



Novel regenerable potassium-based dry sorbents for CO₂ capture at low temperatures

Soo Chool Lee^a, Ho Jin Chae^a, Soo Jae Lee^a, Yong Hee Park^a, Chong Kul Ryu^b, Chang Keun Yi^c, Jae Chang Kim^{a,*}

^a Department of Chemical Engineering, Kyungpook National University, 1370 Sangyeuk-dong, Buk-gu, Daegu 702-701, Republic of Korea

^b Korea Electric Power Research Institute, Daejeon 305-380, Republic of Korea

^c Korea Institute of Energy Research, Daejeon 305-343, Republic of Korea

ARTICLE INFO

Article history:

Available online 29 July 2008

Keywords:

CO₂
Absorption
ZrO₂
K₂CO₃
KHCO₃

ABSTRACT

A novel potassium-based dry sorbent (KZrI) was developed for CO₂ capture at a low temperature range between 50 °C and 200 °C. The CO₂ absorption and regeneration properties of this novel regenerable potassium-based dry sorbent were measured in a fixed-bed reactor during multiple absorption/regeneration cycles at low temperature conditions (CO₂ absorption at 50–100 °C and regeneration at 130–200 °C). The total CO₂ capture capacity of the KZrI sorbent was maintained during the multiple CO₂ absorption/regeneration cycles. The XRD patterns and FTIR analyses of the sorbents after CO₂ absorption showed the KHCO₃ phase only except for the ZrO₂ phase used as support. Even after 10 cycles, any other new structures resulting from the by-product during CO₂ absorption were not observed. This phase could be easily converted into the original phase during regeneration, even at a low temperature (130 °C). The KZrI sorbent developed in this study showed excellent characteristics in CO₂ absorption and regeneration in that it satisfies the requirements of a large amount of CO₂ absorption (91.6 mg CO₂/g sorbent) and the complete regeneration at a low temperature condition (1 atm, 150 °C) without deactivation.

© 2008 Elsevier B.V. All rights reserved.

1. Introduction

Carbon dioxide (CO₂) is a major greenhouse gas that is released into the air due to the use of fossil fuels. As a consequence, CO₂ causes global warming, which may be disastrous to the environment. It can be removed from flue gas and waste gas streams by various methods such as membrane separation, absorption with a solvent, and adsorption using molecular sieves [1–6]. These methods, however, are costly and consume a lot of energy.

One of the improved techniques for the removal of CO₂ is the chemical absorption of CO₂ with dry regenerable sorbents. The use of dry sorbents can be highly cost-effective and an energy efficient way to remove CO₂ [7–24].

Alkali metal carbonates such as Na₂CO₃ and K₂CO₃ react with CO₂ and H₂O and transform to alkali metal hydrogen carbonates after CO₂ absorption by the following reaction: M₂CO₃ + CO₂ + H₂O ⇌ 2MHCO₃ (M=Na, K) [7–20]. Water vapor is always necessary in forming potassium hydrogen carbonate in all reactions as shown in the absorption mechanism. Alkali

metal-based sorbents are employed in CO₂ absorption at low temperatures (50–70 °C) with thermal regeneration easily occurring at low temperatures below 200 °C. Hirano et al. have proposed a modified chemical-absorption method capable of cyclic fixed-bed operations for the recovery of carbon dioxide from flue gases over K₂CO₃-on-carbon [8]. The sorption of CO₂ on the K₂CO₃-Al₂O₃ composite sorbent, in the presence of water vapor, was studied by in-situ IR spectroscopy and X-ray diffraction analysis [11]. Several studies regarding an efficient chemical absorption over K₂CO₃, which was supported either on activated carbon [7–9,17,18] or on other porous matrices such as silica gel, Al₂O₃ and vermiculite [11–13], were also reported using cyclic fixed-bed operations under moist conditions. Lee et al. reported that the K₂CO₃/TiO₂ sorbent showed excellent CO₂ absorption and regeneration properties [17]. In particular, the formation of the KHCO₃ crystal structure only after CO₂ absorption is reported to be an important factor for regeneration, even at low temperatures, unlike K₂CO₃/Al₂O₃ which formed a new alloy structure like KAl(CO₃)₂(OH)₂. Several additives or supports such as SiO₂, Al₂O₃, CaO, MgO, zeolites and others have been used in alkali metal-based sorbents to absorb CO₂. Nonetheless, these sorbents except for K₂CO₃/TiO₂ and K₂CO₃/activated carbon have a disadvantage in that there is a decrease of reactivity during multiple absorptions/regenerations at low temperatures

* Corresponding author. Tel.: +82 53 950 5622; fax: +82 53 950 6615.
E-mail address: kjchang@knu.ac.kr (J.C. Kim).

