Chemical Engineering Journal 253 (2014) 350–355

Contents lists available at ScienceDirect

Chemical Engineering Journal

journal homepage: www.elsevier.com/locate/cej

Adsorption of carbon dioxide by diethanolamine activated alumina beads in a fixed bed

M. Auta [a,b], B.H. Hameed [a,*]

[a] School of Chemical Engineering, Engineering Campus, Universiti Sains Malaysia, 14300 Nibong Tebal, Penang, Malaysia
[b] Department of Chemical Engineering, Federal University of Technology, Minna, Nigeria

HIGHLIGHTS

- Activated alumina was functionalized with 0.8 M diethanolamine (DAAB).
- Physical and chemical characterizations of the adsorbents were carried out.
- Fixed-bed column adsorption of carbon dioxide from the gas mixture (CO_2/N_2).
- Multi-cycles adsorption tests of carbon dioxide.

ARTICLE INFO

Article history:
Received 1 March 2014
Received in revised form 4 May 2014
Accepted 5 May 2014
Available online 14 May 2014

Keywords:
Activated alumina
Diethanolamine
Fixed-bed adsorption
Multi-cycle

ABSTRACT

Application of mesoporous activated alumina functionalized with diethanolamine (DAAB) for selective adsorption of carbon dioxide (CO_2) from its mixture with nitrogen gas was investigated. Morphological structure, elemental composition and the functional groups present in the DAAB were analyzed using the scanning electron microscopy; energy dispersive X-ray technique and Fourier transform infrared analysis. Investigation of effect of the gas mixture feed flow rate, column adsorption temperature, DAAB bed height and concentration of CO_2 in the feed stream revealed that 90 mL/min, 35 °C, 3 g and 10% of CO_2, respectively were the optimum operating conditions for the highest adsorption capacity of 55.94 mg/g. The DAAB multi-cycle CO_2 adsorption test revealed that it can be reused successfully for about 13 times with high sorption capacity. The DAAB is a promising adsorbent that can be used to capture CO_2 pollutant molecules.

1. Introduction

An easy to use, regenerate, multi-cycle and high adsorption capacity adsorbent is the yenning for global community in curbing carbon dioxide environmental pollution [1]. This is feasible by monitoring the physical (surface area and porosity) and chemical properties of adsorbent during preparation [2]. The acidic CO_2 adsorption is favorable on basic surfaces or surfaces of adsorbents with insignificant acidic characteristics [3,4].

Increasing basic functionality of adsorbents can be carried out through: modification of surface oxygen functionalities [5], adsorbent basal planes [6], functionalities with nitrogen containing compounds (NH_3, amines etc.), decomposition of surface acidic functional groups through calcinations [7]. Amine modification of adsorbents for capturing CO_2 is a promising way of evacuating it from flue gases [8,9]. Amine modified adsorbents has high selective adsorption and high rate of diffusion of the CO_2 within the mesopores [10,11]. The modified (amine) adsorbent ability to promote CO_2 adsorption from both flue gas and ambient air also depends on the method (wet impregnation, grafting or insitu polymerization) of the amine monomers immobilization [11]. This is additional to microporous, large pore volume and surface area of adsorbents that promotes physical adsorption of CO_2. Various mesoporous materials such as activated carbons, alumina, silica (MCM-22, MCM-36, MCM-41, MCM-42, SBA-15, SBA-16 etc.) have been modified with amine compounds for CO_2 adsorption. Principally, impregnation and grafting are the two major methods employed for mesoporous adsorbents modification with amine compounds. The later involves interaction of amine molecules with surface hydroxyl group while the former method involves attachment of amine molecules to the mesoporous surface by van der Waals forces [12].

Monoethanol amine is among the commonest solvents used for CO_2 capturing but it requires energy for regeneration and also

* Corresponding author. Fax: +60 45941013.
E-mail address: chbassim@usm.my (B.H. Hameed).

http://dx.doi.org/10.1016/j.cej.2014.05.018
1385-8947/

causes corrosion [5,10]. Despite these limitations, enhancement of effective adsorption and lowering of carbamate (product of CO_2 adsorption on amine reaction ($CO_2 + 2R–NH_2 = R–NHCOO– + R–NH_3^+$)) formation is promoted by the use of the amines (sterically hindered) with bulky substituent lying near. A high mesoporous material with suitable amine group can yield an excellent CO_2 adsorbent [13].

The readily available, cheap, mechanically stable, amphoteric, mesoporous and transitional nature of alumina has been utilized for adsorption purposes [13,14]. Despite the mesoporous alumina inherent ability, its modification with amine for CO_2 adsorption reports is limited in literature [13,15,16].

In this study, mesoporous activated alumina was synthesized with diethanolamine through impregnation for adsorption of CO_2 in a fixed bed column. The relationship between the resulting breakthrough curves of the CO_2 adsorption on the DAAB adsorbent and the adsorption parameters (temperature, concentration, flow rate, bed height, CO_2 %) were evaluated. Regeneration and multi-cycle use of the DAAB adsorbent was investigated.

2. Materials and methods

2.1. Materials

Diethanolamine (2,2′iminodiethanol, Bis(2 hydroxyethyl) amine) and methanol were supplied by Sigma–Aldrich; activated alumina beads was purchased from OMI(M) SDN. BHD., all in Malaysia. High purity carbon dioxide (99.9%) and nitrogen (99.9%) gases were obtained from Well gas company Malaysia.

