Kinetics of Carbon Dioxide Removal Using N-Acetylglucosamine

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ABSTRACT: Glucosamine, the amino sugar made from glucose, is a safe and natural reagent for post-combustion carbon dioxide capture. Its most plentiful derivative, N-acetylglucosamine (or NAG), was studied in this work with respect to its reaction kinetics in aqueous solutions. A stirred cell reactor with a flat gas–liquid interface was used, and it was found that CO2 reacts with NAG via a pathway similar to that with alkanolamines. In the 20–100 mM range of NAG concentration, the second-order rate constant at T = 308 K was 125 kmol m−3 s−1. For the 303–313 K range, the activation energy was 42 kJ mol−1. In a study on vapor–liquid equilibrium, it was found that the loading capacity of NAG (100 mM) at 303 K was 0.6 mol CO2/mol NAG, while the equilibrium partial pressure of CO2 was 0.8 kPa. Three rate promoters were tested, and piperazine showed better efficacy than monoethanolamine and 2-amino-2-methyl-1-propanol in aqueous NAG solutions. This work is expected to stimulate further interest in this new, green CO2 capturing solvent.

1. INTRODUCTION

Gas purification will be more sustainable if CO2 separation solvents are made from natural resources. Amino sugars are one such class of safe and green reagents in which a hydroxyl group in the sugar molecule is replaced with an amine group. They are weaker bases than the usual aliphatic amines, and their acid dissociation constants are determined by the hydration of the amino groups and the influence of the adjacent groups.1 The amino sugars N-methylglucosamine, glucosamine, and galactosamine have pK_a values of 7.86, 7.38, and 7.61 at 303 K correspondingly.2 Glucosamine (C6H13NO5), the amino sugar made from glucose, is widely distributed in nature. It is a constituent of polysaccharides, chitosan, and chitin. In the last decade, Navaza and coworkers3−6 proposed the use of this hexosamine as a candidate solvent for post-combustion capture, because it is inherently safe and decomposable as well as less damaging for equipment and piping. They investigated the gas–liquid mass transfer process into aqueous solutions of this amino sugar3,4 and showed that CO2 reacts with glucosamine via a pathway similar to that with the usual amines, monoethanolamine (MEA) and diethanolamine (DEA).5 However, the regeneration of CO2-rich solutions of glucosamine at mild conditions was reported to constitute a key challenge.6

N-Acetylglucosamine (or NAG), the most plentiful derivative of glucosamine, was studied in this work. The molecular structure of this secondary amide (C8H15NO6) made of glucosamine and acetic acid is represented in Figure 1. This peculiar structure makes this molecule especially interesting; however, its efficacy for CO2 separation has not been published. The molecular weight of NAG (221.2 g/mol) and the biosourced amino acid solvent glycine (75.1 g/mol). The pK_a values of MEA and glycine at 298 K are 9.51 and 9.77, respectively.7 In this study, an in-depth characterization of this prospective solvent NAG was performed. First, reaction kinetics in aqueous solutions of NAG (20−100 mM) was investigated in a stirred cell in the 303−313 K range. Rate constants were evaluated based on absorption rates measured in the moderately fast reaction regime, and the activation energy was found from the Arrhenius relation. Second, the dependence of the loading capacity of this compound on the equilibrium partial pressure of CO2 was studied in a low-temperature vapor–liquid equilibrium setup. Third, the absorption process in NAG solution was accelerated by adding rate activators, such as MEA, 2-amino-2-methyl-1-propanol (AMP), and piperazine (PZ).

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Figure 1. Molecular structure of N-acetylglucosamine.
2. THEORY

NAG (denoted here as AsH), which comprises a secondary amino group, forms unstable carbamate with CO₂ in an aqueous medium. This can be represented as follows:

\[ \text{CO}_2 + 2\text{AsH} \rightleftharpoons \text{AsCOO}^- + \text{AsH}_2^+ \] (1)

Actually, carbamate formation occurs in the following two steps according to the zwitterion mechanism \(^{8-10}\) for the CO₂ reaction with primary and secondary amines:

\[ \text{CO}_2 + \text{AsH} \leftrightarrow \text{AsH}^+\text{COO}^- \] (2)

\[ \text{AsH}^+\text{COO}^- + \text{B} \rightleftharpoons \text{AsCOO}^- + \text{BH}^+ \] (3)

