Korean J. Chem. Eng., 33(12), 3465-3472 (2016)
DOI: 10.1007/s11814-016-0186-3

pISSN: 0256-1115
eISSN: 1975-7220

CO_2 capture using aqueous solutions of K_2CO_3+2-methylpiperazine and monoethanolamine: Specific heat capacity and heat of absorption

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(*Received 25 March 2016 • accepted 28 June 2016*)

Abstract−The specific heat capacity, heat of CO_2 absorption, and CO_2 absorption capacity of aqueous solutions of potassium carbonate (K_2CO_3)+2-methylpiperazine (2-MPZ) and monoethanolamine (MEA) were measured over various temperatures. An aqueous solution of K_2CO_3+2-MPZ is a promising absorbent for CO_2 capture because it has high CO_2 absorption capacity with improved absorption rate and degradation stability. Aqueous solution of MEA was used as a reference absorbent for comprison of the thermodynamic characteristics. Specific heat capacity was measured using a differential scanning calorimeter (DSC), and heat of CO_2 absorption and CO_2 absorption capacity were measured using a differential reaction calorimeter (DRC). The CO_2-loaded solutions had lower specific heat capacities than those of fresh solutions. Aqueous solutions of K_2CO_3+2-MPZ had lower specific heat capacity than those of MEA over the temperature ranges of 303-353 K. Under the typical operating conditions for the process (CO_2 loading=0.23 mol-CO_2·mol^{-1}-solute in fresh solution, T=313 K), the heat of absorption ($-\Delta H_{abs}$) of aqueous solutions of K_2CO_3+2-MPZ and MEA were approximately 49 and 75 kJ·mol-CO_2, respectively. The thermodynamic data from this study can be used to design a process for CO_2 capture.

Keywords: CO_2 Capture, Absorption, Monoethanolamine, Potassium Carbonate

INTRODUCTION

The reduction of greenhouse gases is more becoming important because of natural disasters caused by global warming. Carbon dioxide (CO_2) capture, usage and storage (CCUS) is one of the solutions needed to reduce CO_2 emissions from industrial facilities. Chemical absorption using aqueous solutions of amine is the most commonly used in the CO_2 capture process. The conventional absorption process using chemical absorbents consists of the CO_2 absorber and the stripper [1,2]. In the absorber, CO_2-containing gas is put in contact with an absorbent counter-current. When the CO_2-rich solution is heated (373-393 K), the absorbent is regenerated, and high-purity CO_2 gas is released from the top of the stripper. Therefore, the reboiler heat duty of the stripper is the major energy penalty in the process [3-5]. The heat required to regenerate the absorbent can be represented as follows [6]:

$$Q_{reg}=Q_{sens}+Q_{vap,H_2O}+Q_{abs,CO_2} \quad (1)$$

where Q_{sens} is the sensible heat required to raise the temperature of the absorbent downstream of the heat exchanger to the reboiler temperature, Q_{vap,H_2O} is the heat of evaporation required to produce stripping steam in the reboiler, and Q_{abs,CO_2} is heat of CO_2 absorption.

Good data on the heat capacity and heat of CO_2 absorption of the absorbents are required to design the absorption process. Several researchers have measured and/or calculated heat capacities [7-13] and heats of CO_2 absorption [14-24] of aqueous solutions of amine. Among them, the researchers studied heat of CO_2 absorption of aqueous solutions of alkanolamines: primary amine, monoethanolamine (MEA) [14-19] and 2-amino-2-methyl-1-propanol (AMP) [18-20]; secondary amine, diethanolamine (DEA) [19,21]; tertiary amine, triethanolamine (TEA) [19] and methyldiethanolamine (MDEA) [19,22]. The results showed that heat of CO_2 absorption of theses substances, represented by enthalpy changes ($-\Delta H_{abs}$), followed the order: TEA<MDEA<DEA<MEA. Kim and Svendsen [23] measured heats of CO_2 absorption of aqueous solutions of various amines and amine blends. Chen and Rochelle [24] calculated the heats of CO_2 absorption of concentrated aqueous solutions of piperazine derivatives. The $-\Delta H_{abs}$ values of all the piperazine (PZ) derivatives were around 70 kJ·mol^{-1}-CO_2 (cf. 7 m MEA: 81-84 kJ·mol^{-1}-CO_2) at 313 K.

