Optimization of CO₂ Adsorption on Solid-Supported Amines and Thermal Regeneration Mode Comparison

Yangyang Guo, Lei Luo, Yang Zheng, and Tingyu Zhu

ABSTRACT: For improving the CO₂ adsorption capacity of solid-supported amines, five commercial porous supports have been selected and impregnated with tetraethylenepentamine (TEPA), and their CO₂ adsorption performances have been evaluated using a fixed-bed reactor coupled with mass spectrometry. For solid-supported amines, CO₂ adsorption capacities coincide with the texture characterization of the adsorbent supports (mesoporous alumina, montmorillonite, silica gel, porous resin, MCM-41 molecular sieve), and the optimum TEPA loading amount is mainly affected by the pore volume. The mesoporous supports were found to be more conducive to uniform loading of organic amine, with more than 370 mg/g CO₂ adsorbed per unit TEPA. Other components in flue gas, especially H₂O, favor CO₂ adsorption on solid-supported amines. SO₂ inhibited the CO₂ adsorption, which was mainly attributable to the strong and irreversible binding of SO₂ on some amine sites. NO had little effect on CO₂ adsorption. Thermal stabilities of solid-supported amines have been tested based on thermogravimetry curves, and the main weight loss peak for TEPA appears at 513 K for solid-supported amines. Linear and step regeneration modes have been compared, revealing that the temperature for step regeneration is 37 K lower than that for the linear regeneration mode. Moreover, the desorption peak area for the step regeneration mode is 20% higher than that for the linear regeneration mode, indicating that the step regeneration mode can be used in practical applications, to reduce energy consumption during regeneration.

1. INTRODUCTION

CO₂ is the main component of greenhouse gases; the exacerbation of the greenhouse effect causes increased atmospheric temperature and species’ extinction. CO₂ capture and storage technologies is the main method to reduce CO₂ emissions, though the relatively high capture cost remains the bottleneck of this process.

Applied decarbonization technology is mainly based on ethanolamine solution adsorption, such as the traditional monoethanolamine (MEA) method. The average CO₂ adsorption efficiency by MEA can reach 325.6 mg/g. However, the MEA regeneration process is quite energy-intensive, associated with large wastage of fresh MEA solution and high cost of CO₂ separation, which in combination with the corrosive and toxic nature of MEA, limit its systematic use.

Because of the high affinity between amine and CO₂, amine functional groups supported on solid porous substrates have become the focus for CO₂ removal by solid adsorbents.

Amine solid adsorbents are composed of porous support and organic amine. The supports are generally mesoporous with a large pore volume, for example, zeolites, carbon, metal–organic frameworks (MOFs), and silica, which exhibit adequate affinity for CO₂ under flue gas conditions, even at a low CO₂ concentration and in the presence of moisture. The most widely used organic amines are tetraethylenepentamine (TEPA) and polyethylenimine (PEI). Solid-supported amines have a high CO₂ adsorption capacity and a high CO₂ selectivity and can overcome the limits and drawbacks of currently used technologies (e.g., corrosion, energy-efficient regeneration, oxidation, or degradation of liquid amines). For realizing industrial applications, the current research studies on solid-supported amines for CO₂ adsorption are mainly focused on two points: to improve the CO₂ adsorption capacity and to improve the thermal stability and reduce the regeneration energy consumption of the adsorbents.

Mesoporous supports are the dominant factor for improving CO₂ adsorption in terms of both CO₂ adsorption capacity and the organic amine loading amount. Chen et al. synthesized a hierarchical porous carbon as the amine support, which displays CO₂ adsorption capacity up to 178.2 mg/g at 273 K. McDonald et al. found that diamine-appended MOFs
display a CO₂ adsorption capacity of 149.6 mg/g at 283 K. Pires et al.20 prepared amine-modified clays by the insertion of amino acids in raw clay, the CO₂ adsorption capacity of which reached only 35.2 mg/g at 298 K and 800 kPa. The proper choice of commercial mesoporous supports is crucial for obtaining the ideal CO₂ capture effect. As the mesoporous supports account for over 90% of the preparation cost for absolute adsorbents,1 commercially available cost-effective porous materials are appropriate for use as the supports for amine adsorbents.