2.2. Preparation of CO_2 adsorbent

Activated alumina beads were sieved into different particle sizes (500 μm^{-1} mm, 1–2 mm, 2–3 mm) and dried under vacuum (70 °C) for 6 h after washing with distilled water. The dried different particle sizes beads were used as plain activated alumina (PAA) adsorbent.

Ten grams (10 g) of the prepared PAA was added to 300 mL of 0.8 M diethanolamine (23 mL of diethanolamine plus 277 mL of methanol) and stirred for 5 h at room temperature. The mixture was filtered and washed with methanol and then dried under vacuum at 70 °C for 6 h. The dried activated alumina beads functionalized with diethanolamine (DAAB) were packaged in air tight container for further use.

2.3. Fixed-bed column adsorption

The DAAB adsorbent was preheated for drying in an inert (under constant nitrogen flow) fixed-bed column (42 cm length and 1.1 cm diameter) at 110 °C for 1 h and then cooled to the desired adsorption temperature. In an upward flow pattern, a mixture of carbon dioxide (10% CO_2) and nitrogen (balance of CO_2% v/v) of 99.99% purity each was passed through the adsorption column via an AALBORG (model AFC26 NY, USA) calibrated mass flow controller. An online carbon dioxide analyzer 906 (Quentek instrument, USA) model was used to determine the residual CO_2 in the fixed-bed column adsorption effluent after every 10 s.

Effect of adsorption parameters such as gas influent flow rate (90, 120 and 150 mL/min), percentage of CO_2 in the feed (10, 15, and 20%), amount of adsorbent (DAAB) (2, 3 and 4 g) in the fixed-bed and adsorption column temperature (35, 45 and 55 °C) on the CO_2 adsorption in the fixed-bed column were studied. The column adsorption temperature range selected covers a typical post flue gas desulphurization range of 45–55 °C [17].

2.4. Regeneration of adsorbent

The CO_2 adsorbed on 3 g (1–2 mm size) DAAB at 35 °C of 10% CO_2 influent concentration in the feed flow rate of 90 mL/min was desorbed by raising the column temperature to 110 °C for 1 h under flow of nitrogen gas. A complete desorption was marked by constant residual CO_2 in the exit column effluent determined through the carbon dioxide analyzer. The fixed DAAB in the column was reused for cycles of adsorption as in section 2.3 after purging the trapped gas with a vacuum pump for 30 min.

2.5. Characterization of adsorbent

Nitrogen adsorption–desorption of the DAAB operating with static volumetric technique using an autosorb Brunauer–Emmett–Teller Micrometric (BET) ASAP 2020 was used to determine the BET surface area and porosity. The DAAB sample was first degassed at 300 °C for 2 h to measure the equilibrium pressure of the known volume of liquid nitrogen for the isotherms generation. Then the Barrett–Joyner–Halenda (BJH) and t-plot method evaluation of the average pore size distribution and total pore volume were used, respectively.

The morphological structure and elemental composition of the DAAB were determined using an integrated scanning electron microscopy (SEM) and energy dispersive X-ray (EDX) microanalysis (Oxford INCA 400, Germany).

Chemical functional groups on the DAAB surface before and after adsorption of CO_2 were quantitatively identified using Fourier transform infrared spectroscopy (FTIR) analysis. Potassium bromide (KBr) and the DAAB were mixed in a 20:1 ratio to prepare a 7 mm diameter disc (1 mm thick) using hydraulic press technique. An observable transmission spectrum of the sample was recorded between 4000 and 400 cm^{-1} after 100 scans with the aid of an FTIR Thermo Scientific model IS10 Nicolet spectrometer, U.S.A.

3. Results and discussion

3.1. Characterization of DAAB adsorbent

The morphological and elemental composition of the activated alumina functionalized with diethanolamine adsorbent (DAAB) is shown in Fig. 1. Amorphous and some platelet morphology exhibited by bayerite structure of the plain activated alumina SEM reported in our previous research [18] were traceable in the modified DAAB adsorbent (Fig. 1). This is similar to SEM analysis of acid modified alumina adsorbent as-synthesized diethylmalonate treated mesoporous alumina [14,19]. Presence of peaks of some carbon and nitrogen molecules revealed that successful functionalization of the activated alumina was carried out when compared with the plain activated alumina elemental composition result reported in our previous work [18].

Blockages of pore width of activated alumina were observed after functionalization with diethanolamine. The BET textural analysis revealed a pore size and surface area of 5.3 nm and 205 m^2/g for DAAB as compared with 5.7 nm and 207 m^2/g, respectively of the plain activated alumina reported in our previous work [18]. The decrease in surface area of DAAB is similar to observation made with polyethylenimine-impregnated mesoporous alumina sorbent prepared for CO_2 adsorption [14]. However, a total pore volume of 0.39 nm for DAAB was obtained which showed an enhancement after functionalization. Dissolution of the DAAB wall during functionalization may have caused the expansion or structural changes due to reaction between the diethanolamine and the alumina which is similar to observation made during N-(triethoxysilylpropyl) ethylenediaminetriacetic acid modification of SBA-15