In eq 3, B denotes bases, such as AsH, H₂O, and OH⁻. The carbamate of glucosamine is very unstable due to the alkyl group attached to the amine and hence it is easily hydrolysed. \(^5\)

The concurrent reactions of CO₂ with hydroxyl ions (to form bicarbonate) and water (to form carbonic acid) may be deemed unimportant to the conditions used in this study, due to the low hydroxyl ion concentration in the solution and the slow rate of formation of carbonic acid, correspondingly. \(^5\) The Bicarbonate formation in aqueous solutions of NAG is represented as follows:

\[ \text{AsCOO}^- + \text{H}_2\text{O} \leftrightarrow \text{AsH}^+ + \text{HCO}_3^- \] (4)

Using the \(^{13}\)C nuclear magnetic resonance (NMR) technique, Garcia-Abuin et al.\(^6\) reported the formation of bicarbonate rather than carbamate, in aqueous glucosamine. Bicarbonate formation in aqueous solutions of NAG is represented by eq 5:

\[ \text{CO}_2 + \text{AsH} + \text{H}_2\text{O} \leftrightarrow \text{AsH}^+_2 + \text{HCO}_3^- \] (5)

The overall rate in aqueous solutions of NAG is represented by eq 6:

\[ R_{\text{CO}_2} = \frac{k_2(\text{CO}_2)(\text{AsH})}{1 + \frac{k_{-1}}{k_1(B)}} = \frac{k_2(\text{CO}_2)(\text{AsH})}{1 + \frac{k_{-1}}{k_{\text{B}}(\text{AsH}) + k_{\text{B}}(\text{H}_2\text{O}) + k_{\text{B}}(\text{OH}^-)}} \] (6)

The term \( k_{\text{B}}(B) \) in eq 6 denotes the role of base B in the deprotonation of the zwitterion.

3. RESULTS AND DISCUSSION

3.1. Estimation of Physical Properties. The solution density was measured using a densitometer; the results at 303, 308, and 313 K are represented in Table 1. Furthermore, the viscosity was measured using a capillary viscometer (see Table 1), and viscosity values were used, together with the value of \( \text{N}_2\text{O} \) diffusivity in water, to estimate \( D_{\text{N}_2\text{O}} \) in NAG solutions using the Stokes–Einstein relation reported by Versteeg and van Swaaij.\(^11\) The solubility of \( \text{N}_2\text{O} \) in NAG solutions (\( \text{H}_{\text{N}_2\text{O}} \)) was found using the stirred cell. The \( \text{N}_2\text{O} \) analogy method was applied to find \( D_{\text{CO}_2} \) and \( H_{\text{CO}_2} \).\(^11\) These values are given in Table 1. The values of \( D_{\text{CO}_2} \) (2.17 \times 10^{-9} \text{ m}^2 \text{ s}^{-1}) and \( H_{\text{CO}_2} \) (3.11 \times 10^{-4} \text{ kmol m}^{-3} \text{ kPa}^{-1}) in another green solvent potassium glycinate (0.1 M) at \( T = 303 \text{ K} \) were comparable.\(^12\)

| temp (K) | \( \text{NAG} \) (M) | \( \rho \) (kg m\(^{-3}\)) | \( \mu \) (mPa s) | \( D_{\text{CO}_2} \times 10^9 \) (m\(^2\) s\(^{-1}\)) | \( H_{\text{CO}_2} \times 10^5 \) (kmol m\(^{-3}\) kPa\(^{-1}\)) |
|-------|----------|---------|---------|----------------|----------------|
| 303   | 0.10     | 1062.7  | 0.731   | 2.32           | 3.22           |
| 308   | 0.02     | 1003.8  | 0.590   | 2.84           | 3.23           |
| 308   | 0.04     | 1005.5  | 0.598   | 2.81           | 3.21           |
| 308   | 0.06     | 1007.5  | 0.612   | 2.76           | 3.19           |
| 308   | 0.08     | 1010.1  | 0.632   | 2.69           | 3.17           |
| 310   | 0.10     | 1012.4  | 0.641   | 2.66           | 3.15           |
| 311   | 0.10     | 938.52  | 0.601   | 2.89           | 3.09           |

Vaidya and Mahajani\(^13\) reported a low \( H_{\text{CO}_2} \) value of 2.66 \times 10^{-4} \text{ kmol m}^{-3} \text{ kPa}^{-1} for 2.5 M MEA at 303 K.