Mesoporous silica is commonly used as adsorbent support at present. Zhang et al.21 obtained CO₂ adsorption capacity of 220 mg/g by impregnating TEPA on SBA-15. The TEPA loading amount is ~60 wt %; however, the heterogeneous loading of organic amines on porous support may lead to a channel block, and the effective amount of organic amine needed for CO₂ adsorption has not been considered and calculated. For industrial applications of amine adsorbents, the economic and effective amine loading amount is equally important.

Thermal and chemical stabilities are also crucial factors for solid-supported amines during the regeneration process.22 The stability of solid-supported amines determines the lifetime and replacement frequency of the adsorbent and greatly affects the cost. Drage et al.23 studied the stability of silica-immobilized PEI in air, nitrogen, and CO₂, and reported a good cyclic regeneration capacity of 88 mg/g by temperature-swing regeneration, two different methods, and step thermal regenerations, were compared. Considering that 71% of the CO₂ emissions arise from coal-fired flue gas in China,25,26 the effects of SO₂, NO, and H₂O in flue gas on CO₂ adsorption were also studied.

2. RESULTS AND DISCUSSION
2.1. Adsorbent Characterization. The texture properties of the supports are given in Table 1. The five supports are mesoporous materials with an average pore width (Dₜ) ranging from 3.38 to 11.652 nm. Among the five supports, MCM-41 has the largest specific surface area (S_{BET}) of 1173.6 m²/g and pore volume (Vₚ) of 1.024 mL/g. MMT has the smallest S_{BET} of 94.1 m²/g, Vₚ of 0.125 mL/g, and Dₜ of 3.38 nm, and PR has the largest Dₜ of 11.652 nm.

2.2. CO₂ Adsorption Properties on Solid-Supported Amines. 2.2.1. Effect of Porous Supports and Organic Amine Loading Amount on CO₂ Adsorption Performance. CO₂ adsorption experiments were conducted on blank supports and solid-supported amines. The experimental gas composition of CO₂ adsorption were 5 vol % CO₂, 5 vol % O₂, and a balance of N₂. The TEPA loading ratio was calculated using eq 1

\[ w = \frac{m_{\text{TEPA}}}{m_0} \times 100\% \]

where w is the TEPA loading ratio (%), \( m_{\text{TEPA}} \) is the mass of TEPA (g), and \( m_0 \) is mass of solid-supported amine (the sum of the masses of TEPA and support) (g).

CO₂ adsorption characteristics of different solid-supported amines are summarized in Figure 1. For each solid-supported amine, with increasing TEPA loading amount, CO₂ could hardly be detected at the early stage of adsorption; after a period, CO₂ penetrates the adsorbent bed and the slope of the adsorption curve increases sharply, until the adsorbent bed reaches saturation.

According to a previous research,27 CO₂ first reacts with TEPA on the support surface layer. After the surface TEPA is completely consumed, the CO₂ starts to react with the TEPA molecules in the inner or finer pores. The CO₂ diffusion rate limited the entire process and with increasing CO₂ concentration, the slope of the CO₂ adsorption increases.

| sample          | abbreviation | S_{BET}^a (m²/g) | Vₚ^b (ml/g) | Dₜ^b (nm) |
|-----------------|--------------|------------------|-------------|-----------|
| mesoporous alumina | MA           | 265.5            | 0.331       | 3.775     |
| silica gel      | SG           | 331.4            | 0.895       | 10.798    |
| porous resin    | PR           | 289.7            | 0.886       | 11.652    |
| MCM-41 molecular sieve | MCM-41 | 1173.6           | 1.024       | 3.49      |
| montmorillonite | MMT          | 94.1             | 0.125       | 3.38      |

**Table 1. Texture Characterization of the Supports**

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**Figure 1. CO₂ adsorption curves on solid-supported amines (5 vol % CO₂, 5 vol % O₂, a balance of N₂; 100 mL/min).**
CO₂ adsorption capacities of all the solid-supported amines with increasing TEPA loading ratios. For the MA-solid-supported amine, the CO₂ adsorption capacity is largest on MA-26.5%, reaching 99.6 mg/g. For the SG-solid-supported amine, CO₂ adsorption capacity reaches 161 mg/g on SG-38.7%. For the PR-solid-supported amine, CO₂ adsorption capacity reaches 155.8 mg/g on PR-41.9%. For the MCM-41-solid-supported amine, CO₂ adsorption capacity reaches 199.4 mg/g on MCM-41-55.7%. For the MMT-solid-supported amine, CO₂ adsorption capacity reaches 39.0 mg/g on MMT-23.4%. CO₂ adsorption capacities of MA-26.5%, SG-38.7%, PR-41.9%, MCM-41-55.7%, and MMT-23.4% were 11.2, 50.3, 25.1, 33.8, and 21.6 times greater than those on blank supports, respectively. Compared with ionic liquid sorbents, there are mainly physisorption and chemisorption with CO₂; and ionic liquids undergo physical dissolution or chemical reaction; the absorption capacity can reach 0.28−3.04 mol/kg; solid-supported amines have a better CO₂ capture effect.28