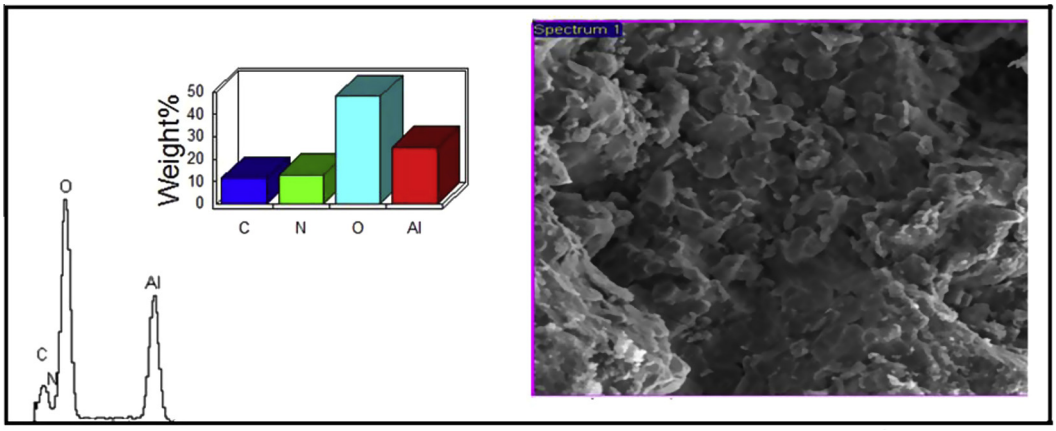

Fig. 1. Elemental composition and morphological structure of the DAAB.

silica [20]. The effect of amine functionalization of the activated alumina further affirmed that adsorption of the CO_2 may not solely have been by single phenomenon but through mass transfer or chemical or physical or combination of the adsorption processes [6,21].

The FTIR spectrums of diethanolamine functionalized activated alumina before adsorption (DAAB) and after adsorption (DAABU) for CO_2 capturing have some symmetrical functional groups peaks; the spectrums are presented in Fig. 2. The symmetrical peaks were found around 3200–3500 cm^{-1}, at 1647 cm^{-1} and 1384 cm^{-1} signifying stretches of O–H or N–H groups, some amide (N–H) group peaks and presence of C–H and C–N groups [22]. The less pronounced peaks at 1647 cm^{-1} and between 3200 and 3500 cm^{-1} on the DAABU spectrum were attributed to the adsorbed CO_2 molecules on its surface which led to extinction of some of the functional groups. Vibration of primary amine NH_2 wag was observed between the DAAB (625 cm^{-1}) and DAABU (610 cm^{-1}). This was due to lowering of the carbamate stability formed from the adsorption of the CO_2 with the amine functionalized activated alumina adsorbent thus promoting effective adsorption of the pollutant [5].

3.2. Effect of DAAB particle size on the fixed-bed adsorption column

Surface area and mono-dispersing of materials have strong affiliation with particle size of adsorbent as they are found to increase with reduction of the sizes which has influence in adsorption of environmental pollutants. The effect of variation of particle size on the breakthrough curves shown in Fig. 3 revealed that the longest breakthrough increased with decrease in DAAB particle sizes.

This was reflected in the larger bed capacity of the column with smaller adsorbent particle sizes (500 μm^{-1} mm, 58 mg/g) than the largest DAAB particle sizes of 2–3 mm with 38 mg/g capacity. The early breakthrough observed with larger particle sizes of DAAB was attributed to smaller mass transfer coefficient due to smaller specific surface area which also revealed the surface rated dependency of the sorption system [23]. Empirically, it can be said that adsorption performance of CO_2 on the DAAB was improved as the adsorbent particle sizes were reduced [24,25].

3.3. Effect of the activated alumina amine concentration on the breakthrough curves

The breakthrough curves of effect of diethanolamine concentration for modification of the activated alumina are presented in Fig. 4. The 0.8 M DAAB adsorbent had the longest breakthrough curve than 0.7 and 0.9 M DAAB adsorbents which translated to adsorption capacities of 55.94, 38.26 and 45.16 mg/g respectively. Insufficient active sites on the 0.7 M DAAB adsorbent may be responsible for the low uptake observed while blockages of the pore width of the 0.9 M DAAB may have hindered physical trapping (physisorption) of the CO_2 molecules on the adsorbent surface [5].

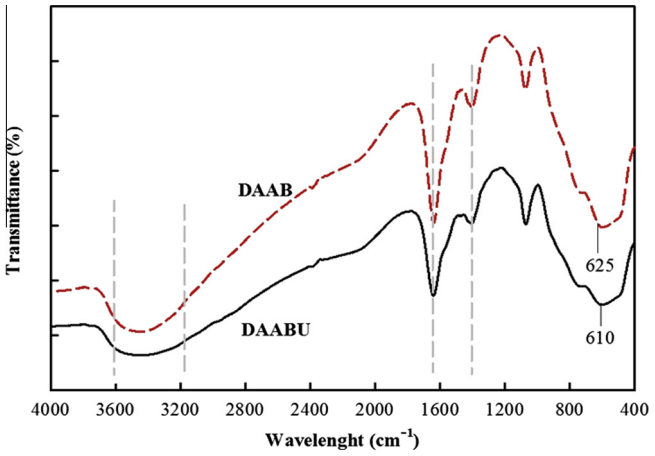

Fig. 2. The FITR spectrums of activated alumina functionalized with diethanolamine before (DAAB) and after usage (DAABU).