Table 1
Experimental conditions of potassium-based dry sorbents

	CO ₂ absorption	Regeneration
Temperature (°C)	50–100	130–200
Pressure (atm)	1	1
Flow rate (ml/min)	40	40
Gas composition (vol.%)	CO ₂ : 1, H ₂ O: 9, N ₂ : balance	N ₂ : balance

(40–200 °C). An ideal dry sorbent must have a high CO₂ capture capacity, high absorption rate, excellent regeneration property, and high attrition resistance (physical and chemical strength) to remove CO₂ from flue gas in a fluidized/transport-bed reactor or fixed-bed reactor. In particular, the ideal alkali metal-based sorbent must have a complete regeneration property at a low temperature range between 130 °C and 200 °C. To design an excellent regenerable dry sorbent, it is very important to find new additives or supports to be used in the alkali metal-based sorbent.

One of the objectives of this study was to develop a new regenerable sorbent for CO₂ capture at low temperature range between 50 °C and 200 °C. In addition, the change in the physical property of the sorbent before/after CO₂ absorption was investigated with the aid of Power X-ray diffraction (XRD; Philips, X'PERT), Fourier transform infrared (FTIR; Mattson Instruments Inc.) and TPD.

2. Experimental

The alkali metal-based sorbent used in this study was prepared by the impregnation method. A typical preparation procedure for the sorbent supported on the zirconium oxide (ZrO₂, Aldrich 99%) or Al₂O₃ (Aldrich 99%) was as follows: 5.0 g of supports were added to an aqueous solution containing 2.5 g of anhydrous alkali metal carbonate (K₂CO₃, Aldrich) in 25 ml of de-ionized water. Then, the content was mixed with a magnetic stirrer for 24 h at room temperature [7,8,17]. After stirring, the mixture was dried in a rotary evaporator at 60 °C. The dried samples were calcined in a furnace with N₂ flow (100 ml/min) for 4 h at 300 °C. The ramping rate of the temperature was maintained at 3 °C/min. We denoted the sorbent as KZrI30 or KAlI30, where K represents K₂CO₃, I represents the impregnation method, and 30 represents the loading amount of K₂CO₃. The amount of alkali metal impregnated was identified by using inductively coupled plasma-atomic emission spectrometry (ICP-AES; GBC Scientific, Integra KL). Power X-ray diffraction (XRD; Philips, X'PERT) at the Korea Basic Science Institute (Daegu) was also measured in order to confirm the structure using Cu K α radiation.

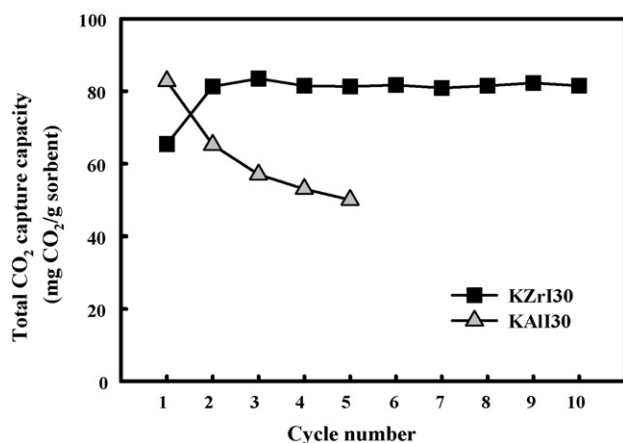


Fig. 1. The total CO₂ capture capacities of the KZrI30 and KAlI30 sorbents as a function of cycle number in the presence of 1 vol.% CO₂ and 9 vol.% H₂O at 60 °C.

CO₂ absorption and regeneration processes were performed in a fixed-bed quartz reactor with a diameter of 1 cm, which was placed in an electric furnace under atmospheric pressure. One-half (0.5) g of the sorbent was packed into the reactor, and space velocity (SV) was maintained at 3000 h⁻¹ to minimize severe pressure drops and channeling phenomena. All volumetric gas flows were measured under standard temperature and pressure (STP) conditions. The conditions of CO₂ absorption and regeneration and the composition of mixed gases are shown in Table 1. Outlet gases from the reactor were automatically analyzed every 4 min by a thermal conductivity detector (TCD; Donam Systems Inc.), which was equipped with Porapak Q (1/8 in. stainless).

