: 66 mg, 369 mg and 1843 mg, which give heights of the adsorbent as 0.9 mm, 5 mm and 25 mm respectively. It is obvious that the absolute adsorbed quantity will be higher for a higher mass. Hence in the present study, normalized uptake is used to analyze the deviation of kinetics parameters with adsorbent heights.

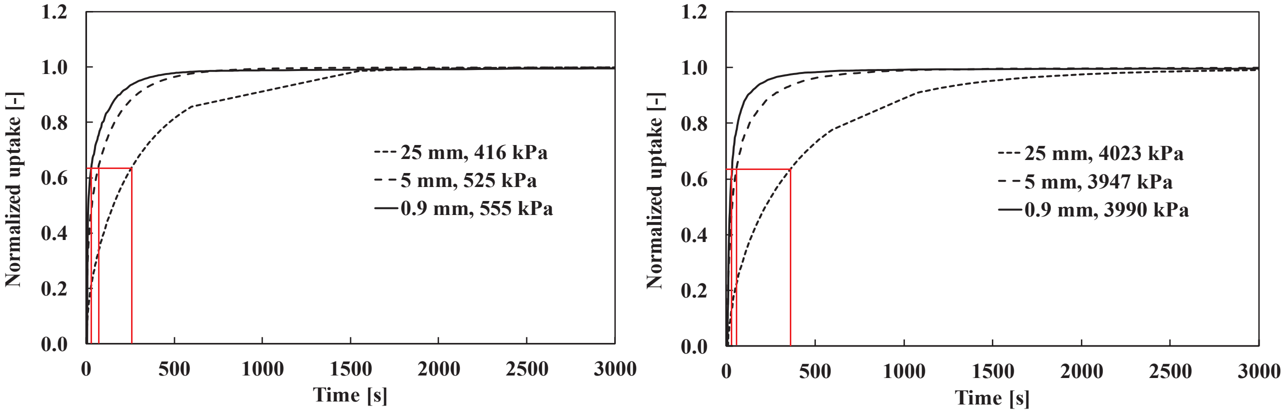


FIGURE 2. Normalized uptake of CO_2 gas onto Maxsorb III powder at a temperature of 30 ºC at two different pressure levels

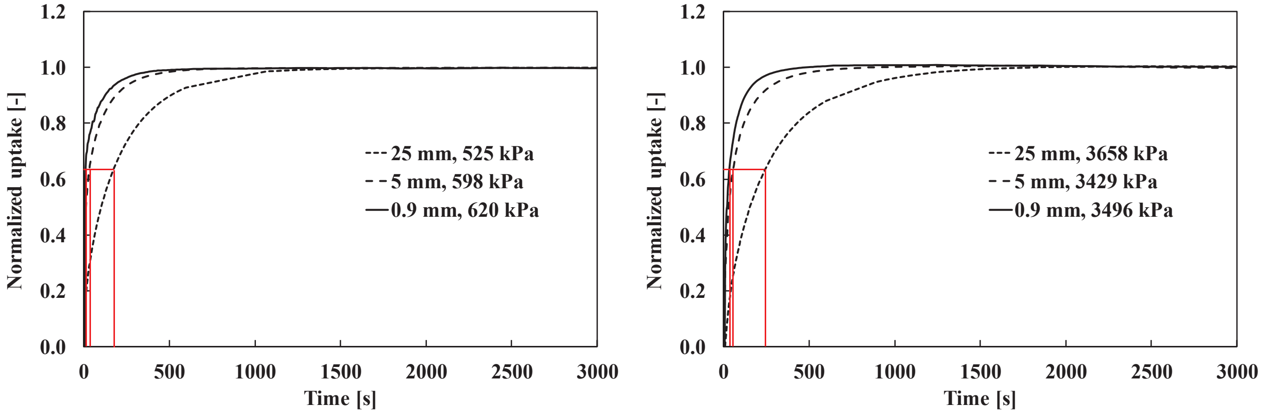


FIGURE 3. Normalized uptake of CO_2 gas onto Maxsorb III powder at a temperature of 70 ºC at two different pressure levels