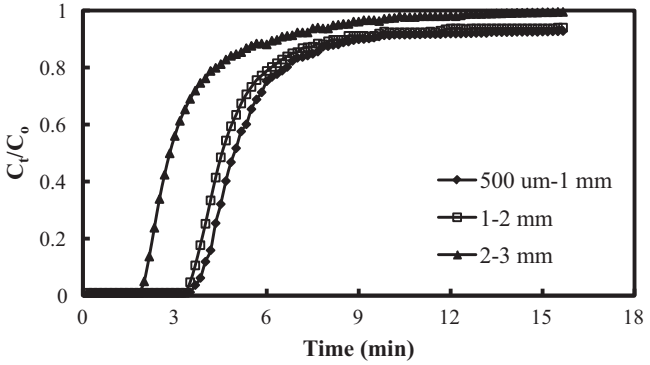

Fig. 3. The CO_2 adsorption breakthrough curve at different DAAB particles sizes, evaluated at temperature of 35 °C, feed flow rate of 90 mL/min, CO_2 concentration of 10% (balance of N_2), 0.8 M DAAB, bed height of 9.7 cm (3 g).

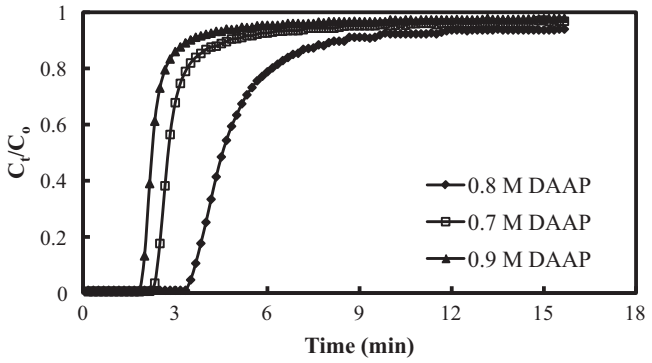

Fig. 4. The CO_2 adsorption breakthrough curve at different concentrations of diethanolamine used for functionalization, evaluated at temperature of 35 °C, feed flow rate of 90 mL/min, CO_2 concentration of 10% (balance of N_2), bed height of 9.7 cm (3 g), particle sizes of 1–2 mm.

3.4. Effect of variation of the feed flow rate on CO_2 adsorption by the DAAB adsorbent

The breakthrough curves profiles for variation of the feed gas mixture flow rate on the adsorption of CO_2 by the DAAB fixed adsorbent in the column are shown in Fig. 5. Adsorption of CO_2 molecules was rapid at the initial stages of the feed flow rate range (90–150 mL/min) studied due to availability of vacant active sites ready for adsorption activities. Lower flow rate (90 mL/min) of the inlet gas mixture was accompanied with low transport of the CO_2 molecules which gave ample diffusion coefficient that resulted to delayed breakthrough as can be seen in Fig. 5. An increase in the flow rate (120–150 mL/min) led to the reduction of the residence time of the adsorbate in the column leading to poor performance of the system or reduction on the adsorption efficiency [26,27]. This reflected on the adsorption capacities presented in Table 1 which were 55.94, 39.36 and 27.03 mg/g for the feed flow rates of 90, 120 and 150 mL/min, respectively. The experimental results showed that DAAB uptake of CO_2 was greatly affected by the feed flow rate which also implies that diffusion was not the only controlling mechanism but external mass transfer.

3.5. Effect of initial feed concentration on CO_2 adsorption by DAAB

The breakthrough curves of effect of initial feed concentration on CO_2 adsorption by DAAB are shown in Fig. 6. The number of molecules of carbon dioxide available per volume of the feed for adsorption by the DAAB was increased as the concentration of CO_2 was varied from 10 to 20%. This gave corresponding increase

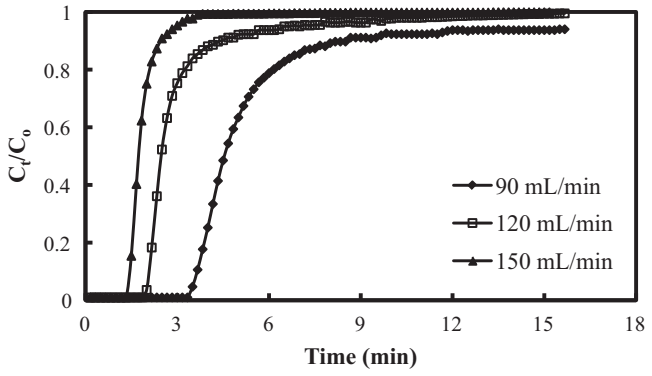

Fig. 5. The CO_2 adsorption breakthrough curve at different feed flow rates, evaluated at temperature of 35 °C, CO_2 concentration of 10% (balance of N_2), bed height of 9.7 cm (3 g), 0.8 M DAAB particle sizes of 1–2 mm.

Table 1
The DAAB CO_2 adsorption capacity and breakthrough time for parameters investigated.