3. Results and discussion

3.1. CO₂ absorption properties

3.1.1. Comparison of the total CO₂ capture capacity

The CO₂ capture capacity of sorbent was evaluated by the breakthrough curve for CO₂ absorption. In this study, the total CO₂ capture capacity of sorbent was calculated from its breakthrough curve during CO₂ absorption in the presence of 9.0 vol.% H₂O and 1 vol.% CO₂. The total CO₂ capture capacity describes the amount of CO₂ absorbed until the output concentration of CO₂ reached 1 vol.%, which is the same value as that of the inlet. Fig. 1 shows the total CO₂ capture capacities of the KZrI30 and KAlI30 sorbents as a function of cycle number. When both CO₂ absorption and regeneration are considered as a one-cycle process, the horizontal axis indicates the number of cycles repeated and the vertical axis indicates the total amount of CO₂ absorbed per 1 g sorbent. CO₂ absorption and regeneration processes were carried out at 60 °C and 200 °C, respectively. As shown in Fig. 1, the total CO₂ capture capacity of the KZrI30 sorbent was about 65.4 mg CO₂/g sorbent at the first cyclic number. The total CO₂ capture capacity of the sorbent increased up to 81.3 mg CO₂/g sorbent at 2 cycles and was maintained during multiple CO₂ absorption/regeneration cycles. However, the total CO₂ capture capacity of the KAlI30 sorbent gradually decreased with the cycle number, regardless of the regeneration temperature of 200 °C. These results indicate that the new KZrI30 sorbent developed in this study shows a relatively high CO₂ capture capacity and is completely regenerated at 200 °C, unlike the KAlI30 sorbent.

Fig. 2 shows the breakthrough curves of the KZrI30 (a) and KAlI30 (b) sorbents during CO₂ absorption in the presence of 9.0 vol.% H₂O and 1 vol.% CO₂ at 60 °C. It was observed that the

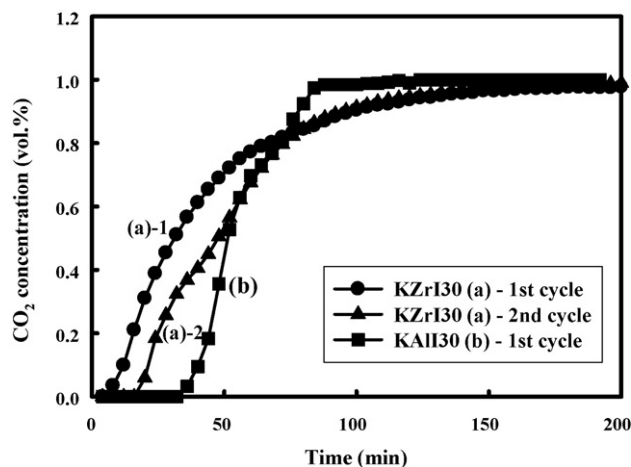


Fig. 2. The breakthrough curves of the KZrI30 (a) and KAlI30 (b) sorbents during CO₂ absorption in the presence of 9.0 vol.% H₂O and 1 vol.% CO₂ at 60 °C.

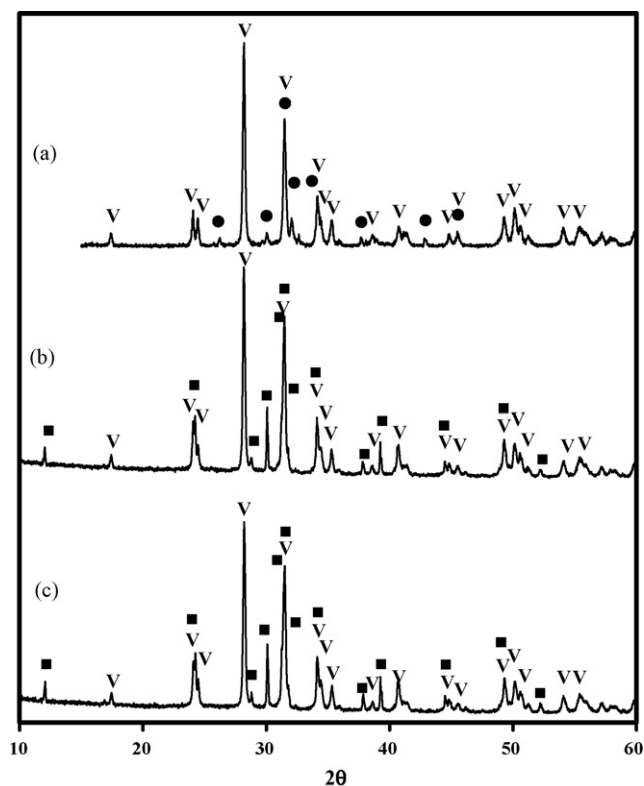


Fig. 3. The XRD patterns of the KZr130 sorbent before (a) /after CO₂ absorption at 1 cycle (b) and 10 cycles (c).

breakthrough times of the KZr130 (a) for 1st and 2nd cycle were 4 min and 16 min, respectively. After 3rd cycle, the breakthrough was not changed. The both absorption rates of the KZr130 and KAl130 sorbents estimated from the initial slope of the transition ranges of the breakthrough curves were similar even through the deactivation phenomenon was clearly different, as shown in Fig. 1. Further study is required to enhance the CO₂ absorption rate, but the important point to note is that the new KZr130 sorbent developed in this study is completely regenerated at 200 °C.

