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APPENDICES

Appendix A CO_2 Adsorption Isotherms of Adsorbents at 30, 50, and 75 °C

Table A1 CO_2 adsorption isotherms of adsorbents at 30 °C

Adsorbent	P_{eq} (atm)	$N_{accumulation}$ (mmol/g)
PSAC	0.2082	2.4201
	0.4463	2.5580
	0.6252	2.6233
	0.8252	2.6853
	1.0204	2.7619
	1.0884	2.8763
CSAC	0.2082	2.5438
	0.4340	2.7469
	0.6381	2.8783
	0.8163	2.9910
	1.0293	3.1018
	1.1354	3.1652
0.27 wt% PBZ/CSAC methanol	0.1701	2.5944
	0.4551	2.7920
	0.6211	2.8881
	0.8034	2.9993
	1.0245	3.1034
	1.1054	3.1210

Table A1 CO_2 adsorption isotherms of adsorbents at 30 °C (cont.)

Adsorbent	P_{eq} (atm)	$N_{accumulation}$ (mmol/g)
0.92 wt% PBZ/CSAC methanol	0.2129	2.5109
	0.4252	2.6551
	0.6122	2.7747
	0.8163	2.8604
	1.0204	2.9341
	1.1054	2.9598
2.60 wt% PBZ/CSAC methanol	0.2340	2.3487
	0.4252	2.4801
	0.6211	2.5179
	0.8204	2.5530
	1.0204	2.6197
	1.0803	2.6941
0.58 wt% PBZ/CSAC chloroform	0.174	1.6096
	0.4170	1.7552
	0.6381	1.8358
	0.8333	1.9008
	1.0245	1.9658
	1.1184	1.9970
1.97 wt% PBZ/CSAC chloroform	0.1959	1.4983
	0.4082	1.6259
	0.6293	1.7050
	0.8293	1.7689
	1.0333	1.8173
	1.0884	1.8505

Table A2 CO_2 adsorption isotherms of adsorbents at 50 °C

Adsorbent	P_{eq} (atm)	$N_{accumulation}$ (mmol/g)
PSAC	0.2510	1.7331
	0.4422	1.8243
	0.6170	1.8782
	0.8163	1.9176
	1.0286	1.9746
	1.1014	2.0022
CSAC	0.2299	1.8235
	0.4293	1.9414
	0.6163	1.9907
	0.8034	2.0669
	1.0204	2.1260
	1.0884	2.1647
0.27 wt% PBZ/CSAC methanol	0.2041	1.8839
	0.4082	1.9923
	0.6122	2.1110
	0.8163	2.1878
	1.0204	2.2747
	1.0884	2.3069

Table A2 CO_2 adsorption isotherms of adsorbents at 50 °C (cont.)

Adsorbent	P_{eq} (atm)	$N_{accumulation}$ (mmol/g)
0.92 wt% PBZ/CSAC methanol	0.2041	1.8433
	0.4340	1.9396
	0.6163	1.9947
	0.8163	2.0761
	1.0204	2.1213
	1.0884	2.1466
2.60 wt% PBZ/CSAC methanol	0.2340	1.6990
	0.4170	1.788
	0.6041	1.8862
	0.8122	1.9551
	1.0204	2.0009
	1.0884	2.0332
0.58 wt% PBZ/CSAC chloroform	0.2299	1.2357
	0.4000	1.3578
	0.6122	1.4188
	0.8293	1.4652
	1.0122	1.4945
	1.0973	1.5092
1.97 wt% PBZ/CSAC chloroform	0.2211	1.2091
	0.4041	1.2711
	0.6122	1.3182
	0.825	1.3479
	1.0204	1.3950
	1.1054	1.4098

Table A3 CO_2 adsorption isotherms of adsorbents at 75 °C

Adsorbent	P_{eq} (atm)	$N_{accumulation}$ (mmol/g)
PSAC	0.2422	1.0342
	0.4463	1.0765
	0.6163	1.1373
	0.825	1.1709
	1.0333	1.2098
	1.0884	1.2518
CSAC	0.3238	1.1190
	0.4463	1.1830
	0.6122	1.2221
	0.7952	1.2692
	1.0204	1.3061
	1.1143	1.3251
0.27 wt% PBZ/CSAC methanol	0.1912	1.2605
	0.4082	1.2916
	0.6163	1.3325
	0.8204	1.3978
	1.0245	1.4596
	1.0884	1.4779

Table A3 CO_2 adsorption isotherms of adsorbents at 75 °C (cont.)