Figure 2 and Figure 3 present the normalized uptake of CO_2 gas onto 3 different quantities of Maxsorb III powder at temperatures of 30 ºC and 70 ºC respectively. The results are reported for 2 different pressure steps. From the figures, it is evident that a shorter height of adsorbent causes faster adsorption rate. For adsorption temperature of 30 ºC, to attain 63.2% of the maximum uptake, time required are 255 s at 416 kPa, 69 s at 525 kPa and 28 s at 555 kPa for adsorbent heights of 25 mm, 5 mm and 0.9 mm respectively. Similarly, at pressure of about 4000 kPa, the time constants obtained are 356 s, 53 s and 30 s for adsorbent heights of 25 mm, 5 mm and 0.9 mm respectively. These results indicate that a faster kinetics is obtained with a lower adsorbent height and a similar trend is observed at adsorption temperature of 70 ºC. The result also signifies that the fastest kinetics can be obtained in the case of adsorption onto a monolayer adsorbent.

The reason for the deviation in the kinetics can be explained through mass transfer analysis within the adsorbent bed. Although the pressure applied is about the same to different quantities of adsorbent, the sample with 25 mm height is not able to attain that pressure wholly due to higher resistance to mass transfer because of its larger height. As a result, the bottom part of that adsorbent experiences lower pressure as compared to the adsorbent with 0.9 mm height. Furthermore, it is also evident from the figures that the difference in kinetics for 5 mm and 25 mm is insignificant, compared to the same for 0.9 mm and 5 mm for both the pressure ranges. Hence, from the kinetics' perspective, it can be opined that above an optimum value of adsorbent height the kinetic performance of the system does not deteriorate much, but obviously, the absolute uptake of the adsorbent increases because of the higher mass.

The adsorption rate of refrigerant essentially determines the cycle time of an adsorption refrigeration system. The faster the kinetics, the lower will be the cycle time. To determine the specific cooling capacity of a refrigeration system, first the equilibrium uptake is determined from equation (5). The values of different parameters used, are presented in **TABLE 1**.

TABLE 1. Numerical value of parameters used [11]

Parameter	**Value**
W_0 (cm^3/kg)	1.5408
E (J/mol)	5254.76
n	1.326
R (J/mol K)	8.314

A refrigeration system is assumed to operate at evaporator and adsorption temperature of 5 ºC and 30 ºC, respectively. At evaporator temperature, the saturation pressure and enthalpy of vaporization are found to be 3969.5 kPa and 214.98 kJ/kg respectively. From Equation (5), the equilibrium uptake is calculated as 0.2165 kJ/kg and from Equation (3) SCE is calculated as 46.5 kJ/kg. Now $t_{0.8}$ and SCC are determined for 3 different adsorbent heights and presented in **TABLE 2**.

TABLE 2. $t_{0.8}$ and SCC for three different adsorbent heights

Adsorbent height (mm)	$t_{0.8}$ **(s)**	**SCC (W/kg)**
25	398.5	116.7
5	128	363.3
0.9	70	664.8

It is observed that with an increase in adsorbent height, the specific cooling capacity decreases. Hence it is obvious that the highest cooling capacity can be obtained for an adsorbent having monolayer thickness. But in such a case, the absolute adsorbed quantity would be a minimum.

In an adsorption heat exchanger, the adsorbents are packed within the fins and the height of adsorbent is essentially determined by the height of the fin. Hence, while designing such heat exchanger chamber, the kinetics parameters taken into calculation must consider the geometry of the adsorbent bed used in the experimental investigation. The adsorbent bed cannot be considered as a lumped model, since a spatial variation of pressure and temperature is observed within a bed of large size. On the other hand, the kinetics parameters reported after experimental investigation need mentioning of the geometry, considered in the experiments.

CONCLUSION

Adsorption kinetics of CO_2 gas is analyzed for three different heights of Maxsorb III adsorbents, at 30 ºC and 70 ºC and at two different pressure steps. For an adsorption refrigeration system, the cycle time is an important parameter which is determined by the adsorption rate of refrigerant onto the adsorbent material. To maximize the performance of an adsorption refrigeration system, it is necessary to minimize the optimum cycle time. The faster the adsorption rate, the lower can be the cycle time. It is observed that the adsorption rate, as well as the specific cooling capacity of a refrigeration system, is higher for adsorbent with lower height than that with a larger height. In an adsorption heat exchanger, the height of the adsorbent is essentially determined by the height of the fins. Hence the kinetics parameters, applied in designing an adsorption heat exchanger, need mentioning of the height of adsorbents, used in the experiments. Furthermore, the adsorbent bed cannot be modeled using lumped capacitance equations as there are pressure and temperature variations within the bed.