3.2. Estimation of \( k_L \). Previously, Littel et al.\(^14\) used a physical absorption process to estimate the liquid-side mass transfer coefficient (\( k_L \)) in a stirred cell. From the material balance for the solute gas, they showed that the following relationship holds

\[ \ln \left( \frac{P(t) - P_{\text{final}}}{P_{\text{initial}} - P_{\text{final}}} \right) = - \left( \frac{mV_L + V_G}{V_L V_G} \right) k_L \Delta t \] (7)

Their method was applied in this work. The absorption of CO₂ in water was studied at 303 K. The values of \( P_{\text{initial}}, P_{\text{final}} \) and \( P(t) \) were recorded. Using the other known parameters (\( m = 0.28 \text{ mol/mol}, V_G = 860 \text{ cm}^3, V_L = 400 \text{ cm}^3, \) and \( A = 45 \text{ cm}^2 \)), the value of \( k_L \) was found to be 0.0048 cm/s. This value is typical for stirred cell reactors.

3.3. Reaction Kinetics. The concentration of CO₂ in the bulk liquid was very low under the conditions used in this work. If \( (\text{CO}_2) \) is the saturation concentration of CO₂ and \( k_i \) (\( \text{CO}_2 \)) is the absorption rate for the purely mass transfer-controlled reaction regime (wherein the reaction occurs in the bulk liquid), the rate for the fast reaction regime is given by eq 8 according to Doraiswamy and Sharma:\(^15\)

\[ R_{\text{CO}_2} = k_i(\text{CO}_2)E \] (8)

where \( E \) is the enhancement factor due to the reaction, and its value is equal to the Hatta number, the ratio of the maximum possible reaction rate to the mass transfer rate, defined in eq 9:

\[ \text{Ha} = \frac{2 \text{ } (m+1) D_{\text{CO}_2} k_{m,a}(\text{CO}_2)^{m-1}(\text{AsH})^n}{k_L} \] (9)

In eq 9, \( k_{m,a} \) denotes the rate constant, while \( m \) and \( n \) are reaction orders with respect to CO₂ and AsH. Further, \( D_{\text{CO}_2} \) denotes the diffusivity of CO₂ in the liquid phase. In the fast regime, the inequality \( 10 < \text{Ha} < (E_i - 1) \) is satisfied. If the two-film theory is applied, the value of \( E_i \) viz. the instantaneous enhancement factor, is given by

\[ E_i = 1 + \left( \frac{\text{AsH}}{z(\text{CO}_2) D_{\text{CO}_2}} \right) \] (10)

Here, \( z \) is the stoichiometric reaction coefficient and \( D_{\text{AsH}} \) is the diffusivity of AsH in the liquid phase. From eqs 8 and 9, the reaction rate is given by

\[ R_{\text{CO}_2} = \sqrt{\frac{2}{m+1} D_{\text{CO}_2} k_{m,a}(\text{CO}_2)^{m+1}(\text{AsH})^n} \] (11)
From Henry’s law, the saturation concentration of CO$_2$ can be found by $[\text{CO}_2] = P_{\text{CO}_2} H_{\text{CO}_2}$. It is known that the reaction order with CO$_2$ is unity, and hence, eq 11 transforms to

$$R_{\text{CO}_2} = P_{\text{CO}_2} H_{\text{CO}_2} \sqrt{D_{\text{CO}_2} k_{1,\text{asH}} (\text{AsH})^n}$$

(12)

Eq 12 can be written as follows:

$$\log \left( \frac{R_{\text{CO}_2}}{P_{\text{CO}_2} H_{\text{CO}_2} \sqrt{D_{\text{CO}_2}}} \right) = \left[ \frac{1}{2} \log (k_{1,\text{asH}}) \right] + \left[ \frac{n}{2} \log (\text{AsH}) \right]$$

(13)