CO_2 absorption process using aqueous solution of potassium carbonate (K_2CO_3) is effective at high temperatures and pressures (*e.g.*, the Benfield process). At low temperatures, however, the performance of the aqueous solution of K_2CO_3 is limited by several factors, such as a slow CO_2 absorption rate and solid salt (potassium bicarbonate, $KHCO_3$) formation. Various amines have been added to aqueous solutions of K_2CO_3 to hybridize their CO_2 absorption performance. Laddha and Danckwerts [25] studied the kinetics of the reactions of aqueous solutions of K_2CO_3+MEA and K_2CO_3+DEA; the presence of electrolytes appeared to increase the rates of reaction between CO_2 and these amines. Several researchers concluded that adding certain amines to aqueous solutions of K_2CO_3 enhanced absorption rates and reduced heat of absorption at typical absorber conditions for CO_2 removal [26-29]. Cullinane

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‡This article is dedicated to Prof. Sung Hyun Kim on the occasion of his retirement from Korea University.

and Rochelle [27] measured the CO_2 absorption rates into aqueous solutions of K_2CO_3+PZ in a wetted-wall column (WWC). The CO_2 absorption rate into the aqueous solution of 20 wt% K_2CO_3+5 wt% PZ was found to be similar to that of an aqueous solution of 30 wt% MEA. The addition of PZ to the aqueous solution of K_2CO_3 increased the absorption capacity because the large quantity of bicarbonate (HCO_3^-)/carbonate (CO_3^{2-}) in the solutions served as a buffer that reduced the protonation of PZ [28,29].

K_2CO_3 forms ions such as K^+, OH^-, and HCO_3^- in the aqueous solution. In the pH range of interest for commercial operation (pH >10), and using an aqueous K_2CO_3 solution, the predominant reaction is the direct reaction between the CO_2 (aq) and the hydroxyl ion (OH^-) as indicated in reaction of Eq. (2) [30].

$$CO_2(aq)+OH^- \leftrightarrow HCO_3^- \quad (2)$$

$$HCO_3^-+OH^- \leftrightarrow CO_3^{2-}+H_2O \quad (3)$$

The general reaction mechanism for both inorganic and organic rate-promotion-additives in the carbonate solution can be represented as following the two steps indicated by reactions in Eqs. (4) and (5) [30,31]:

$$CO_2(aq)+promoter \leftrightarrow intermediate \quad (4)$$

$$intermediate+OH^- \leftrightarrow HCO_3^-+promoter \quad (5)$$

The difference between the homogeneous catalysis and shuttle mechanism additives is related to the relative rate of the second step (Eq. (5)) [32]. If the promoter is a kind of primary or secondary amine, in the region near the gas-liquid interface, CO_2 reacts with promoter to form an intermediate. When the amine type promoter is used at moderate temperature, this reaction of Eq. (4) is fast enough to enhance the mass transfer rate, while the reaction of Eq. (5) is so much slower that it can only take place in the bulk of the liquid.

Aqueous solution of K_2CO_3+2-methylpiperazine (2-MPZ), is a promising absorbent-combination due to its high CO_2 absorption capacity and degradation stability, and is expected to have a low heat of absorption [33,34]. However, there is no literature presenting the specific heat capacity and heat of CO_2 absorption data for this absorbent. Therefore, we investigated the physical and thermodynamic characteristics of the aqueous solution of K_2CO_3+2-MPZ to obtain information for CO_2 capture process design.

EXPERIMENTAL

1. Materials

Absorbent concentrations of 15+5, 15+7.5, and 15+10 wt% K_2CO_3+2-MPZ were prepared using deionized water. The absorbent concentrations selected were determined based on the results of the previous study [33]. Aqueous solutions of 20-30 wt% MEA have been used in industrial processes [35]; therefore, 20, 22.5, 25, and 30 wt% aqueous solutions of MEA were prepared using deionized water for comparison. The following reagents were used as received: K_2CO_3 (Samchun Chemicals Co. Korea, anhydrous 99.5%), 2-MPZ (Acros Co., 98%), and MEA (Sigma-Aldrich Co., 99%). 30 vol% CO_2 gas mixed with 70 vol% N_2 was used to obtain the heat of CO_2 absorption in the absorbents, using a differential reaction calorimeter (DRC).