Adsorbent	P_{eq} (atm)	$N_{accumulation}$ (mmol/g)
0.92 wt% PBZ/CSAC methanol	0.2082	1.1884
	0.4122	1.2506
	0.6122	1.3095
	0.8204	1.3400
	1.0204	1.3568
	1.0925	1.3799
2.60 wt% PBZ/CSAC methanol	0.2211	1.1104
	0.4211	1.1559
	0.599	1.2156
	0.8204	1.2487
	1.024	1.2806
	1.0803	1.2978
0.58 wt% PBZ/CSAC chloroform	0.2422	0.7388
	0.4211	0.7524
	0.6211	0.7660
	0.8163	0.7956
	1.0245	0.8115
	1.0884	0.8410
1.97 wt% PBZ/CSAC chloroform	0.3531	0.6939
	0.4510	0.7078
	0.6122	0.7217
	0.8082	0.7495
	1.0122	0.7633
	1.1014	0.7772

Appendix B CO_2 Adsorption Isotherms in Three Times of the Adsorption-desorption Cycles Over Adsorbents at 30, 50, and 75 °C

Table B1 CO_2 adsorption isotherms at 30 °C of the CSAC and the regenerated CSAC

Adsorbent	P_{eq} (atm)	$N_{accumulation}$ (mmol/g)
CSAC	0.2082	2.5438
	0.4340	2.7469
	0.6381	2.8783
	0.8163	2.9910
	1.0293	3.1018
	1.1354	3.1652
1st regenerated CSAC	0.2253	2.4677
	0.4381	2.6319
	0.6422	2.6981
	0.825	2.7961
	1.0293	2.8623
	1.1054	2.9126
2nd regenerated CSAC	0.2211	2.6112
	0.4510	2.7294
	0.6163	2.8173
	0.8082	2.9025
	1.0163	2.9877
	1.0973	3.0042

Table B2 CO_2 adsorption isotherms at 30 °C of the 0.27 wt% PBZ/CSAC and the regenerated sample

Adsorbent	P_{eq} (atm)	$N_{accumulation}$ (mmol/g)
0.27 wt% PBZ/CSAC	0.1701	2.5944
	0.4551	2.7920
	0.6211	2.8881
	0.8034	2.9993
	1.024	3.1034
	1.1054	3.1210
1st regenerated 0.27 wt% PBZ/CSAC	0.2211	2.5803
	0.4252	2.7123
	0.6211	2.8198
	0.8204	2.9699
	1.0163	3.0836
	1.1013	3.1017
2nd regenerated 0.27 wt% PBZ/CSAC	0.2170	2.5765
	0.4170	2.7465
	0.5990	2.8282
	0.8163	2.9271
	1.0204	3.0543
	1.0803	3.065

Table B3 CO_2 adsorption isotherms at 30 °C of the 0.92 wt% PBZ/CSAC and the regenerated sample

Adsorbent	P_{eq} (atm)	$N_{accumulation}$ (mmol/g)
0.92 wt% PBZ/CSAC	0.2129	2.5109
	0.425	2.6551
	0.6122	2.7747
	0.8163	2.8604
	1.0204	2.9341
	1.1054	2.9598
1st regenerated 0.92 wt% PBZ/CSAC	0.2082	2.4448
	0.4082	2.6285
	0.61222	2.7159
	0.8204	2.7932
	1.0293	2.8869
	1.0973	2.8969
2nd regenerated 0.92 wt% PBZ/CSAC	0.2082	2.4639
	0.4122	2.6504
	0.6122	2.7395
	0.8204	2.7827
	1.0204	2.8812
	1.0925	2.8723

Table B4 CO_2 adsorption isotherms at 30 °C of the 2.60 wt% PBZ/CSAC and the regenerated sample

Adsorbent	P_{eq} (atm)	$N_{accumulation}$ (mmol/g)
2.60 wt% PBZ/CSAC	0.2340	2.3487
	0.425	2.4800
	0.6211	2.5179
	0.8204	2.5530
	1.0204	2.6196
	1.0803	2.6941
1st regenerated 2.60 wt% PBZ/CSAC	0.2082	2.2903
	0.4082	2.4223
	0.6122	2.4798
	0.8204	2.5499
	1.0293	2.5636
	1.0973	2.6517
2nd regenerated 2.60 wt% PBZ/CSAC	0.1871	2.2693
	0.4122	2.4025
	0.6211	2.4552
	0.8163	2.5193
	1.0204	2.5495
	1.0844	2.5905