Parameters	Values	Breakthrough time (s)	Adsorption capacity (mg/g)
CO_2 % in the feed	10	930	55.94
	15	670	64.20
	20	600	70.20
Adsorption temperature (°C)	35	930	55.94
	45	610	31.56
	55	490	26.26
Feed flow rate (mL/min)	90	930	55.94
	120	486	39.36
	150	280	27.03
Amount of adsorbent in the adsorption column (g)	2	390	28.90
	3	930	55.94
	4	1020	67.27

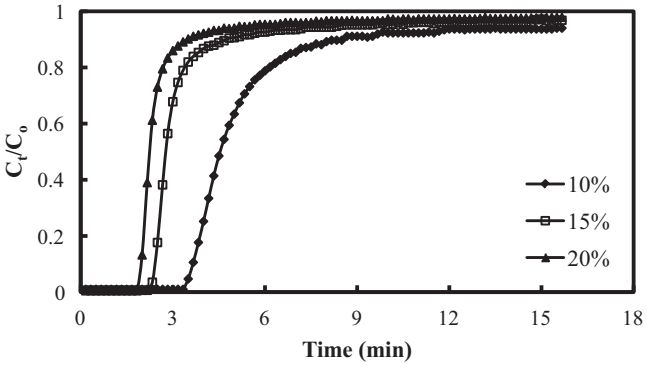

Fig. 6. The CO_2 adsorption breakthrough curve at different CO_2 concentration of the feed (balance of N_2), evaluated at temperature of 35 °C, feed flow rate of 90 mL/min, bed height of 9.7 cm (3 g), 0.8 M DAAB particle sizes of 1–2 mm.

of adsorption capacity of the adsorbent from 55.94 to 70.20 mg/g for the feed percentage increase of CO_2 from 10 to 20%, respectively (Table 1). The porosity of the DAAB enhanced physical adsorption while, the numerous amine groups on its surface (revealed by the FTIR spectrum) promoted chemical interaction with the CO_2 molecules which was found to be increasing with corresponding increase of the feed concentration. Increasing the feed concentration corresponded to increase in the concentration gradient or driving force and this led to shortening of the breakthrough point as depicted in Fig. 6. Consequently, decreasing the initial inlet (mixed CO_2 and N_2) concentration enhanced treatment of larger volume of the effluent as reflected by longer breakthrough curve due to reduced mass transfer or diffusion coefficient and slower saturation of the system [28].

3.6. Effect of adsorption column temperature on CO_2 capture

Effects of CO_2 capture temperature at various column temperatures (35, 45 and 55 °C) are presented in Fig. 7. The performance of an adsorbent with respect to the operating temperature gives information on its suitability in post or pre-combustion gas system. Unfavorable CO_2 capture was observed with increase in the adsorption column temperature such that the maximum capacities were 55.94, 31.56 and 26.26 mg/g for 35, 45 and 55 °C, respectively (Table 1). The CO_2 exothermic adsorption by DAAB was physisorptive which was attributed to the porous nature of the adsorbent as determined by the BET analysis. It was observed that lower temperature of adsorption promoted intense selective interactions

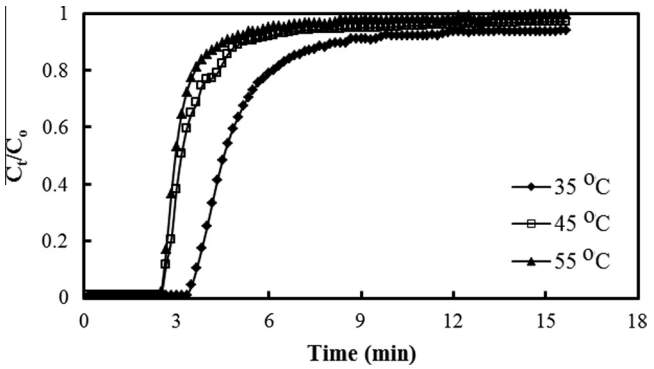

Fig. 7. The CO_2 adsorption breakthrough curve at different column temperatures, evaluated at feed flow rate of 90 mL/min, 10% CO_2 feed concentration (balance of N_2), bed height of 9.7 cm (3 g), 0.8 M DAAB particle sizes of 1–2 mm.

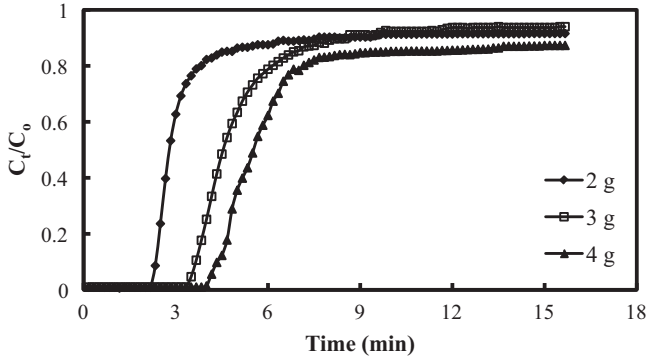

Fig. 8. The CO_2 adsorption breakthrough curve at different bed heights, evaluated at temperature of 35 °C, feed flow rate of 90 mL/min, 10% CO_2 concentration in the feed (balance of N_2), 0.8 M DAAB particle sizes of 1–2 mm.

between impregnated basic amine group on the activated alumina (DAAB) and the acidic CO_2 gas resulting to higher adsorption capacity; in a similar manner, carbon adsorbent modified with nitrogen compound showed higher adsorption of CO_2 gas at room temperature than at elevated temperatures [29].