2. Experimental Procedure

The specific heat capacities of the fresh and CO_2-loaded absorbents were measured with a differential scanning calorimeter (DSC) (μDSC3 evo model, Setaram Co.) [34]. Two closed batch cells, a reference cell and a measuring cell, were used in the specific heat capacity measurements. The measuring cell was filled with samples and put in the calorimetric block. Before measurement was started, the temperature of the furnace was kept at the initial temperature of 300.5 K for at least 10 min. The initial and final temperatures were maintained for 20 min at 300.5 K and 355.5 K, respectively, and the scanning rate was 0.2 K·min^{-1}. The CO_2-loaded samples for specific heat capacity measurements were prepared by using a semi-batch-type absorption apparatus. The configuration and experimental procedure of the semi-batch-type apparatus were similar to that previously reported except for the reactor size (diameter, height) and gas flow rate [36]. The reactor (internal volume 500 mL) was filled with 250 mL of fresh absorbent. Then, 30 vol% CO_2 was injected at a rate of 500 mL·min^{-1} using a mass flow controller (MFC; 5850E model, Brooks Co.). Gas emitted from the reactor was sent to the gas chromatograph (GC; 7890A model, Agilent Co.) for measuring CO_2 concentration. The CO_2 loading of the absorbents was calculated by gas analysis using the GC.

The heat of CO_2 absorption of the absorbents was measured with a DRC (Setaram Co.). The experimental apparatus and procedure were described in previous publications [36,37]. The reactors (internal volume 250 mL) were each filled with 150 g of absorbent, and were stirred at 250 rpm. Next, 99.999 vol% N_2 was piped into the measuring reactor to remove impurities, and then 30 vol% CO_2 was injected into the measuring reactor at a flow rate of 150 mL·min^{-1} by using an MFC.

RESULTS AND DISCUSSION

1. Specific Heat Capacity

Figs. 1 and 2 represent specific heat capacity (C_p) values over the temperature range from 303 to 353 K. The measurements were conducted four times for every sample in this study, and average values were used in Figs. 1 and 2.

The standard deviation (SD) of the data was calculated by fol-

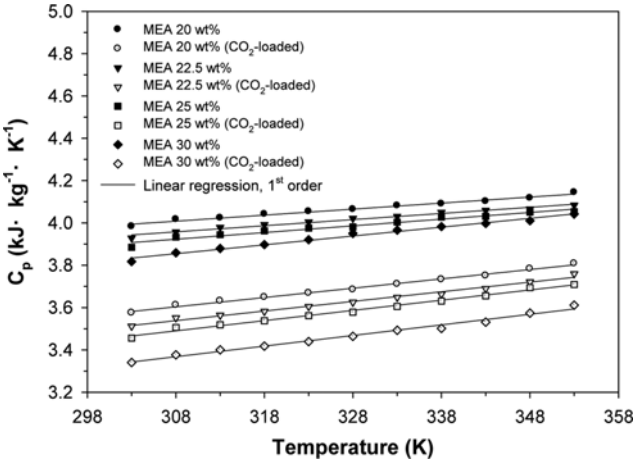

Fig. 1. Specific heat capacities of aqueous solutions of MEA.

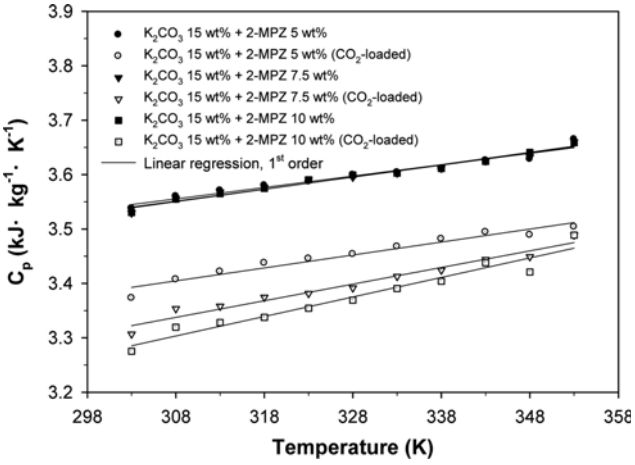

Fig. 2. Specific heat capacities of aqueous solutions of K_2CO_3+2-MPZ.