Provided that the dependence of $R_{\text{CO}_2}$ on (AsH) is known, a plot of $\log \left( \frac{R_{\text{CO}_2}}{P_{\text{CO}_2} H_{\text{CO}_2} \sqrt{D_{\text{CO}_2}}} \right)$ vs $\log (\text{AsH})$ will give the values of $k_{1,n}$ and $n$. If $n$ is also equal to unity, eq 12 simplifies to

$$R_{\text{CO}_2} = P_{\text{CO}_2} H_{\text{CO}_2} \sqrt{D_{\text{CO}_2} k_{2} (\text{AsH})^2}$$

(14)

The rates of CO$_2$ absorption in aqueous NAG solutions at 303, 308, and 313 K are represented in Table 2. The molarity of NAG in solutions was changed between 20 and 100 mM, while the CO$_2$ partial pressure varied in the range of 5−7 kPa. The rise in molarity of NAG resulted in higher rates of absorption. At 303 K, the rate increased from 1.27 × 10$^{-7}$ (NAG = 0.02 M) to 2.5 × 10$^{-7}$ kmol m$^{-2}$ s$^{-1}$ (NAG = 0.10 M). The rates were higher for the temperature equal to 313 K, and, as we moved from dilute solutions (0.02 M) to more concentrated ones (0.1 M), the rate increased from 1.88 × 10$^{-7}$ to 3.76 × 10$^{-7}$ kmol m$^{-2}$ s$^{-1}$. In Figure 2, plots of $R_{\text{CO}_2}$ vs (NAG) at 303, 308, and 313 K are shown. Clearly, this behaviour was not linear, and the reaction was not instantaneous.

Next, the CO$_2$ partial pressure was varied in the 5−25 kPa range, and the absorption rate was measured at $T = 308$ K and amino sugar concentration equal to 0.1 M. A linear trend was observed (see Figure 3), thereby confirming that the reaction was of the first order with respect to CO$_2$. Using eq 13, plots of $\log \left( \frac{R_{\text{CO}_2}}{P_{\text{CO}_2} H_{\text{CO}_2} \sqrt{D_{\text{CO}_2}}} \right)$ vs log(NAG) at various temperatures were built (see Figure 4). From the values of the slope, it was evident that the reaction order with respect to NAG is one. Earlier, Gómez-Díaz and Navaza$^5$ reported an identical reaction order for glucosamine. From eq 6, it is evident that zwitterion deprotonation is fast when compared to the reverse reaction between CO$_2$ and NAG and the inequality $k_{-1} \ll [k_{\text{AsH}} (\text{AsH}) + k_{\text{H}_2\text{O}} (\text{H}_2\text{O}) + k_{\text{OH}^-} (\text{OH}^-)]$ holds. As a result, formation of the zwitterion is rate-determining, and the reaction is overall of the second order, viz. $R_{\text{CO}_2} = k_{2,\text{AsH}} (\text{CO}_2) (\text{AsH})$. Using Figure 4, the value of $k_2$ was estimated as 125 (±1) M$^{-1}$ s$^{-1}$ at $T = 308$ K. This value is higher than the rate constant for glucosamine (10.14 M$^{-1}$ s$^{-1}$) reported by Gómez-Díaz and Navaza$^5$ at $T = 298$ K. It was considered worthwhile to compare the reactivity of NAG with other solvents. When a few trials were performed using the standard amine MEA, it was found that the $k_2$ value for MEA was significantly higher (9764 M$^{-1}$ s$^{-1}$) at $T = 308$ K. Further, another class of biosourced solvents, viz. amino acid salts, was chosen for comparison. It was found from preliminary runs.