3.7. Effect of DAAB bed height on CO_2 adsorption breakthrough curves

It is known that specific surface area and fixable binding sites for adsorbate is increased with increase in the adsorbent bed height thereby leading to more volume of effluent gas treatment as a result of larger service area provided [30]. In this research, maximum adsorption capacities of 28.90, 55.94 and 67.27 mg/g were obtained for bed depth increments by addition of 2 (6.3 cm), 3 (9.7 cm) and 4 g (13 cm) DAAB, respectively. The breakthrough curves for effect of bed heights on the CO_2 adsorption are presented in Fig. 8. It is believed that shorter bed depths promotes axial dispersion due to insufficient contact period or interaction between the CO_2 gas molecules and the DAAB surfaces in the column adsorption experiments [31].

3.8. Comparison of adsorption capacity of DAAB for CO_2 uptake

The adsorption capacity of the functionalized activated alumina beads with 0.8 M ethylenediamine (DAAB) for CO_2 uptake (evaluated at temperature of 35 °C, feed flow rate of 90 mL/min, 10% CO_2 concentration in the feed (balance of N_2), 3 g of 0.8 M DAAB particle sizes of 1–2 mm) was compared with other adsorbents in the literature. An appreciable sorption capacity exhibited by the DAAB was attributed to the presence of some amine groups emanating from the modification carried out. Vivid comparison of the CO_2 sorption capacity of DAAB adsorption can be seen in Table 2.

3.9. Reusability of DAAB for CO_2 adsorption

Adsorbent reusability is an excellent quality for economic viability of adsorption processes as it aids in efficient treatment of effluents [2]. The DAAB adsorbent was subjected to thirteen multi-cycles adsorption at a synthetic flue gas (CO_2 and N_2) flow rate of 90 mL/min, DAAB mass of 3 g, column temperature of 35 °C, CO_2 feed stream concentration of 10% and DAAB particle size of 1–2 mm. The DAAB reusability adsorption capacities for the thirteen multi-cycles are shown in Fig. 9.

Observation showed that stability in adsorption capacity of the DAAB was approximately maintained except for the sudden drop after the first cycle. The sorption capacity for the first, second and the thirteenth runs were 55.94, 52.48 and 51.88 mg/g, respectively; there was about 6.4% drop in the DAAB capacity during the thirteenth run. Some residual chemisorbed molecules of the CO_2 that could not be removed at 110 °C may have contributed to the sudden decline in the DAAB capacity [37]. This pattern of adsorption exhibited by DAAB was similarly observed with 3-aminopropyltriethoxysilane/silica fume sorbent employed for multiple CO_2 adsorption/desorption cycling tests [38].

Table 2
Comparison of adsorption capacity of adsorbents for CO_2 adsorption.

Adsorbent	CO_2% in the feed	Adsorption temperature (°C)	Feed flow rate (mL/min)	Adsorption capacity (mmol CO_2/g)	Refs.
DAAB	10	35	90	1.27	This study
TEPA[a]-MCM-41	10	35	–	2.7	[8]
EDA[b]-MCM-41	10	35	–	0.7	[8]
Amine-impregnated titanium oxide	10	75	20	2.24	[9]
DWSNT[c]–NH–$(CH_2)_2$–NH–$(CH_2)_2$–NH_2[d]	–	25	–	2.23	[32]
Amine-based sorbent	1	30	300	1.92	[33]
Carbon vulcan XC72R modified with paraphenylenediamine	100	40	100	0.24	[34]
3-Aminopropyltrimethoxysilane-grafted mesoporous SAPO-34	–	25	–	1.77	[35]
TEPA[e]-TiNT[f]-69	15	60	40	4.37	[36]

[a] TEPA-MCM-41 is tetraethylenepentamine.
[b] EDA is ethylenediamine.
[c] DWSNT is double-walled silica nanotube.
[d] NH–$(CH_2)_2$–NH–$(CH_2)_2$–NH_2 is 3-[2-(2-aminoethylamino) ethylamino] propyl-trimethoxysilane.
[e] TiNT is TiO_2 nanotubes.
[f] TEPA is tetraethylenepentamine.

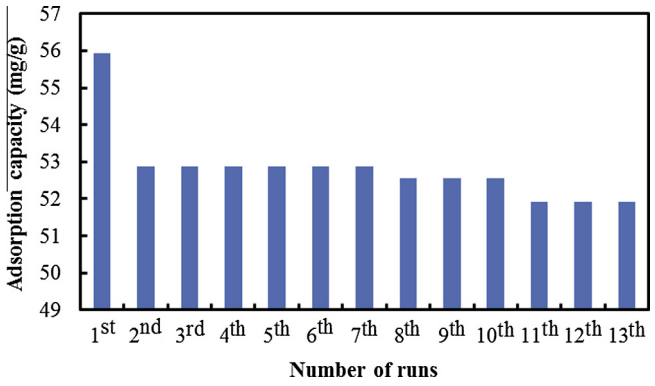

Fig. 9. The 0.8 M DAAB multi-cycle CO_2 adsorption test evaluated at temperature of 35 °C, feed flow rate of 90 mL/min, 10% CO_2 concentration in the feed (balance of N_2), 3 g of DAAB particle sizes of 1–2 mm.