lowing equation:

$$SD = \sqrt{\frac{\sum_{i=1}^{n}(X_i - \overline{X})^2}{n-1}} \quad (6)$$

where X_i and $\overline{X}$ are each value in the population and the mean of the sample, respectively, and n is the number of values in the sample. The relative standard deviation percent (%RSD) was calculated as follows:

$$\%RSD = \frac{SD}{\overline{X}} \cdot 100 \quad (7)$$

Standard uncertainty of the mean (SU) and the relative standard uncertainty percent (%RSU) were calculated using Eqs. (8) and (9) (A-type method).

$$SU = \frac{SD}{\sqrt{n}} \quad (8)$$

$$\%RSU = \frac{SU}{\overline{X}} \cdot 100 \quad (9)$$

The %RSD of C_p value measurements of fresh MEA solutions and CO_2-loaded MEA solutions were 0.03-0.70% and 0.08-0.83%, respectively. The %RSD of the C_p value measurements of the fresh K_2CO_3+2-MPZ solutions, and CO_2-loaded K_2CO_3+2-MPZ solutions were 0.44-0.97% and 0.07-1.32%, respectively. All %RSU of the C_p values in this study were less than 0.4%.

The CO_2-loaded absorbents had lower C_p values than those of fresh absorbents. The C_p values of fresh MEA solutions decreased according to increasing concentration of MEA (20→30 wt%), whereas concentrations of 2-MPZ in the fresh K_2CO_3+2-MPZ solutions did not affect C_p values. Furthermore, K_2CO_3+2-MPZ solutions had lower C_p values than those of MEA over the temperature range 303-353 K. The CO_2-loaded absorbents had lower C_p than those of fresh absorbents. The specific heat capacity, C_p, was expressed as the unit of $kJ \cdot kg^{-1} \cdot K^{-1}$. CO_2-loaded absorbent comprises species derived from solute (K_2CO_3 and/or amine)-H_2O-CO_2 system, and fresh absorbent consists of solute and H_2O. The percentage of species in the samples was changed according to CO_2 loading. The difference affects the physical properties.

Tables 1 and 2 present the C_p values and the equation parameters of the C_p of aqueous solutions of MEA and K_2CO_3+2-MPZ. The parameters in Tables 1 and 2 were obtained from first-order linear regression presented in Figs. 1 and 2.

Table 1. Parameters for the linear regression of C_p values of aqueous solutions of MEA

Absorbent (wt%)	CO_2 loading (mol CO_2/mol MEA)	a[a]	10^{-3}b[a]	R^2
MEA 20	Fresh solution	3.1315	2.8478	0.9839
	0.634	2.2470	4.4044	0.9940
MEA 22.5	Fresh solution	3.0666	2.8945	0.9815
	0.616	2.1374	4.5492	0.9877
MEA 25	Fresh solution	2.9523	3.1530	0.9648
	0.597	1.9983	4.8434	0.9903
MEA 30	Fresh solution	2.5661	4.1847	0.9865
	0.581	1.8252	5.0097	0.9862

[a]$C_p(kJ \cdot kg^{-1} \cdot K^{-1}) = a + b \cdot T$

Table 2. Parameters for the linear regression of C_p values of aqueous solutions of K_2CO_3+2-MPZ

Absorbent (wt%)	CO_2 loading (mol CO_2/(mol K_2CO_3+mol 2-MPZ))	a[a]	10^{-3}b[a]	R^2
K_2CO_3 15+2-MPZ 5	Fresh solution	2.9096	2.0964	0.9580
	0.898	2.6704	2.3836	0.9518
K_2CO_3 15+2-MPZ 7.5	Fresh solution	2.8725	2.2038	0.9683
	0.902	2.3969	3.0542	0.9645
K_2CO_3 15+2-MPZ 10	Fresh solution	2.8510	2.2703	0.9791
	0.860	2.1992	3.5851	0.9510

[a]$C_p(kJ \cdot kg^{-1} \cdot K^{-1}) = a + b \cdot T$

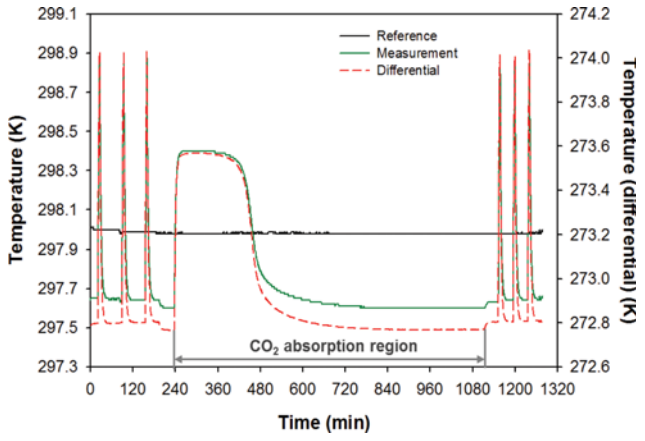

Fig. 3. DRC curves of aqueous solutions of 30 wt% MEA during CO_2 absorption at 298 K.