### Table 2. Rates of CO$_2$ Absorption in Aq NAG Solutions at 303, 308, and 313 K

| temp (K) | (NAG) (M) | $P_{\text{CO}_2}$ (kPa) | $R_{\text{CO}_2} \times 10^7$ (kmol m$^{-2}$ s$^{-1}$) |
|---------|-----------|-------------------------|---------------------------------------------------|
| 303     | 0.02      | 5.5                     | 1.27                                              |
|         | 0.04      | 5.6                     | 1.88                                              |
|         | 0.06      | 6.5                     | 2.18                                              |
|         | 0.08      | 5.3                     | 2.36                                              |
|         | 0.10      | 5.2                     | 2.50                                              |
| 308     | 0.02      | 5.9                     | 1.61                                              |
|         | 0.04      | 6.2                     | 2.34                                              |
|         | 0.06      | 5.6                     | 2.53                                              |
|         | 0.08      | 5.3                     | 2.75                                              |
|         | 0.10      | 5.3                     | 3.02                                              |
| 313     | 0.02      | 5.8                     | 1.88                                              |
|         | 0.04      | 6.0                     | 2.63                                              |
|         | 0.06      | 6.1                     | 3.19                                              |
|         | 0.08      | 5.6                     | 3.41                                              |
|         | 0.10      | 5.6                     | 3.76                                              |
using sodium glycinate (SG) in this work that the rate constant at 303 K for SG was $5565 \text{ M}^{-1} \text{ s}^{-1}$. For the potassium salt of glycine, the rate constant was earlier found to be equal to $6290 \text{ M}^{-1} \text{ s}^{-1}$ at $T = 303 \text{ K}$. Thus, the amino sugar NAG is less reactive than other traditional solvents, and it is essential to improve absorption kinetics in NAG solutions using activators of the absorption rate.

Furthermore, the temperature dependence of $k_2$ was studied. The Arrhenius plot is represented in Figure 5. The relation between $k_2$ and $T$ was correlated by eq 15:

$$k_2,\text{NAG} = (1.59 \times 10^5)\exp\left(-\frac{5035}{T}\right)$$

(15)

The activation energy was 42 (±1) kJ mol$^{-1}$, which is lower than the value published by Gómez-Díaz and Navaza for glucosamine (47.6 kJ mol$^{-1}$). The values of $H_a$ and $E_i$ at NAG = 0.1 M are shown in Table 3. They were much higher than that in the aqueous NAG solution (0.1 M). Clearly, PZ was the best performing activator, as NAG/PZ mixtures exhibited the highest rates. The efficacies of the amines as activators decreased in the order of PZ > MEA > AMP. Next, the CO$_2$ partial pressure was varied in the 5–25 kPa range and linear dependence of the overall CO$_2$–NAG reaction was in parallel with the CO$_2$–amine reaction, viz.

$$R_{\text{CO}_2} = k_{2,\text{AsH}}(\text{CO}_2)(\text{AsH}) + k_{2,\text{AmH}}(\text{CO}_2)(\text{AmH})$$

(17)

The rates in aqueous mixtures of AmH (0.5 M) and NAG (0.1 M) were measured at 308 K and they are given in Table 4.

They were much higher than that in the aqueous NAG solution (0.1 M). Clearly, PZ was the best performing activator, as NAG/PZ mixtures exhibited the highest rates. The efficacy of the amines as activators decreased in the order of PZ > MEA > AMP. Next, the CO$_2$ partial pressure was varied in the 5–25 kPa range and linear dependence of the
absorption rate on the partial pressure of CO₂ was observed (see Figure 6).

![Figure 6](https://example.com/figure6.png)

**Figure 6.** Plots of $R_{CO_2}$ vs $P_{CO_2}$ at $T = 308$ K (NAG/activator = 0.1/0.5 M).

### 3.5. Measurement of Equilibrium Solubility of CO₂

The dependency of the equilibrium CO₂ partial pressure of ($P^{eq}_{CO_2}$) on the loading capacity ($\propto$) of aq NAG solution (0.1 M) was investigated at $T = 303$ K. The results are presented in Figure 7. A polynomial relation was found:

$$\log(P^{eq}_{CO_2}) = 0.422 - 4.417 \propto + 17.78 \propto^2 - 15.55 \propto^3$$  

(18)

The highest value of loading capacity was 0.6 mol CO₂/mol amino sugar, when the equilibrium CO₂ pressure was 0.8 kPa. These results highlight the good performance of the proposed solvent. In a previous study performed at 313 K, the CO₂ loading in the green amino acid salt sodium sarcosinate (5 mol sarcosine/kg of total solution) at low partial pressure (1 kPa) was around 0.6 mol/mol. The equilibrium CO₂ partial pressure in this work was low, due to the limitations in the experimental technique. However, it is not uncommon to investigate the equilibrium features at low partial pressures. Typically, the values of $P^{eq}_{CO_2}$ are low in the top section of an industrial absorber, and low-pressure equilibrium data are useful to find the packed height in the absorber. The CO₂ equilibrium partial pressure in the gas phase will increase with increasing CO₂ loading. The rise in molarity of NAG will enhance the loading capacity. In a forthcoming work, we are going to investigate the equilibrium features of the proposed solvent in a high-pressure setup.