4. Conclusion

Mesoporous activated alumina was functionalized with diethanolamine and used for selective adsorption of CO_2 from its mixture with nitrogen. The study revealed that the optimum DAAB CO_2 adsorption was at 90 mL/min flow rate, column temperature of 35 °C and CO_2 feed stock concentration of 10%. Modification of the 1–2 mm particle size alumina with 0.8 M diethanolamin gave the best CO_2 adsorption performance. Characterization of the DAAB revealed shrinking of the pore size in the N_2-adsorption test and successful functionalization by the presence of N_2 group in the energy dispersive X-ray microanalysis spectrum. Multi-cycle DAAB CO_2 adsorption experiment revealed that the adsorbent can be reused a number of times before discarding. The DAAB is a promising adsorbent for alleviation of CO_2 pollutant.

Acknowledgments

The authors acknowledge the research grant provided by the Ministry of Science, Technology and Innovation (MOSTI), Malaysia under Science Fund grant (Project No. 06-01-05-SF0513), that resulted in the article.

References

[1] E.R. Monazam, J. Spenik, L.J. Shadle, Fluid bed adsorption of carbon dioxide on immobilized polyethylenimine (PEI): kinetic analysis and breakthrough behavior, Chem. Eng. J. 223 (2013) 795–805.
[2] L. Stevens, K. Williams, W.Y. Han, T. Drage, C. Snape, J. Wood, J. Wang, Preparation and CO_2 adsorption of diamine modified montmorillonite via exfoliation grafting route, Chem. Eng. J. 215–216 (2013) 699–708.
[3] S. García, M.V. Gil, C.F. Martín, J.J. Pis, F. Rubiera, C. Pevida, Breakthrough adsorption study of a commercial activated carbon for pre-combustion CO_2 capture, Chem. Eng. J. 171 (2011) 549–556.
[4] W. Cai, J. Yu, C. Anand, A. Vinu, M. Jaroniec, Facile synthesis of ordered mesoporous alumina and alumina-supported metal oxides with tailored adsorption and framework properties, Chem. Mater. 23 (2011) 1147–1157.
[5] C.S. Lee, Y.L. Ong, M.K. Aroua, W.M.A.W. Daud, Impregnation of palm shell-based activated carbon with sterically hindered amines for CO_2 adsorption, Chem. Eng. J. 219 (2013) 558–564.
[6] R. Chatti, A.K. Bansiwal, J.A. Thote, V. Kumar, P. Jadhav, S.K. Lokhande, R.B. Biniwale, N.K. Labhsetwar, S.S. Rayalu, Amine loaded zeolites for carbon dioxide capture: amine loading and adsorption studies, Microporous Mesoporous Mater. 121 (2009) 84–89.
[7] M.S. Shafeeyan, W.M.A.W. Daud, A. Houshmand, A. Shamiri, A review on surface modification of activated carbon for carbon dioxide adsorption, J. Anal. Appl. Pyrolysis 89 (2010) 143–151.
[8] Z.-L. Liu, Y. Teng, K. Zhang, Y. Cao, W.-P. Pan, CO_2 adsorption properties and thermal stability of different amine-impregnated MCM-41 materials, J. Fuel Chem. Technol. 41 (2013) 469–475.
[9] L. Ma, R. Bai, G. Hu, R. Chen, X. Hu, W. Dai, H.F.M. Dacosta, M. Fan, Capturing CO_2 with amine-impregnated titanium oxides, Energy Fuels 27 (2013) 5433–5439.
[10] S.-T. Yang, J.-Y. Kim, J. Kim, W.-S. Ahn, CO_2 capture over amine-functionalized MCM-22, MCM-36 and ITQ-2, Fuel 97 (2012) 435–442.
[11] S. Bali, T.T. Chen, W. Chaikittisilp, C.W. Jones, Oxidative stability of amino polymer-alumina hybrid adsorbents for carbon dioxide capture, Energy Fuels 27 (2013) 1547–1554.
[12] C.-H. Yu, A review of CO_2 capture by absorption and adsorption, Aerosol Air Qual. Res. 12 (2012) 745–769.
[13] C. Chen, W.-S. Ahn, CO_2 capture using mesoporous alumina prepared by a sol–gel process, Chem. Eng. J. 166 (2011) 646–651.
[14] H. Wu, L. Chen, G. Gao, Y. Zhang, T. Wang, S. Guo, Treatment effect on the adsorption capacity of alumina for removal fluoride, Nano Biomed. Eng. 2 (2010) 231–235.
[15] J.C. Fisher, J. Tanthana, S.S.C. Chuang, Oxide-supported tetraethylene-pentamine for CO_2 capture, Environ. Prog. Sustainable Energy 28 (2009) 589–598.
[16] M.G. Plaza, C. Pevida, B. Arias, J. Fermoso, A. Arenillas, F. Rubiera, J.J. Pis, Application of thermogravimetric to the evaluation of aminated solid sorbents for CO_2 capture, J. Therm. Anal. Calorim. 92 (2008) 601–606.
[17] F. Su, C. Lu, S.-C. Kuo, W. Zeng, Adsorption of CO_2 on amine-functionalized Y-type zeolites, Energy Fuels 24 (2010) 1441–1448.