2. Heat of Absorption and CO_2 Loading Capacity

The differential temperature (T_{diff}) curve between the reference cell and the measuring cell over time was obtained from DRC experiments. The T_{diff} curve was used to calculate the heat of CO_2 absorption represented by enthalpy changes during CO_2 absorption ($-\Delta H_{abs}$). Fig. 3 shows the temperature curves from DRC experiments for the aqueous 30 wt% MEA solution at 298 K.

The experimental temperature ranges of DRC experiments (298, 303, and 313 K) were absorption conditions used in conventional absorption processes. The heat of absorption and CO_2 loading capacity of aqueous solutions of MEA and K_2CO_3+2-MPZ are shown in Fig. 4, and the individual values are presented in Tables 3-8. The CO_2 absorption capacity can be represented as CO_2 loading (mol-CO_2·mol^{-1}-solute in fresh solution). The heat of absorption was calculated at the CO_2 loadings of 1/4, 1/2, and 3/4 of the reaction endpoint, and at CO_2 loading (mol-CO_2·mol^{-1}-solute in fresh solution)=0.23 for comparison. Generally, in the typical MEA process, CO_2 loading of the CO_2-lean solution is maintained at 0.15-0.30 [38-40]. At CO_2 loading=0.23 and T=313 K, the heat of absorption of the K_2CO_3+2-MPZ and MEA solutions was approximately 49 and 75 kJ·mol^{-1}-CO_2, respectively. Increase in the amine concentration did not significantly affect the heat of absorption within the range of this study. Furthermore, temperature dependence of the heat of absorption was weak for MEA and K_2CO_3+2-MPZ absorbents at 298-313 K. A similar result of weak temperature dependence on heat of absorption was also shown in the literature [41].

The moles of CO_2 (mol-CO_2) in the CO_2-saturated MEA solutions was higher than that in the K_2CO_3+2-MPZ; however, the CO_2 loading (mol-CO_2·mol^{-1}-solute in fresh solution) of aqueous solutions of MEA was lower than that of K_2CO_3+2-MPZ. The CO_2-saturated solution contains maximum amount of CO_2 that absorbent can absorb CO_2 at the specific condition. The heat of absorption of CO_2 in the aqueous solutions of K_2CO_3+2-MPZ was lower than that of aqueous solutions of MEA. These results can be explained by differences in the reaction mechanisms presented below. Theoretically, one mole of MEA can react with 0.5 mole of CO_2. In the aqueous MEA solution, MEA (RNH_2) reacts with CO_2 to form an intermediate (zwitterion, $RNH_2^+COO^-$), and the zwitterion reacts with base (RNH_2, OH^-, H_2O) in the solution [32,42,43]. More specifically, the zwitterion ($RNH_2^+COO^-$) primarily reacts with MEA (RNH_2) and forms MEA carbamate ($RNHCOO^-$) and protonated MEA (RNH_3^+). In the aqueous 2-MPZ solution, 2-MPZ reacts with CO_2 to form 2-MPZ carbamate (2-MPZCOO$^-$) and 2-MPZ bicarbamate (2-MPZ(COO$^-$)$_2$); however, the amount