3.1.2. Identification of the structure of the KZr130 sorbent before/after CO₂ absorption

Fig. 3 shows the XRD patterns of the KZr130 sorbent, which was calcined at 300 °C under nitrogen, before (a) /after CO₂ absorption at 1 cycle (b) and 10 cycles (c). As shown in the XRD pattern of Fig. 3(a), the fresh KZr130 sorbent showed a K₂CO₃ phase (JCPDS No. 71-1466) and a ZrO₂ phase (JCPDS No. 86-1451). As shown in Fig. 3(b) and (c), the XRD patterns of the sorbent after CO₂ absorp-

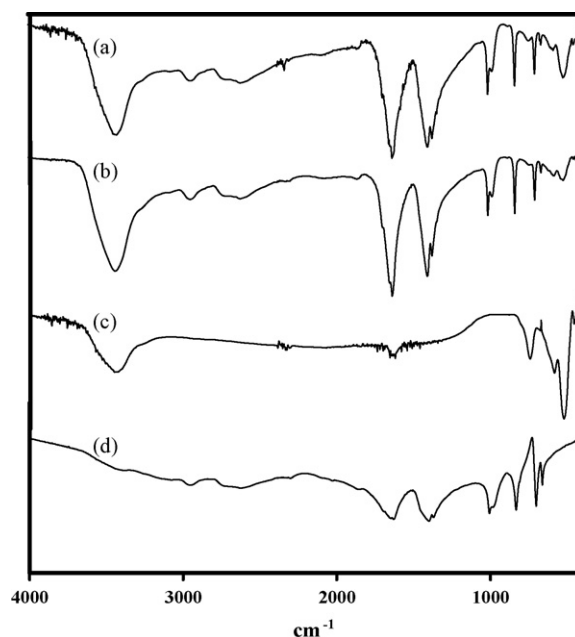


Fig. 4. The FTIR results of the KZr130 sorbent at 1 cycle (a) and 10 cycles (b), ZrO₂ (c), and a pure KHCO₃ (d).

tion showed the only KHCO₃ phase except for the ZrO₂ phase used as a support. In particular, it must be noted that even after 10 cycles, no other new structures resulting from the by-product during CO₂ absorption were observed except for KHCO₃ in the XRD results. To precisely identify the formation of the only KHCO₃ phase during CO₂ absorption, the FTIR experiments for the KZr130 sorbent at 1 cycle (a) and 10 cycles (b), ZrO₂ (c), and a pure KHCO₃ (d), were carried out in the range from 4000 to 400 cm⁻¹. These results are shown in Fig. 4. The peak appearing at 3422.96 cm⁻¹ was assigned to that by ZrO₂ as shown in Fig. 4(c). Table 2 summarizes the characteristic absorption peaks except for the peaks representing ZrO₂ and its corresponding position [25,26]. These results are in agreement with those obtained not only by Abouelhassan et al. and Nakamoto et al., but also by a pure KHCO₃. The important point to note here is that no other peaks were observed from the FTIR experiments, as well as from the XRD results. From these results, it was confirmed that the only KHCO₃ phase was formed during CO₂ absorption in the presence of 9 vol.% H₂O and 1 vol.% CO₂. In our previous paper, we suggested that the formation of the KHCO₃ phase during CO₂ absorption was an important factor regarding the maintenance of the CO₂ capture capacity at low regeneration temperatures below 200 °C [17]. Also, it has previously been shown that decreases in the CO₂ capture capacities of K₂CO₃/Al₂O₃

Table 2
The characteristic of absorption peaks and the corresponding position

Peak position of our study (cm ⁻¹)		Expected bond [25]	Peak positions of references	
At 1 cycle	At 10 cycles		Ref. [25]	Ref. [26]
2949	2949	O–H...O + C=O	2949	2920
2627	2627	O–H	2627	2620
1631	1630	C=O	1633	1618
1398	1401	O–H...O	1409	1405
1367	1371	C...O	1368	1367
1007	1007	C–O + C...O	1007	1001
981	981	O–H...O	979	988
832	833	CO ₃	832	830
702	702	C=O + O...H	703	698
662	663	O ₁ CO ₂	662	655