Table B5 CO_2 adsorption isotherms at 50 °C of the CSAC and the regenerated CSAC

Adsorbent	P_{eq} (atm)	$N_{accumulation}$ (mmol/g)
CSAC	0.2299	1.8235
	0.4293	1.9414
	0.6163	1.9907
	0.8034	2.0669
	1.0204	2.1260
	1.0884	2.1647
1st regenerated CSAC	0.2129	1.8166
	0.4211	1.9569
	0.6163	2.0195
	0.8293	2.0346
	1.0163	2.1122
	1.1054	2.1273
2nd regenerated CSAC	0.3061	1.6615
	0.4170	1.8315
	0.6163	1.9001
	0.825	1.9494
	1.0204	2.0015
	1.1143	2.0179

Table B6 CO_2 adsorption isotherms at 50 °C of the 0.27 wt% PBZ/CSAC and the regenerated sample

Adsorbent	P_{eq} (atm)	$N_{accumulation}$ (mmol/g)
0.27 wt% PBZ/CSAC	0.2041	1.8839
	0.4082	1.9923
	0.6122	2.1110
	0.8163	2.1878
	1.0204	2.2747
	1.0884	2.3068
1st regenerated 0.27 wt% PBZ/CSAC	0.2211	1.8586
	0.4170	1.9703
	0.6122	2.0717
	0.8163	2.1334
	1.0204	2.2403
	1.0925	2.2875
2nd regenerated 0.27 wt% PBZ/CSAC	0.1912	1.8201
	0.4381	1.9563
	0.6122	2.069
	0.8252	2.1234
	1.0292	2.2097
	1.0884	2.2343

Table B7 CO_2 adsorption isotherms at 50 °C of the 0.92 wt% PBZ/CSAC and the regenerated sample

Adsorbent	P_{eq} (atm)	$N_{accumulation}$ (mmol/g)
0.92 wt% PBZ/CSAC	0.2041	1.8433
	0.4340	1.9396
	0.6163	1.9947
	0.8163	2.0761
	1.0204	2.1213
	1.0884	2.1466
1st regenerated 0.92 wt% PBZ/CSAC	0.1870	1.8064
	0.4293	1.9224
	0.6122	1.9559
	0.8082	2.0179
	1.0204	2.1110
	1.0925	2.1174
2nd regenerated 0.92 wt% PBZ/CSAC	0.2082	1.8135
	0.4122	1.9389
	0.6122	1.9623
	0.8163	2.0254
	1.0245	2.0976
	1.0925	2.1143

Table B8 CO_2 adsorption isotherms at 50 °C of the 2.60 wt% PBZ/CSAC and the regenerated sample

Adsorbent	P_{eq} (atm)	$N_{accumulation}$ (mmol/g)
2.60 wt% PBZ/CSAC	0.2340	1.6990
	0.4170	1.788
	0.6041	1.8862
	0.8122	1.9551
	1.0204	2.001
	1.0884	2.0332
1st regenerated 2.60 wt% PBZ/CSAC	0.2211	1.6434
	0.4122	1.7344
	0.6082	1.8601
	0.8204	1.9182
	1.0245	1.9746
	1.0925	2.0063
2nd regenerated 2.60 wt% PBZ/CSAC	0.2041	1.6631
	0.4082	1.7523
	0.6122	1.8243
	0.8163	1.8838
	1.0204	1.9469
	1.0884	1.9759

Table B9 CO_2 adsorption isotherms at 75 °C of the CSAC and the regenerated CSAC

Adsorbent	P_{eq} (atm)	$N_{accumulation}$ (mmol/g)
CSAC	0.3238	1.1190
	0.4463	1.1830
	0.6122	1.2221
	0.7952	1.2692
	1.0204	1.3061
	1.1143	1.3251
1st regenerated CSAC	0.2381	1.0448
	0.4292	1.1181
	0.6211	1.1594
	0.8292	1.2029
	1.0245	1.2602
	1.0973	1.2739
2nd regenerated CSAC	0.2510	1.1021
	0.4252	1.1760
	0.5993	1.2810
	0.8082	1.3406
	1.0333	1.3549
	1.1143	1.3692