REFERENCES

1. Coulomb, D. Statement by the Director of the International Institute of Refrigeration. in *United Nations Climate Change Conference (COP12)* (2006).
2. Saha, B. B. *et al.* Waste heat driven dual-mode, multi-stage, multi-bed regenerative adsorption system. *Int. J. Refrig.* **26,** 749–757 (2003).
3. Palomba, V., Aprile, M., Motta, M. & Vasta, S. Study of sorption systems for application on low-emission fishing vessels. *Energy* **134,** 554–565 (2017).
4. Ng, K. C., Thu, K., Saha, B. B. & Chakraborty, A. Study on a waste heat-driven adsorption cooling cum desalination cycle. *Int. J. Refrig.* **35,** 685–693 (2012).
5. Askalany, A. A. & Saha, B. B. Experimental and theoretical study of adsorption kinetics of Difluoromethane onto activated carbons. *Int. J. Refrig.* **49,** 160–168 (2015).
6. Ghazy, M., Harby, K., Askalany, A. A. & Saha, B. B. Adsorption isotherms and kinetics of activated carbon/difluoroethane adsorption pair: theory and experiments. *Int. J. Refrig.* **70,** 196–205 (2016).
7. Saha, B. B., El-Sharkawy, I. I., Thorpe, R. & Critoph, R. E. Accurate adsorption isotherms of R134a onto activated carbons for cooling and freezing applications. *Int. J. Refrig.* **35,** 499–505 (2012).
8. El-Sharkawy, I. I., Saha, B. B., Koyama, S. & Ng, K. C. A study on the kinetics of ethanol-activated carbon fiber: Theory and experiments. *Int. J. Heat Mass Transf.* **49,** 3104–3110 (2006).
9. Aristov, Y. I., Tokarev, M. M., Freni, A., Glaznev, I. S. & Restuccia, G. Kinetics of water adsorption on silica Fuji Davison RD. *Microporous Mesoporous Mater.* **96,** 65–71 (2006).
10. Saha, B. B., Jribi, S., Koyama, S. & El-Sharkawy, I. I. Carbon Dioxide Adsorption Isotherms on Activated Carbons. *J. Chem. Eng. Data* **56,** 1974–1981 (2011).
11. Jribi, S. *et al.* Equilibrium and kinetics of CO2 adsorption onto activated carbon. *Int. J. Heat Mass Transf.* **108,** 1941–1946 (2017).
12. Mitra, S., Muttakin, M., Thu, K. & Saha, B. B. Study on the influence of adsorbent particle size and heat exchanger aspect ratio on dynamic adsorption characteristics. *Appl. Therm. Eng.* **133,** (2018).
13. Alam, K. C. A. K., Saha, B. B. B., Kang, Y. Y. T., Akisawa, A. & Kashiwagi, T. Heat exchanger design effect on the system performance of silica gel adsorption refrigeration systems. *Int. J. Heat Mass Transf.* **43,** 4419–4431 (2000).
14. Niazmand, H., Talebian, H. & Mahdavikhah, M. Bed geometrical specifications effects on the performance of silica/water adsorption chillers. *Int. J. Refrig.* **35,** 2261–2274 (2012).
15. Pal, A. *et al.* Experimental investigation of CO2 adsorption onto a carbon based consolidated composite adsorbent for adsorption cooling application. *Appl. Therm. Eng.* **109,** 304–311 (2016).
16. Muttakin, M., Mitra, S., Thu, K., Ito, K. & Saha, B. B. Theoretical framework to evaluate minimum desorption temperature for IUPAC classified adsorption isotherms. *Int. J. Heat Mass Transf.* **122,** (2018).
17. Saha, B. B. *et al.* Thermodynamic formalism of minimum heat source temperature for driving advanced adsorption cooling device. *Appl. Phys. Lett.* **91,** (2007).
18. Singh, V. K. & Kumar, E. A. Experimental investigation and thermodynamic analysis of CO2 adsorption on activated carbons for cooling system. *J. CO2 Util.* **17,** 290–304 (2017).