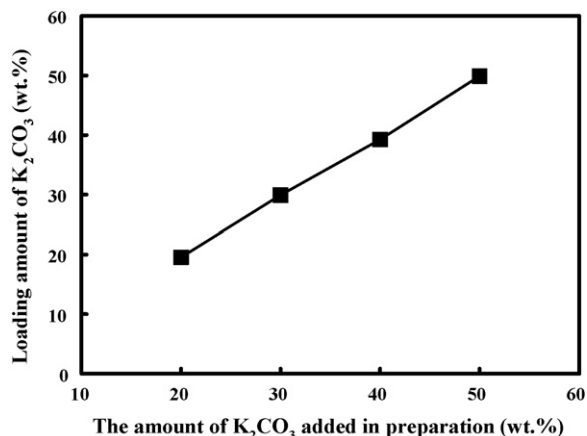


Fig. 5. The loading amount of K_2CO_3 as a function of the amount of K_2CO_3 added in the preparation of sorbent.

and K_2CO_3/MgO sorbents after regeneration, at temperatures lower than $200^\circ C$, were due to the formation of new structures such as $KAl(CO_3)_2(OH)_2$, $K_2Mg(CO_3)_2$ and $K_2Mg(CO_3)_2 \cdot 4(H_2O)$, except for the $KHCO_3$ phase. From these results, it was concluded that a complete regeneration during multiple CO_2 absorption/regeneration cycles was due to the formation of the only $KHCO_3$ without the formation of new structures during CO_2 absorption.

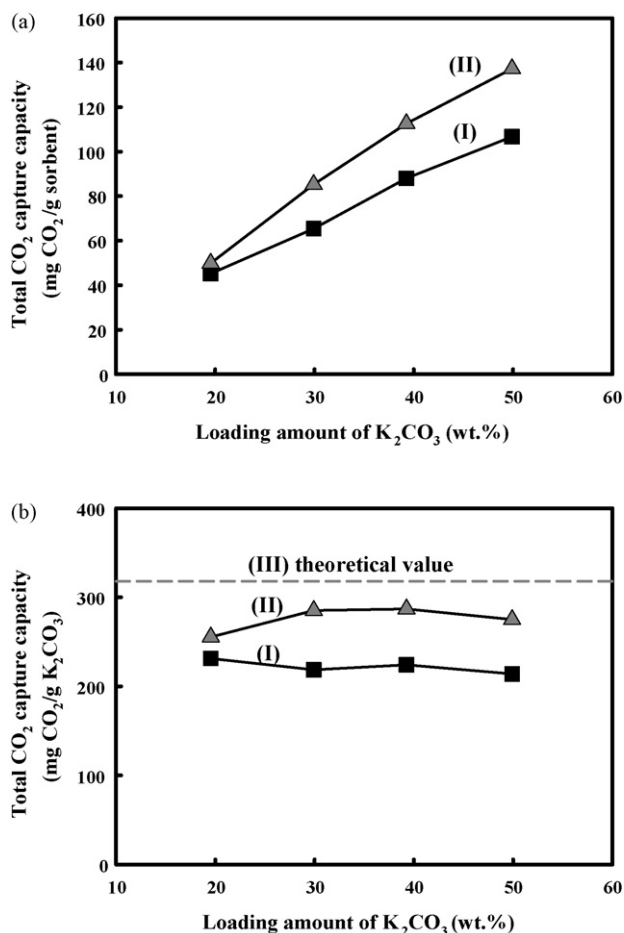


Fig. 6. The total CO_2 capture capacity (a) and the amount of the CO_2 absorption per 1 g of K_2CO_3 and (b) of the KZrI sorbent for 1 cycle (I) and 2 cycles (II) as a function of the loading amount of K_2CO_3 in the presence of 1 vol.% CO_2 and 9 vol.% H_2O at $60^\circ C$.

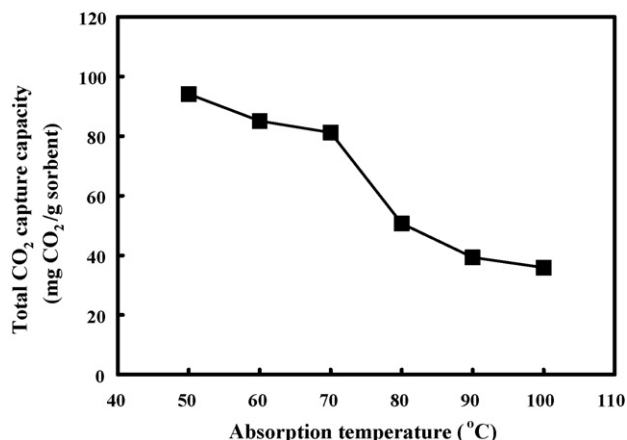


Fig. 7. The total CO_2 capture capacity of the KZrI30 sorbent in the range of temperature between $50^\circ C$ and $100^\circ C$ in the presence of 9 vol.% H_2O .