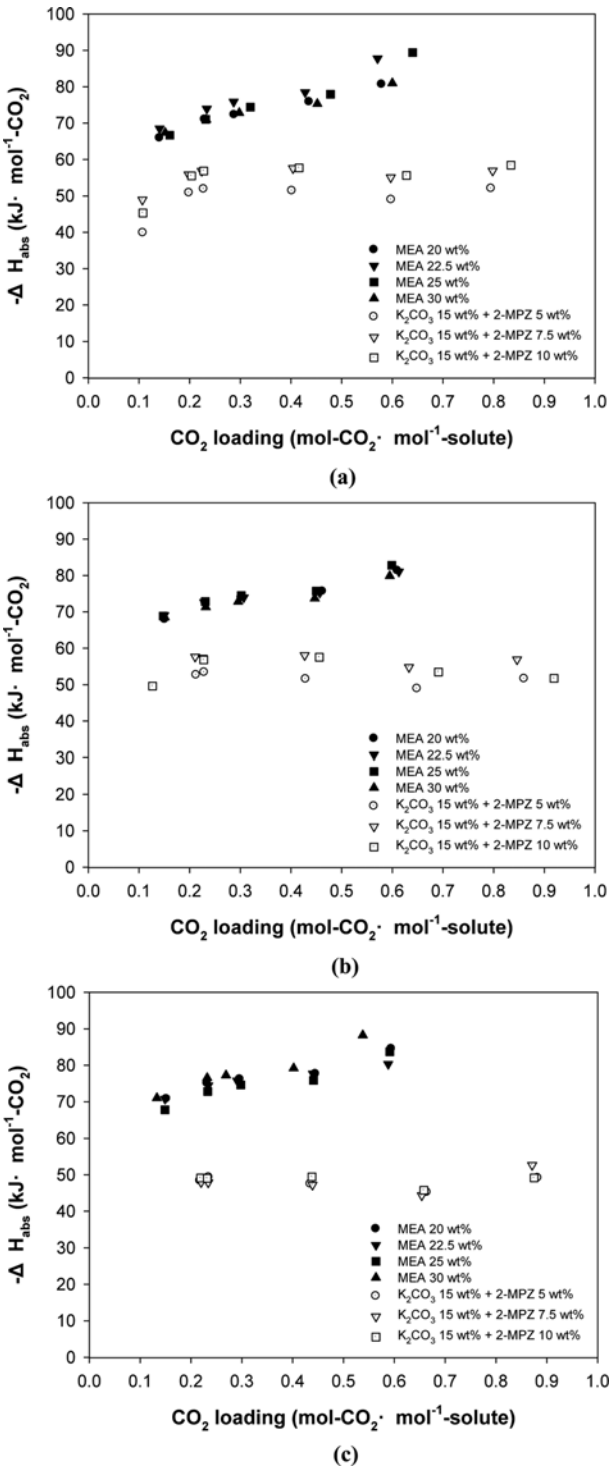

Fig. 4. Heats of CO_2 absorption of aqueous solutions of K_2CO_3+2-MPZ and MEA: (a) 298 K; (b) 303 K; (c) 313 K.

Table 3. Heats of CO_2 absorption in aqueous solutions of MEA at 298 K

Absorbent (wt%)	CO_2 loading		$-\Delta H_{abs}$		$-Q$
	(mol CO_2)	(mol CO_2/mol MEA)	(kJ/mol CO_2)	(kJ/g CO_2)	(kJ)
MEA 20	0.069	0.141	65.914	1.498	4.548
	0.113	0.230	71.037	1.614	8.027
	0.142	0.288	72.304	1.643	10.267
	0.214	0.436	75.860	1.724	16.234
	0.285	0.579	80.647	1.833	22.985
MEA 22.5	0.078	0.141	68.486	1.557	5.342
	0.129	0.234	73.954	1.681	9.540
	0.158	0.287	75.847	1.724	11.984
	0.236	0.428	78.478	1.784	18.521
	0.315	0.571	87.753	1.994	27.642
MEA 25	0.099	0.161	66.680	1.515	6.601
	0.143	0.232	71.035	1.614	10.158
	0.197	0.320	74.381	1.690	14.653
	0.294	0.478	77.943	1.771	22.915
	0.393	0.640	89.413	2.032	35.139
MEA 30	0.112	0.152	67.387	1.532	7.547
	0.172	0.233	70.938	1.612	12.201
	0.219	0.298	72.835	1.655	15.951
	0.333	0.452	75.319	1.712	25.081
	0.442	0.600	80.980	1.840	35.793