Table B10 CO_2 adsorption isotherms at 75 °C of the 0.27 wt% PBZ/CSAC and the regenerated sample

Adsorbent	P_{eq} (atm)	$N_{accumulation}$ (mmol/g)
0.27 wt% PBZ/CSAC	0.1912	1.260
	0.4082	1.2916
	0.6163	1.3325
	0.8204	1.3978
	1.024	1.4596
	1.0884	1.4779
1st regenerated 0.27 wt% PBZ/CSAC	0.2592	1.2295
	0.4252	1.259
	0.6163	1.3092
	0.8293	1.3568
	1.0333	1.4106
	1.1054	1.4330
2nd regenerated 0.27 wt% PBZ/CSAC	0.1660	1.2353
	0.4463	1.2754
	0.6122	1.3106
	0.8082	1.3758
	1.0204	1.4322
	1.1014	1.4534

Table B11 CO_2 adsorption isotherms at 75 °C of the 0.92 wt% PBZ/CSAC and the regenerated sample

Adsorbent	P_{eq} (atm)	$N_{accumulation}$ (mmol/g)
0.92 wt% PBZ/CSAC	0.2082	1.1884
	0.4122	1.2506
	0.6122	1.3095
	0.8204	1.3400
	1.0204	1.3568
	1.0925	1.3799
1st regenerated 0.92 wt% PBZ/CSAC	0.2252	1.1448
	0.4252	1.2285
	0.6082	1.2759
	0.8163	1.3032
	1.0333	1.3269
	1.1054	1.3469
2nd regenerated 0.92 wt% PBZ/CSAC	0.2129	1.1221
	0.4252	1.2044
	0.6122	1.2554
	0.8163	1.2921
	1.0204	1.3242
	1.1054	1.3321

Table B12 CO_2 adsorption isotherms at 75 °C of the 2.60 wt% PBZ/CSAC and the regenerated sample

Adsorbent	P_{eq} (atm)	$N_{accumulation}$ (mmol/g)
2.60 wt% PBZ/CSAC	0.2211	1.1104
	0.4211	1.1559
	0.599	1.2156
	0.8204	1.2487
	1.024	1.2806
	1.0803	1.2978
1st regenerated 2.60 wt% PBZ/CSAC	0.2082	1.0753
	0.4082	1.1263
	0.6122	1.1937
	0.8204	1.2072
	1.0293	1.2510
	1.0973	1.2685
2nd regenerated 2.60 wt% PBZ/CSAC	0.2340	1.0620
	0.4252	1.1189
	0.6211	1.1873
	0.8204	1.2275
	1.0204	1.2450
	1.0803	1.2543

Appendix C Comparison of CO_2 Adsorption Capacity of Adsorbents at 1 atm

Table C1 Comparison of CO_2 adsorption capacity of adsorbents at 1 atm

Adsorbent	Amine	%wt	Temperature (°C)	CO_2 adsorption capacity (mmol/g)	reference
AC	PBZ	0.27	30	3.01	This work
AC	PEI	0.73	30	3.08	Ritmongkolpun, 2013
AC	PEI	0.22	30	2.75	Pipatsantipong, 2012
AC	PBZ	0.27	50	2.23	This work
AC	PEI	0.16	50	2.13	Ritmongkolpun, 2013
PME	PEI	30	50	2.61	Heydari-Gorji and Sayari, 2011
AC	PBZ	0.27	75	1.42	This work
AC	PEI	1.16	75	1.35	Ritmongkolpun, 2013
AC	PEI	0.28	75	2.84	Pipatsantipong, 2012
Silica gel	PEI	50	75	3.07	Xu *et al.*, 2003
MCM-41	PEI	50	75	2.55	Xu *et al.*, 2003
MCM-41	PEI	75	75	3.02	Xu *et al.*, 2003
MCM-48	PEI	50	75	2.70	Son *et al.*, 2008
KIT-6	PEI	50	75	3.07	Son *et al.*, 2008
SBA-16	PEI	50	75	2.93	Son *et al.*, 2008
SBA-15	PEI	50	75	2.89	Ma *et al.*,2009

Appendix D Calculation for CO_2 Adsorption Capacity in Unit of mmol/g of Adsorbent