3.1.3. Effects of the loading amount of K_2CO_3 on the CO_2 absorption

The effect of the loading amount of K_2CO_3 on the total CO_2 capture capacity of sorbent in the presence of 9.0 vol.% H_2O and 1 vol.% CO_2 at $60^\circ C$ was investigated. Fig. 5 shows the loading amount of K_2CO_3 as investigated by ICP-AES analysis of the fresh sorbents. As shown in Fig. 5, the loading amount of K_2CO_3 was almost proportional to the amount of K_2CO_3 added in preparation of the sorbent. Fig. 6(a) shows the amount of the CO_2 capture per 1 g of sorbent for 1 cycle (I) and 2 cycles (II) as a function of the loading amount of K_2CO_3 . In both cases, the total CO_2 capture capacity of the sorbent increased with the loading amount of K_2CO_3 . In order to investigate effects of the loadings of K_2CO_3 on the total CO_2 capture capacity of sorbent in detail, the amount of CO_2 absorption per 1 g of K_2CO_3 was calculated from Fig. 6(a). These results are shown in Fig. 6(b). The theoretical value of the sorbent, which was calculated from moles of K_2CO_3 involved in the sorbent, was $318.3 \text{ mg } CO_2/\text{g } K_2CO_3$ as shown in Fig. 6(b-III). The CO_2 capture capacities of the sorbents with 30 wt.% and 40 wt.% K_2CO_3 were higher than those of the other sorbents for 2 cycles as shown in Fig. 6(b-II) and these values were equivalent to about 90 percent of their theoretical value. These results indicated that the KZrI30 and KZrI40 sorbents were suitable for use as the sorbent for CO_2 capture in that the sorbents with 30 wt.% and 40 wt.% K_2CO_3 showed the high CO_2 capture capacity comparable to its theoretical value. Another interesting fact observed in Fig. 6 was that the CO_2 capture capaci-

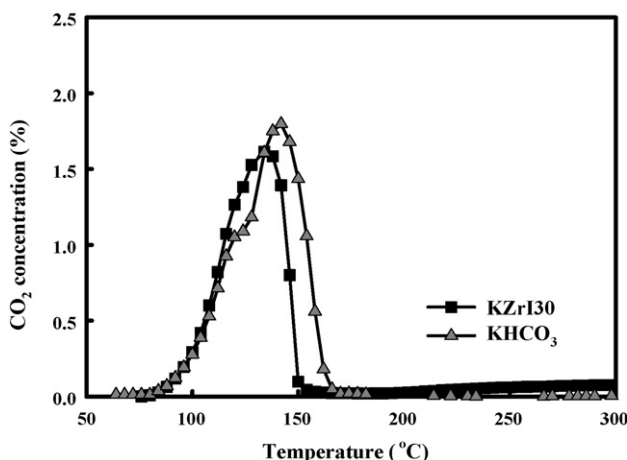


Fig. 8. The TPD results of the KZrI30 sorbent after CO_2 absorption and a pure $KHCO_3$.

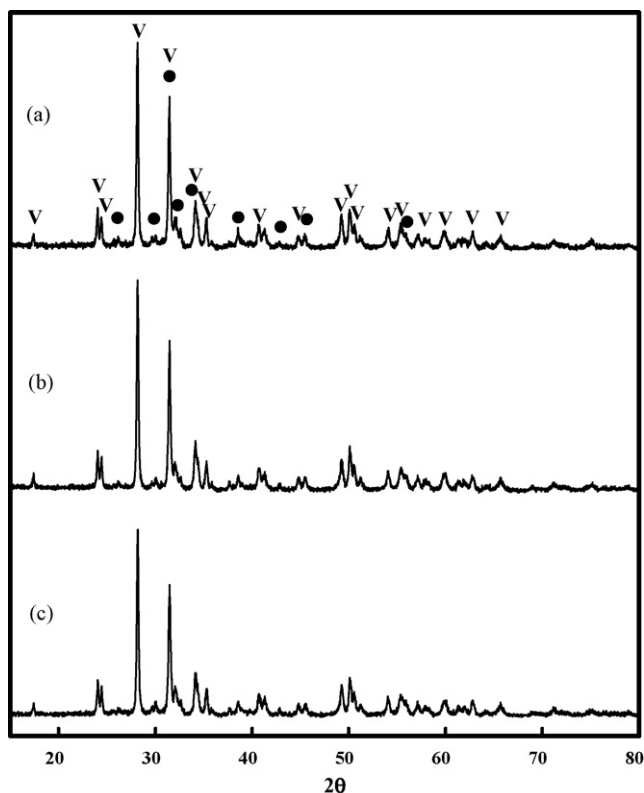


Fig. 9. The XRD patterns of the sorbents after regeneration at various temperatures such as 130 °C (a), 150 °C (b), and 200 °C (c).