Table 4. Heats of CO_2 absorption in aqueous solutions of MEA at 303 K

Absorbent (wt%)	CO_2 loading		$-\Delta H_{abs}$		$-Q$
	(mol CO_2)	(mol CO_2/mol MEA)	(kJ/mol CO_2)	(kJ/g CO_2)	(kJ)
MEA 20	0.074	0.151	67.962	1.545	5.029
	0.113	0.231	72.597	1.650	8.203
	0.149	0.302	73.924	1.680	11.015
	0.227	0.462	75.667	1.720	17.146
	0.300	0.610	81.371	1.849	24.411
MEA 22.5	0.083	0.150	69.084	1.570	5.734
	0.126	0.229	72.666	1.652	9.156
	0.170	0.307	73.970	1.681	12.575
	0.253	0.457	75.278	1.711	19.045
	0.339	0.613	81.035	1.842	27.471
MEA 25	0.091	0.148	68.863	1.565	6.267
	0.142	0.231	72.857	1.656	10.346
	0.185	0.302	74.510	1.693	13.784
	0.276	0.450	75.716	1.721	20.878
	0.368	0.599	82.784	1.881	30.465
MEA 30	0.111	0.151	68.520	1.557	7.606
	0.171	0.232	71.296	1.620	12.192
	0.218	0.296	72.847	1.656	15.881
	0.329	0.447	73.717	1.675	24.253
	0.438	0.595	79.884	1.816	34.989

of bicarbamate could be small due to hydrolysis of the carbamate adjacent to methyl groups causing steric hindrance [34]. The CO_2 absorption mechanism of the aqueous solution of K_2CO_3+2-MPZ complies with the shuttle mechanism mentioned in the Introduc-

Table 5. Heats of CO_2 absorption in aqueous solutions of MEA at 313 K

Absorbent (wt%)	CO_2 loading		$-\Delta H_{abs}$		$-Q$
	(mol CO_2)	(mol CO_2/mol MEA)	(kJ/mol CO_2)	(kJ/g CO_2)	(kJ)
MEA 20	0.075	0.152	70.809	1.609	5.311
	0.114	0.232	75.071	1.706	8.559
	0.145	0.296	76.204	1.732	11.050
	0.219	0.445	77.670	1.765	17.010
	0.292	0.594	84.516	1.921	24.679
MEA 22.5	0.082	0.149	70.803	1.609	5.806
	0.129	0.234	74.477	1.693	9.608
	0.161	0.291	75.780	1.722	12.201
	0.243	0.440	77.689	1.766	18.878
	0.325	0.588	80.351	1.826	26.114
MEA 25	0.092	0.149	67.823	1.541	6.240
	0.143	0.233	72.847	1.656	10.417
	0.183	0.298	74.626	1.696	13.657
	0.271	0.441	75.884	1.725	20.655
	0.363	0.591	83.720	1.903	30.390
MEA 30	0.098	0.133	71.051	1.615	6.963
	0.171	0.232	76.567	1.740	13.091
	0.198	0.269	77.275	1.756	15.300
	0.296	0.402	79.222	1.801	23.450
	0.397	0.538	88.242	2.006	35.032

Table 6. Heats of CO_2 absorption in aqueous solutions of K_2CO_3+2-MPZ at 298 K

Absorbent (wt%)	CO_2 loading		$-\Delta H_{abs}$		$-Q$
	(mol CO_2)	(mol CO_2/(mol K_2CO_3+mol 2-MPZ))	(kJ/mol CO_2)	(kJ/g CO_2)	(kJ)
K_2CO_3 15+2-MPZ 5	0.026	0.108	39.875	0.906	1.037
	0.047	0.199	50.859	1.156	2.390
	0.054	0.228	51.888	1.179	2.802
	0.096	0.402	51.423	1.169	4.937
	0.142	0.598	48.943	1.112	6.950
	0.189	0.795	52.025	1.182	9.833
K_2CO_3 15+2-MPZ 7.5	0.029	0.107	48.928	1.112	1.419
	0.055	0.198	55.864	1.270	3.073
	0.062	0.224	56.867	1.292	3.526
	0.111	0.404	57.596	1.309	6.393
	0.164	0.597	55.087	1.252	9.034
	0.220	0.798	56.921	1.294	12.523
K_2CO_3 15+2-MPZ 10	0.034	0.108	45.285	1.029	1.540
	0.064	0.204	55.506	1.262	3.552
	0.071	0.228	56.868	1.292	4.038
	0.130	0.416	57.713	1.312	7.503
	0.196	0.628	55.626	1.264	10.903
	0.261	0.834	58.429	1.328	15.250

tion. A large amount of bicarbonate/carbonate is formed in the aqueous solutions of K_2CO_3+2-MPZ, but the CO_2 is relatively easier to decompose from the bicarbonate/carbonate by heating, than from carbamate.