From; $$n_i = \frac{P_1(V_1+V_2)}{ZRT} - \frac{P_2(V_1+V_2)}{ZRT}$$

where,

n_i= mole of adsorbed CO_2, mol

P_1 = pressure of the system before equilibrium, atm

P_2= pressure of the system after equilibrium, atm

V_1= volume of a manifold, cm^3

V_2= volume of a cylinder with adsorbent, cm^3

Z = compressibility factor

R = 82.05 cm^3atm/mol K

T = temperature of the sample, K

Properties of CO_2 (Daubert *et al.*, 1982)

Critical Temperature (T_r) = 31.04 °C (304.2 K)

Critical Pressure (P_r) = 72.8 atm (7382 kPa)

Acentric Factor (ω) = 0.2276

Step 1: To find pressure reduced (Pr)

Data:

Initial Pressure (P_1) = 11.81 psi (0.8034 atm)

Equilibrium Pressure (P_2) = 2.19 psi (0.1490 atm)

Solution;

$$P_r = \frac{P}{P_C}$$

$$P_{r1} = \frac{P}{P_C} = \frac{P_1}{P_c} = \frac{0.8034 \text{ atm}}{72.8 \text{ atm}} = 0.0110$$

P_{r2}=0.0020

Step 2: To find temperature reduced (T_r)

Data: Temperature adsorption = 30 °C (303 K)

Solution;

$$T_r = \frac{T}{T_c}$$

$$T_r = \frac{T}{T_c} = \frac{303\ K}{304.2\ K} \sim 1$$

Step 3: To find compressibility factor (Z)

Data: $P_{r1} = 0.0110$, $P_{r2} = 0.0020$

$T_r = 1$

From Figure D1, Compressibility factor (Z_1) = 0.98

Compressibility factor (Z_2) = 0.99

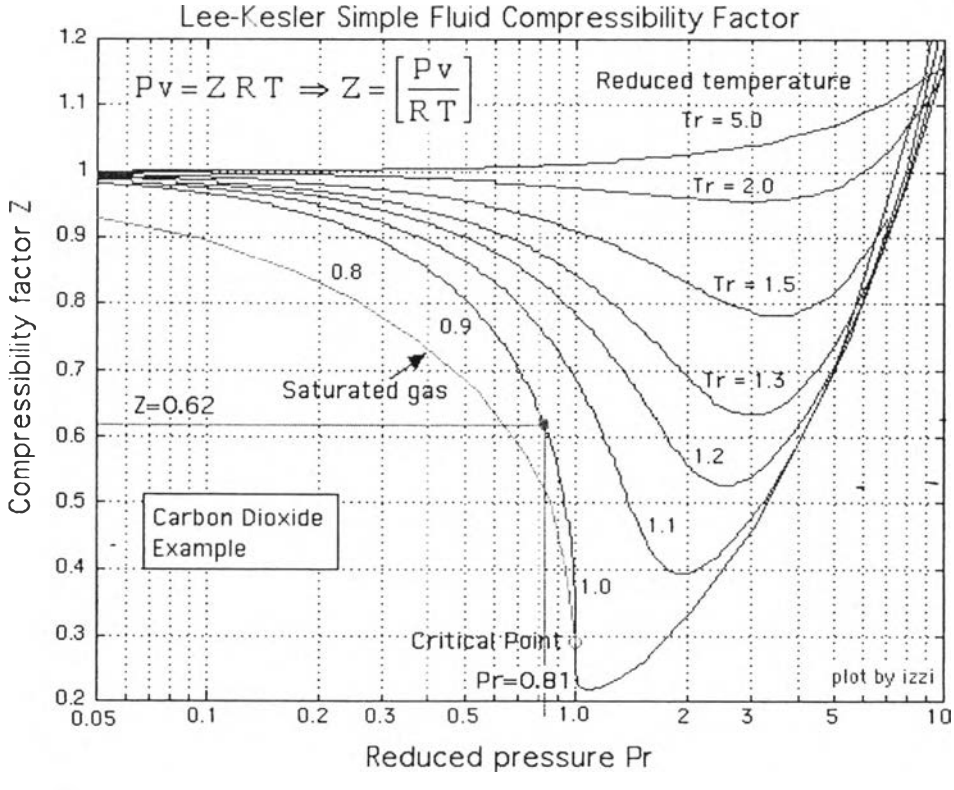

Figure D1 Relationship between the reduced pressure and reduced temperature related on compressibility factor (Lee and Kesler, 1975).