ties of the sorbents for 2 cycles were much higher than those for 1 cycle. The reason for the increase in the CO₂ capture capacity of the sorbent at 2 cycles is not clear, but it is thought to result from the re-dispersion of K₂CO₃ supported on ZrO₂ owing to regeneration at 200 °C.

3.1.4. Effects of the absorption temperature on the CO₂ absorption

Fig. 7 shows the total CO₂ capture capacity of the KZrI30 sorbent at a temperature range between 50 °C and 100 °C in the presence of 9 vol.% H₂O. The KZrI30 sorbent showed very low CO₂ capture capacity above 80 °C, while at 50 °C the sorbent showed 91.6 mg CO₂/g sorbent. This value was about 96% of the theoretical value of the sorbent. These results were thought to be due to an increase in relative humidity resulting from a decrease in the absorption temperature.

3.2. Regeneration properties

In addition to the CO₂ capture capacity, regeneration property is one of the most important factors to be considered. To investigate the regeneration property of the KZrI30 sorbent, TPD (temperature programmed desorption) and XRD analyses were performed. Fig. 8 shows the TPD results of the KZrI30 sorbent after CO₂ absorption and a pure KHCO₃. TPD tests were carried out by measuring the concentration of CO₂ desorbed when the temperature ramping rate was 1 °C/min. In the case of the KZrI30 sorbent, most CO₂ was desorbed in the temperature range between 100 °C and 150 °C. The CO₂ desorption peak of the sorbent was almost consistent with that of a pure KHCO₃ which was at around 130 °C. Lee et al. reported that the CO₂ desorption peaks in the TPD results of the K₂CO₃/AC and K₂CO₃/TiO₂ sorbents, which formed the only KHCO₃ after CO₂ absorption, were observed at around 130 °C [23].

These results indicated that the desorbed CO₂ of the KZrI30 sorbent at around 130 °C was due to the decomposition of KHCO₃ as the K₂CO₃/AC and K₂CO₃/TiO₂ sorbents. Also, it was known that it was possible to regenerate the KZrI30 sorbent after CO₂ absorption, even at 130 °C. To identify this regeneration property of the KZrI30 sorbent in detail, the XRD patterns of the sorbents after regeneration at various temperatures, such as at 130 °C, 150 °C, and 200 °C, were observed. These results are shown in Fig. 9. The separated K₂CO₃ crystal structure was observed in the XRD patterns at all temperatures. These results indicated that the carbonated sorbent after CO₂ absorption was completely regenerated even at 130 °C. This fact agreed well with the TPD result shown in Fig. 8. It was concluded that the formation of the only KHCO₃ crystal structure, through the CO₂ absorption of the KZrI sorbent in the presence of water, plays an important role in complete regeneration at low temperature range between 130 °C and 200 °C. It was also concluded that ZrO₂ could be used as a support and additive to prepare a sorbent having the potential for CO₂ capture and regeneration at low temperatures below 150 °C.

4. Conclusions

The potassium-based dry sorbent (KZrI30) developed in this study showed 91.6 mg CO₂/g sorbent, which was about 96% of the theoretical value of the sorbent, in the presence of 9 vol.% H₂O at 50 °C. In particular, the total CO₂ capture capacity of the KZrI30 sorbent was maintained during the multiple CO₂ absorption/regeneration cycles at low temperature conditions (CO₂ absorption at 60 °C and regeneration at 200 °C). The KZrI30 sorbent after CO₂ absorption formed the only KHCO₃ phase except for the ZrO₂ phase used as support. Even after 10 cycles, it was confirmed from the XRD, FTIR, and TPD results that no other new structures resulting from the by-product during CO₂ absorption were formed except for KHCO₃. The carbonated sorbent after CO₂ absorption, could be completely regenerated, even at 130 °C. The formation of the only KHCO₃ crystal structure plays an important role in a complete regeneration at a low temperature range between 130 °C and 200 °C. Considering that the regeneration capacity was an important factor in addition to the CO₂ capture capacity, the new regenerable potassium-based dry sorbent (KZrI) developed in this study could be used as a sorbent having the potential for CO₂ capture at low temperature ranges.