Below the optimal loading amount, more TEPA favors CO₂ adsorption, whereas above the optimal loading amount, TEPA blocks the pores inside the support, hampering CO₂ adsorption. For different adsorbents, the trend of CO₂ adsorption curves is consistent for different loading amounts. With increasing loading amount, the penetration time of the CO₂ adsorption curve increases and the slope decreases. After reaching the optimal loading amount, the penetration time decreases and the slope increases. Figure 2 shows the CO₂ adsorption capacities of different solid-supported amines with increasing TEPA loading ratios.

Figure 2. CO₂ adsorption capacities on different solid-supported amines with increasing TEPA loading ratios (5 vol % CO₂, 5 vol % O₂, a balance of N₂; 100 mL/min).

CO₂ adsorption capacities of all the five solid-supported amines studied increased with increasing TEPA loading ratios until the optimum TEPA loadings are reached, after which the adsorption capacities started to decrease.

Among the five supports, the highest CO₂ adsorption capacities at 343 K and 101 kPa are in the following order: MCM-solid-supported amine > SG-solid-supported amine > PR-solid-supported amine > MA-solid-supported amine > MMT-solid-supported amine. For the SG-solid-supported amine, the maximum CO₂ adsorption capacity is 160.9 mg/g; the value of the adsorption capacity is similar to that of Linneen’s investigation (silica aerogel-solid-supported amine with TEPA).29 This shows that the structure of the support and the type of amines are the key to determine the adsorption capacity. In accordance with the pore volumes (Table 1), for mesoporous or macroporous supports, the optimum TEPA loading amount is mainly affected by the pore volume and the CO₂ adsorption capacity is determined by the optimum TEPA loading amount. It is because TEPA molecules rely on the van der Waals force to load on the surface of the support. The pore volume and pore structure of the supports are the decisive factors for the loading of TEPA. When the TEPA loading exceeds the maximum loading, excess TEPA deposits were blocked on the surface of the support, causing a decrease in CO₂ adsorption efficiency.

2.2.2. Utilization Efficiency of TEPA under the Optimum Loading Ratio. According to the reaction of 2RNH₂ + CO₂ → R₃NH₃⁺ + RNCOO⁻ (in the absence of water), the theoretical CO₂ adsorption capacity of a solid-supported amine can be calculated as follows

\[ \nu_T = \frac{m_{TEPA} \times w}{M_{TEPA}} \times 2.5 \times M_{CO_2} \]  

(2)

\[ \nu_T = \text{CO}_2 \text{ theoretical adsorption capacity on solid-supported amine, mg/g. } M_{TEPA} = \text{the molecular weight of TEPA, 189.3 mol/g. } M_{CO_2} = \text{the molecular weight of CO}_2, 44 \text{ mol/g.} \]

Figure 3 shows the comparison between the theoretical and experimental CO₂ adsorption capacities for the optimal TEPA loading ratios. The result shows that the experimental adsorption capacities of all the solid-supported amines are smaller than the corresponding theoretical adsorption capacities. The difference between the experimental and theoretical adsorption capacities is the largest for MMT-23.4%; the theoretical and experimental CO₂ adsorption capacities were 139.1 and 31.5 mg/g, respectively, the difference exceeding 100 mg/g; the differences for MA-26.5% and SG-38.7% were relatively small (∼60 mg/g).

TEPA utilization efficiency, which refers to the amount of adsorbed CO₂ per unit organic amine, can be calculated as follows

\[ Q = \frac{\nu}{w} \]  

(3)

Q—CO₂ adsorption capacity per unit TEPA, mg/g. \( \nu \)—CO₂ adsorption capacity, mg/g. \( w \)—the TEPA loading ratio, %.