[18] M. Auta, N.D.A. Darbis, A.T. Mohd Din, B.H. Hameed, Fixed-bed column adsorption of carbon dioxide by sodium hydroxide modified activated alumina, Chem. Eng. J. 233 (2013) 80–87.
[19] W.Q. Jiao, M.B. Yue, Y.M. Wang, M.-Y. He, Synthesis of morphology-controlled mesoporous transition aluminas derived from the decomposition of alumina hydrates, Microporous Mesoporous Mater. 147 (2012) 167–177.
[20] N. Kothalawala, J.P. Blitz, V.M. Gun'ko, M. Jaroniec, B. Grabicka, R.F. Semeniuc, Post-synthesis surface-modified silicas as adsorbents for heavy metal ion contaminants Cd(II), Cu(II), Cr(III), and Sr(II) in aqueous solutions, J. Colloid Interface Sci. 392 (2013) 57–64.
[21] M.R. Davidson, IEA Greenhouse Gas R&D Programme (IEA & GHG), Post combustion carbon capture from coal fired plants-solid sorbents and membranes, in: IEA Clean Coal Centre, Gemini House, 10-18 Putney Hill, London, SW16 6AA, UK, London, 2009, pp. 1–68 .
[22] W. Cai, L. Tan, J. Yu, M. Jaroniec, X. Liu, B. Cheng, F. Verpoort, Synthesis of amino-functionalized mesoporous alumina with enhanced affinity towards Cr(VI) and CO_2, Chem. Eng. J. 239 (2014) 207–215.
[23] C.K. Danny, F.P. John, G. McKay, Film-pore diffusion model for the fixed-bed sorption of copper and cadmium onto bone char, Water Res. 35 (2001) 3876–3886.
[24] E. Malkoc, Y. Nuhoglu, Removal of Ni(II) ions from aqueous solutions using waste of tea factory: adsorption on a fixed-bed column, J. Hazard. Mater. 135 (2006) 328–336.
[25] S. Tushar, K. Asheesh, K. Sanjal, R. Kumar, Carbon dioxide capture using amine functionalized silica gel, Indian J. Chem. 51A (2012) 1214–1222.
[26] M. Auta, B.H. Hameed, Coalesced chitosan activated carbon composite for batch and fixed-bed adsorption of cationic and anionic dyes, Colloids Surf. B 105 (2013) 199–206.
[27] M. Auta, B.H. Hameed, Acid modified local clay beads as effective low-cost adsorbent for dynamic adsorption of methylene blue, J. Ind. Eng. Chem. 19 (2013) 1153–1161.
[28] M.T. Uddin, M. Rukanuzzaman, M.M.R. Khan, M.A. Islam, Adsorption of methylene blue from aqueous solution by jackfruit (*Artocarpus heteropyllus*) leaf powder: a fixed-bed column study, J. Environ. Manage. 90 (2009) 3443–3450.
[29] M.G. Plaza, C. Pevida, A. Arenillas, F. Rubiera, J.J. Pis, CO_2 capture by adsorption with nitrogen enriched carbons, Fuel 86 (2007) 2204–2212.
[30] I.A.W. Tan, A.L. Ahmad, B.H. Hameed, Adsorption of basic dye using activated carbon prepared from oil palm shell: batch and fixed bed studies, Desalination 225 (2008) 13–28.
[31] V.C. Taty-Costodes, H. Fauduet, C. Porte, Y.-S. Ho, Removal of lead (II) ions from synthetic and real effluents using immobilized *Pinus sylvestris* sawdust: adsorption on a fixed-bed column, J. Hazard. Mater. 123 (2005) 135–144.
[32] Y.G. Ko, H.J. Lee, H.C. Oh, U.S. Choi, Amines immobilized double-walled silica nanotubes for CO_2 capture, J. Hazard. Mater. 250–251 (2013) 53–60.
[33] L. He, M. Fan, B. Dutcher, S. Cui, X.-D. Shen, Y. Kong, A.G. Russell, P. McCurdy, Dynamic separation of ultradilute CO_2 with a nanoporous amine-based sorbent, Chem. Eng. J. 189–190 (2012) 13–23.
[34] A. Grondein, D. Bélanger, Chemical modification of carbon powders with aminophenyl and aryl-aliphatic amine groups by reduction of in situ generated diazonium cations: applicability of the grafted powder towards CO_2 capture, Fuel 90 (2011) 2684–2693.
[35] J.-Y. Kim, J. Kim, S.-T. Yang, W.-S. Ahn, Mesoporous SAPO-34 with amine-grafting for CO_2 capture, Fuel 108 (2013) 515–520.
[36] F. Song, Y. Zhao, Y. Cao, J. Ding, Y. Bu, Q. Zhong, Capture of carbon dioxide from flue gases by amine-functionalized TiO_2 nanotubes, Appl. Surf. Sci. 268 (2013) 124–128.
[37] J.A. Thote, R.V. Chatti, K.S. Iyer, V. Kumar, A.N. Valechha, N.K. Labhsetwar, R.B. Biniwale, M.K.N. Yenkie, S.S. Rayalu, N-doped mesoporous alumina for adsorption of carbon dioxide, J. Environ. Sci. 24 (2012) 1979–1984.
[38] J.-L. Liu, R.-B. Lin, Structural properties and reactivities of amino-modified silica fume solid sorbents for low-temperature CO_2 capture, Powder Technol. 241 (2013) 188–195.