Acknowledgments

This research was supported by a grant (DA3-201) from Carbon Dioxide Reduction & Sequestration Research Center, one of the 21st Century Frontier Programs funded by the Ministry of Science and Technology of Korean Government.

References

- [1] D.P. Hagewiesche, S.S. Ashour, H.A. Al-Ghawas, O.C. Sandall, *Chem. Eng. Sci.* 50 (7) (1995) 1071.
- [2] M. Mavroudi, S.P. Kaldis, G.P. Sakellariopoulos, *Fuel* 82 (2003) 2153.
- [3] S.W. Park, B.S. Choi, S.S. Kim, J.W. Lee, *Korean J. Chem. Eng.* 21 (6) (2004) 1205.
- [4] W.K. Choi, T.I. Kwon, Y.K. Yeo, H. Lee, H.K. Song, B.K. Na, *Korean J. Chem. Eng.* 20 (4) (2003) 617.
- [5] Y. Takamura, S. Narita, J. Aoki, S. Hironaka, S. Uchida, *Sep. Purif. Technol.* 24 (2001) 519.
- [6] M. Wilson, P. Tontiwachwuthikul, A. Chakma, R. Idem, A. Veawab, A. Aroonwilas, D. Gelowitz, J. Barrie, C. Mariz, *Energy* 29 (2004) 1259.
- [7] H. Hayashi, J. Taniuchi, N. Furuyashiki, S. Sugiyama, S. Hirano, N. Shigemoto, T. Nonaka, *Ind. Eng. Chem. Res.* 37 (1998) 185.
- [8] S. Hirano, N. Shigemoto, S. Yamaha, H. Hayashi, *Bull. Chem. Soc. Jpn.* 68 (1995) 1030.
- [9] S.C. Lee, B.Y. Choi, S.J. Lee, S.Y. Jung, C.K. Ryu, J.C. Kim, *Stud. Surf. Sci. Catal.* 153 (2004) 527.

- [10] Y. Liang, D.P. Harrison, *Energy Fuels* 18 (2004) 569.
- [11] A.G. Okunev, V.E. Sharonov, A.V. Gubar, I.G. Danilova, E.A. Paukshtis, E.M. Moroz, T.A. Kriger, V.V. Malakhov, Y.I. Aistov, *React. Russ. Chem. Bull. Int. Ed.* 52 (2) (2003) 359.
- [12] A.G. Okunev, V.E. Sharonov, Y.I. Aistov, V.N. Parmon, *React. Kinet. Catal. Lett.* 71 (2) (2000) 355.
- [13] V.E. Sharonov, E.M. Tyschishchin, E.M. Moroz, A.G. Okunev, Y.I. Aristov, *Russ. J. Appl. Chem.* 74 (3) (2001) 409.
- [14] V.E. Sharonov, G. Alexey, A.G. Okunev, Y.I. Aristov, *React. Kinet. Catal. Lett.* 82 (2) (2004) 363.
- [15] T.A. Nalette, P.J. Birbara, J.R. Aylward, US Patent 5,079,209 (1992).
- [16] D. Gidaspow, M. Onischak, US Patent 3,865,924 (1975).
- [17] S.C. Lee, B.Y. Choi, T.J. Lee, C.K. Ryu, Y.S. Ahn, J.C. Kim, *Catal. Today* 111 (2006) 385.
- [18] S.C. Lee, B.Y. Choi, C.K. Ryu, Y.S. Ahn, T.J. Lee, J.C. Kim, *Korean J. Chem. Eng.* 23 (3) (2006) 374.
- [19] S.C. Lee, J.C. Kim, *Catal. Surv. Asia* 11 (2007) 171.
- [20] S.C. Lee, H.J. Chae, S.J. Lee, B.Y. Choi, C.K. Lee, J.B. Lee, C.K. Ryu, J.C. Kim, *Environ. Sci. Technol.* 42 (2008) 2736.
- [21] C. Salvador, D. Lu, E.J. Anthony, J.C. Abanades, *Chem. Eng. J.* 96 (2003) 187.
- [22] J.C. Abanades, *Chem. Eng. J.* 90 (2002) 303.
- [23] H. Gupta, L.S. An, *Ind. Eng. Chem. Res.* 41 (2002) 4035.
- [24] J.I. Yang, J.N. Kim, *Korean J. Chem. Eng.* 23 (1) (2006) 77.
- [25] S. Abouelhassan, F. Salman, M. Elmansy, E. Sheha, *Surf. Rev. Lett.* 11 (1) (2004) 83.
- [26] K. Nakamoto, Y.A. Sarama, H. Ogoshi, *J. Chem. Phys.* 43 (1965) 1177.