Figure 4 shows the TEPA utilization efficiency on the five adsorbents for the optimal loading ratios. CO₂ adsorption capacities per unit TEPA for MA, SG, PR, and MCM are close, exceeding 370 mg/g, whereas for MMT, the TEPA utilization efficiency reaching only 131 mg/g, which is 35% of that obtained for SG-38.7%. Thus, it can be found that the main
factors that affect TEPA utilization efficiency were pore volume (\(V_T\)) and specific surface area (\(S_{BET}\)); MMT had the smallest \(V_T\) and \(S_{BET}\). Larger \(V_T\) and \(S_{BET}\) can increase the TEPA utilization efficiency.

2.2.3. Atmosphere Effect on CO\(_2\) Adsorption. The presence of SO\(_2\), NO, and H\(_2\)O in flue gas might influence CO\(_2\) adsorption. Figure 4 shows that SG-38.7% has the highest CO\(_2\) adsorption capacity per unit TEPA; therefore, SG-38.7% was adopted to investigate the atmospheric effect. The atmosphere tags and descriptions are given in Table 2.

Figure 5 shows the CO\(_2\) adsorption capacities under different atmospheres on SG-38.7%. The CO\(_2\) adsorption capacity under different atmospheres was quite different; for C + H, the CO\(_2\) adsorption capacity was 197.9 mg/g, it was 18.7% higher than that of C. Moisture in flue gas favors CO\(_2\) adsorption on solid-supported amines, according to the reaction of 2RNH\(_2\) + CO\(_2\) \(\leftrightarrow\) (NH\(_3^+\))(NHCOO\(^-\)) (R\(_i\)) NH\(_3\)+ CO\(_2\)+ H\(_2\)O \(\leftrightarrow\) (NH\(_3^+\))(HCOO\(^-\)). But in the presence of SO\(_2\), the CO\(_2\) adsorption capacity was reduced by 25.0% (C + S), in the presence of NO (C + N), the CO\(_2\) adsorption capacity was almost unchanged from C. The results showed that SO\(_2\) inhibited the CO\(_2\) adsorption, and NO had little effect on CO\(_2\) adsorption. It can be attributed to the strong binding of SO\(_2\) on some amine sites, and NO had little interaction with TEPA.\(^{31}\)

2.3. Thermal and Regeneration Properties of Solid-Supported Amines. 2.3.1. Thermal Stability of Solid-Supported Amines. The solid-supported amines used in this study were prepared by the physical impregnation method, in which the organic amine molecules distributed on the support surface are mainly subjected to two forces: attraction between TEPA molecules and support and the interaction between the organic amine molecules. These two forces mainly include van der Waals forces and hydrogen bonds, which are overcome by the solid-supported amines on heating.\(^{32}\)

Figure 6 shows the derivative thermogravimetry (DTG) curves for TEPA and the five solid-supported amines with the optimal TEPA loading amount. For pure TEPA, only one major weight loss peak appeared at 523 K. For the solid-supported amines, the DTG curves of the solid amine absorbers at 318 K might be due to vapor volatilization from the supports. The major weight loss peak for TEPA appears at 513 K. The difference between the two peak positions is only 10 K, indicating that the affinity between the TEPA molecules and the support is smaller than the interaction between the organic amine molecules. The weight loss can be mainly attributed to volatilization of TEPA;\(^{33}\) when the temperature was higher than 623 K, TEPA was degraded, and the degradation products may include diethylenetriamine and triethylenetetramine (see the Supporting Information for additional details).

2.3.2. Linear and Step Regeneration of Solid-Supported Amines. The thermal stability results of the solid-supported amines show that TEPA would volatilize when heated. It begins to volatilize at temperatures higher than 373 K, and the volatilization rate of TEPA maximizes at 513 K. The difference between the two peak positions is only 10 K, indicating that the affinity between the TEPA molecules and the support is smaller than the interaction between the organic amine molecules. The weight loss can be mainly attributed to volatilization of TEPA;\(^{33}\) when the temperature was higher than 623 K, TEPA was degraded, and the degradation products may include diethylenetriamine and triethylenetetramine (see the Supporting Information for additional details).
For linear regeneration, CO₂ mainly desorbed at 329 K, and was completely desorbed at ~410 K. For step regeneration, CO₂ desorption occurred in five steps, at temperatures of 293, 313, 333, 353, and 373 K, the majority of CO₂ being desorbed at 293 and 313 K. After the first four regeneration steps, hardly any CO₂ was desorbed at 373 K, showing that the temperature for step regeneration can be set below 373 K, which is 37 K lower than that of the linear regeneration mode. The regeneration temperature range can achieve a good regeneration effect.²⁹ Compared with ionic liquid sorbents, the absorb system recovers essentially 100% of its CO₂ capacity at as low as 343 K; the regeneration temperature is lower than that of a solid-supported amine, but the temperature rise of the liquid needs to consume a lot of energy.²⁸

The regeneration effect can be compared by using the area integrals of the CO₂ desorption peaks. The desorption peak area for the linear regeneration mode (S₁) is 432, and that for step regeneration mode (S₂) is 518, S₂ being 20% higher than that of S₁, indicating that the regeneration effect in the step regeneration desorption mode is more complete than in the linear desorption mode.