Step 4: To find CO_2 adsorption capacity (mmol/g)

Data:

Temperature adsorption = 30 °C (303 K)

Volume of reactor and manifold (V_1+V_2) = 94.82845 cm^3

R = 82.05 cm^3*atm/mol/K

Solution;-

$$n_i = \frac{P_1(V_1+V_2)}{ZRT} - \frac{P_2(V_1+V_2)}{ZRT}$$

$$n_i = \frac{0.8034(94.82845)}{(0.98)(82.05)(303)} - \frac{0.8034(94.82845)}{(0.98)(82.05)(303)} = 2.5041\times10^{-3} \text{ mol/g}$$

n_i= 2.5041 mmol/g

Appendix E CO_2 Adsorption Measurement

From the CO_2 adsorption experiment

The plot of the data between CO_2 pressure and time is shown as below.

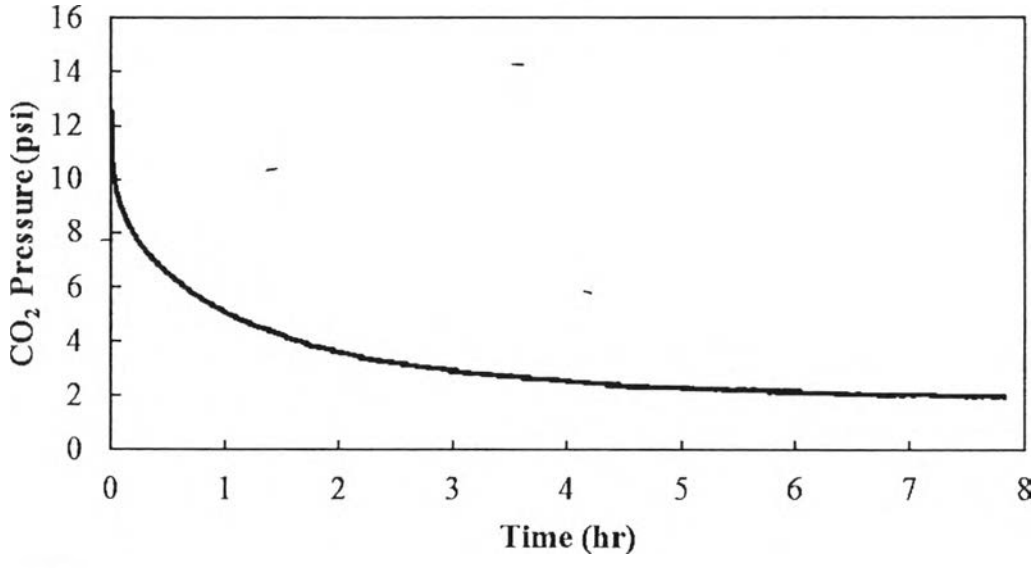

Figure E1 CO_2 pressure of CO_2 adsorption measurement as a function of time.

Appendix F Calculation the BZ-impregnated on the CSAC

From; $$q_e=(C_0-C_e)\frac{V_{BZ\ solution}}{m_{adsorbent}}$$

Step 1: Measure concentration via UV-visible spectrometer

The absorbance at 279 nm

Concentration of BZ solution before impregnation → 3.831 g/L

Concentration of BZ solution after impregnation → 2.536 g/L

Step 2: Calculate BZ- impregnated sample

$$q_e=(3.831-2.536)\text{g/L}\frac{20\text{ mL}}{1\text{ g}}\text{x}\frac{1\text{ L}}{1000\text{ mL}}$$

q_e=0.026 gBZ/gCSAC

q_e=2.60 wt% BZ/CSAC

So; BZ-impregnated on CSAC = 2.60 wt% BZ/AC

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Presentations and Proceedings:

1. Puntuchinrungsima, S.; Rangsunvigit, P.; Chaisuwan, T.; and Kulprathipanja, S. (2014, April 22) Enhancement of CO_2 Adsorption on Modified Activated Carbon and Novel Adsorbents. Proceedings of The 5th Research Symposium on Petrochemical and Materials Technology and The 20th PPC Symposium on Petroleum, Petrochemicals, and Polymers, Bangkok, Thailand.
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