CONCLUSIONS

The physical properties and CO_2 absorption characteristics of aqueous solutions of K_2CO_3+2-MPZ were investigated. The spe-

Table 7. Heats of CO_2 absorption in aqueous solutions of K_2CO_3+2-MPZ at 303 K

Absorbent (wt%)	CO_2 loading		$-\Delta H_{abs}$		$-Q$
	(mol CO_2)	(mol CO_2/(mol K_2CO_3+mol 2-MPZ))	(kJ/mol CO_2)	(kJ/g CO_2)	(kJ)
K_2CO_3 15+2-MPZ 5	0.051	0.213	52.649	1.197	2.685
	0.055	0.229	53.398	1.214	2.937
	0.102	0.429	51.526	1.171	5.256
	0.154	0.649	48.911	1.112	7.532
	0.204	0.860	51.640	1.174	10.535
K_2CO_3 15+2-MPZ 7.5	0.058	0.211	57.672	1.311	3.345
	0.062	0.226	57.350	1.303	3.556
	0.117	0.427	58.065	1.320	6.794
	0.174	0.633	54.811	1.246	9.537
	0.233	0.846	56.915	1.294	13.261
K_2CO_3 15+2-MPZ 10	0.040	0.127	49.606	1.127	1.984
	0.071	0.228	56.816	1.291	4.034
	0.143	0.456	57.524	1.307	8.256
	0.216	0.691	53.464	1.215	11.548
	0.287	0.919	51.729	1.176	14.846

Table 8. Heats of CO_2 absorption in aqueous solutions of K_2CO_3+2-MPZ at 313 K

Absorbent (wt%)	CO_2 loading		$-\Delta H_{abs}$		$-Q$
	(mol CO_2)	(mol CO_2/(mol K_2CO_3+mol 2-MPZ))	(kJ/mol CO_2)	(kJ/g CO_2)	(kJ)
K_2CO_3 15+2-MPZ 5	0.052	0.218	48.354	1.099	2.514
	0.056	0.235	49.334	1.121	2.763
	0.103	0.435	47.485	1.079	4.891
	0.158	0.664	45.199	1.027	7.142
	0.210	0.882	49.158	1.117	10.323
K_2CO_3 15+2-MPZ 7.5	0.060	0.220	47.981	1.090	2.879
	0.064	0.234	47.896	1.089	3.065
	0.121	0.439	47.222	1.073	5.714
	0.180	0.654	44.343	1.008	7.982
	0.240	0.871	52.647	1.167	12.635
K_2CO_3 15+2-MPZ 10	0.068	0.219	49.123	1.116	3.340
	0.072	0.232	49.034	1.114	3.530
	0.137	0.438	49.443	1.124	6.774
	0.206	0.658	45.756	1.040	9.426
	0.274	0.875	49.150	1.117	13.467

cific heat capacity of fresh and CO_2-loaded K_2CO_3+2-MPZ solutions was measured in the temperature range 300 to 353 K, using DSC. Heat of absorption and CO_2 loading capacity of aqueous solutions of K_2CO_3+2-MPZ were measured at 303 and 313 K, which are temperatures typically used in conventional CO_2 absorption processes. CO_2-loaded solutions of K_2CO_3+2-MPZ had lower C_p values than those of fresh absorbents. Concentrations of 2-MPZ (5, 7.5, 10 wt%) in aqueous solutions of K_2CO_3+2-MPZ did not affect C_p values; however, C_p values of the absorbents decreased after CO_2 absorption. The C_p values of fresh aqueous solutions of 15 wt% K_2CO_3+10 wt% 2-MPZ were lower than those of aqueous solutions of 30 wt% MEA; however, C_p values of CO_2-saturated solutions were similar. Temperature and amine concentration did not significantly affect the heat of absorption within the range of this study; however, the heat of absorption was changed according to CO_2 loading. Aqueous solutions of K_2CO_3+2-MPZ have the advantages of lower heat of absorption and higher CO_2 loading capacity, compared to MEA. Although the heat of absorption is directly related to regeneration energy of absorbent, other important factors such as CO_2 loading capacity, absorption rate, and physical properties are also thoroughly considered for selection of absorbent.

ACKNOWLEDGEMENTS

This work was supported by the Energy Demand Management Technology Program of the Korea Institute of Energy Technology

Evaluation and Planning (KETEP), granted financial resource from the Ministry of Trade, Industry and Energy, Republic of Korea (No. 20152010201940).

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