Although the step regeneration mode has a lower regeneration temperature and imparts a more complete regeneration effect, the regeneration time is more than that for the linear regeneration mode. Energy consumption and the number of operation cycles should also be considered for the selection of industrial applications; to this end, more comprehensive research is still needed for ideal operation.

### 3. CONCLUSIONS

For solid-supported amines, CO₂ adsorption capacities follow the order of MCM-41-solid-supported amine > SG-solid-supported amine > PR-solid-supported amine > MA-solid-supported amine > MMT-solid-supported amine, which is coincident with the texture characterization results of the supports. For mesoporous and macroporous supports, the optimum TEPA loading amount is mainly affected by the pore volume, and the CO₂ adsorption capacity is in turn determined by the optimum TEPA loading amount.

CO₂ adsorption capacities per unit TEPA for MA, SG, PR, and MCM are close, exceeding 370 mg/g, showing that the effect of the same type of supports on TEPA utilization is insignificant, whereas the macroporous support of MMT limits TEPA utilization efficiency, reaching only 131 mg/g, 35% of that obtained for SG-38.7%. Thus, mesoporous supports are more conducive to uniform loading of organic amines, affording a higher TEPA utilization efficiency.

Study of the atmosphere effect on CO₂ adsorption properties revealed that moisture and acidic gases in flue gas favors CO₂ adsorption on solid-supported amines. The actual flue gas has no negative effect on CO₂ adsorption by solid-supported amines, instead is suitable for this system.

For solid amine adsorbents, the major weightlessness peak for TEPA appeared at 513 K, indicating that the affinity between TEPA molecules and the support is relatively smaller than the interaction between the organic amine molecules. The weight loss of solid-supported amines can be attributed to volatilization of TEPA.

In the linear regeneration mode, CO₂ desorption was mainly concentrated at 329 K, and it is completely desorbed at about 423 K. The temperature for the step regeneration mode can be set below 373 K, which is 37 K lower than that for the linear regeneration mode.

The desorption peak area for the step regeneration mode is 20% larger than that for the linear regeneration mode, indicating that the regeneration effect for the step regeneration desorption mode is more complete than that for the linear desorption mode.

### 4. EXPERIMENTAL SECTION

#### 4.1. Solid-Supported Amine Preparation

MA (Jiuzhou Chemicals Co., Ltd., PR; purity ≥ 99.7%), MMT (Aladdin Bio-Chem Technology Co., Ltd., PR; purity ≥ 98.0%), SG (Haiyang Chemical Co., Ltd., PR; purity ≥ 99.5%), PR (Sinopharm Chemical Reagent Co., Ltd., PR; wet true density: 1.02 g/mL; water content: 65.3%), and MCM-41 (catalyst plant of Nankai University, PR; SiO₂/Al₂O₃ = 25; crystallinity ≥ 95.0%) were ground into powder and dried in an oven at 383 K for 24 h each time before use.

The supports were impregnated with TEPA (189.3 g/mol, Xilong Chemical Ltd., PR) as follows. TEPA (189.3 g/mol, Xilong Chemical Ltd., PR) was dissolved in 40 mL of methanol under stirring for about 15 min, followed by adding the supports (10 g) to the TEPA/methanol solution. The slurry was continuously stirred for 2 h and then dried at 373 K for 24 h. The prepared adsorbent was named as X-Y (X: support, Y: loading ratio). The solid-supported amines were then tableted, milled, and sieved to a 20–40 mesh. The samples were stored in a desiccator before use.

#### 4.2. Solid-Supported Amine Characterization

The nitrogen adsorption and desorption isotherms were obtained at 77 K on an Autosorb iQ (Quantachrome, USA). The adsorbent (100 mg) was placed in the sample cell and was degassed at 323 K for 8 h. The adsorption points’ relative pressure range from 10⁻⁷ to 1 (p/p₀). The specific surface area (Sₐ) was calculated from the N₂ adsorption isotherms using the Brunauer–Emmett–Teller (BET) equation. The pore

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CO₂ adsorption capacities per unit TEPA for MA, SG, PR, and MCM are close, exceeding 370 mg/g, showing that the effect of the same type of supports on TEPA utilization is insignificant, whereas the macroporous support of MMT limits TEPA utilization efficiency, reaching only 131 mg/g, 35% of that obtained for SG-38.7%. Thus, mesoporous supports are more conducive to uniform loading of organic amines, affording a higher TEPA utilization efficiency.

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The desorption peak area for the step regeneration mode is 20% larger than that for the linear regeneration mode, indicating that the regeneration effect for the step regeneration desorption mode is more complete than that for the linear desorption mode.
volume ($V_T$), average pore width ($D_0$), and pore size distributions were also calculated by the Barrett–Joyner–Halenda (BJH) method.

Thermal stabilities of the adsorbents were studied using a thermogravimetric (TG) analyzer (VersaTherm HM, Thermo, USA). Approximately 50 mg of a solid-supported amine was placed in a quartz crucible, and heated to 373 K for 30 min with 300 mL/min $N_2$ flow to remove moisture. Then, the samples were cooled to room temperature (~293 K), and heated to 1273 K at 10 K/min with $N_2$ flow, and the weight change of the sample with increasing temperature was recorded simultaneously. The TG analysis curves and DTG curves were obtained. The DTG is the first derivative of the TG analysis curve versus temperature.

4.3. CO$_2$ Adsorption Tests. CO$_2$ adsorption capacity of a solid-supported amine was investigated using a fixed-bed reactor. The quartz tube reactor had an external diameter of 20 and a height of 500 mm, with a sieve plate placed in the middle. Figure 8 is the experimental setup for CO$_2$ adsorption and desorption. The experimental gas was produced by the cylinder standard gas, and the volume flow corresponding to the concentration of different reaction gases could be calculated. The volume flow of the gas was controlled by a mass flow controller, which can accurately control the volume of experimental component gases.

The gas flow was 100 mL/min. The amount of solid-supported amine was 1.0 g. The simulated flue gas comprising 5 vol% CO$_2$, 5 vol% O$_2$, and a balance of N$_2$ (99.99%), 1000 ppm SO$_2$, 1000 ppm NO, and 5 vol% H$_2$O was used for investigating the effect of other pollutants. The gas adsorption temperature was set as 343 K. After thorough mixing in the mixing vessel, the gas was fed into the reactor, and the effluent gas was continuously detected using a quadrupole mass spectrometer (GAM200, IPI). CO$_2$ was identified by the major mass ion of 44.

The CO$_2$ adsorption capacity was calculated from the area integral of the breakthrough curve, given by the following equation

$$\nu = \frac{F_0 M}{22.4 \times m_0} \int_0^t (C_0 - C_t) \, dt$$

where $\nu$ is the adsorption capacity (mg/g), $M$ is the mole fraction of the adsorbate, $F_0$ is the volumetric feed flow rate (mL/min), $m_0$ is the adsorbent mass (g), 22.4 is the molar volume of the adsorbate (L/mol), $C_0$ is the adsorbate feed concentration (ppm), $C_t$ is the adsorbate concentration (ppm) at time $t$, and $dt$ is a minimal amount of time variation.

4.4. Solid-Supported Amine Regeneration Test. The regeneration experiments were all conducted using the fixed-bed reactor mentioned in Section 2.3. The adsorption-saturated adsorbent (300 mg) was placed in the middle of the reactor, and 100 mL/min $N_2$ was flowed through, with the effluent gas continuously detected by the mass spectrometer.

The linear regeneration temperature was 293–423 K with the heating rate set at 2 K/min, and the temperature was maintained at 423 K for 60 min. For step thermal regeneration, the initial and terminal regeneration temperatures were 293 and 423 K. The regeneration process was divided into six steps, at 293, 313, 333, 353, 373, and 393 K. Each temperature step was maintained for 60 min, and the heating rate of each gradient was 5 K/min.

ASSOCIATED CONTENT

Supporting Information
The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsomega.9b03374.

CO$_2$ adsorption capacities on different adsorbents, experimental and theoretical CO$_2$ adsorption on different adsorbents, and nitrogen isothermal adsorption–desorption curves of different adsorbents (PDF)

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Notes

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