### 3.6. Some General Remarks

Navaza and coworkers recommended the natural reagent glucosamine for separating CO₂ from gaseous mixtures. In this work, we studied reaction kinetics and equilibrium of its N-acetyl derivative, which was hitherto not reported. Also, we established that absorption kinetics in aqueous NAG solutions could be accelerated by using promoters, such as MEA, AMP, and PZ, thereby enlarging the scope for the possible application of this new class of solvents. While the results are certainly encouraging, it is, however, necessary to tackle some problems that NAG may face in the actual industrial CO₂ capture process. For instance, its relatively high molecular weight (221.2 g/mol); the high amount of energy required for the regeneration of aqueous solutions (due to the high heat capacity and evaporation enthalpy of water); and the probable influence of sugar concentration, type of promoter, temperature, and oxygen on the degradation of its solutions may increase the cost of operations. The use of practical solutions to these challenges will decide the efficacy of NAG and its blends in post-combustion CO₂ capture. Solvent regeneration and degradation were not considered here; however, these issues will be investigated in a forthcoming study.

### 4. CONCLUSIONS

It is especially advantageous to apply aqueous solutions of amino sugars for CO₂ capture because they are safe, green and abundant. In this work, the reactivity of the N-acetyl derivative of glucosamine, viz. NAG, was investigated in a stirred cell reactor in the 303–313 K temperature range. The molarity of NAG in the solution was varied between 20 and 100 mM. The reaction between CO₂ and NAG was first order with respect to both reactants, and thus, overall second order. At $T = 308$ K, the rate constant was found to be equal to 125 M⁻¹ s⁻¹, while the activation energy was 42 kJ mol⁻¹. The VLE measurement at the near-ambient pressure brought about the CO₂ loading of NAG solution (100 mM) at 303 K equal to 0.6 mol CO₂/mol NAG; the respective equilibrium partial pressure of CO₂ was 0.8 kPa. The effect of the addition of activators on the absorption rate was investigated too. Three innovative blends of NAG with MEA, PZ, and AMP were explored, and PZ showed the best performance as the activator.

### 5. EXPERIMENTAL SECTION

#### 5.1. Materials

Most reagents used in this study were purchased from local vendors in Mumbai. For instance, NAG, MEA, and PZ (purity is 98%) were procured from S.D. Fine Chemicals Pvt. Ltd., while AMP (purity is 98%) was purchased from Spectrochem Pvt. Ltd. Gas cylinders containing pure CO₂, N₂, and nitrous oxide (N₂O) were purchased from Inox.
Air Products Ltd. Finally, CO_2 standard and buffer solutions for the ion-selective electrode were purchased from Thermo-Fisher Scientific, U.S.A.

5.2. Stirred Cell Kinetics. In a recent work,^17 the setup and procedure for studying reaction kinetics in a stirred cell were described. In summary, a jacketed, stirred reactor with a flat gas–liquid interface was used. Its interfacial area (45 cm^2) and volume (1260 cm^3) were known. Initially, the reactor was flushed with inert N_2 evacuated using vacuum pump, filled with liquid (400 cm^3), and kept at the desired temperature (303, 308, or 313 K) using a water circulation bath (accuracy = 0.1 K). The liquid-phase impeller rotated at 60 rpm (accuracy = 1 rpm) so that the gas–liquid interface was undisturbed. Then, pure CO_2 was charged inside and the pressure change was checked by the conductivity probe. After equilibrium was reached, the gas and liquid phases were analyzed by a CO_2 ion-selective electrode (Orion, U.S.A.). The error in measurements of the value reported by Hikita et al.19 (viz. 10,069 M) was checked by the conductivity probe. After equilibrium was realized by a blower. Reaching equilibrium was considered as validated.

In a stirred cell, the gas-side mass transfer resistance is unimportant if the inert gas pressure is low and the stirring speed is high.18 Thus, such a resistance was neglected in this work. The stirring speed in liquid was increased to 100 rpm; however, the absorption rate was identical to its value at 60 rpm. Clearly, this rate was independent of the impeller speed, and hence, the value of k_L. Thus, it was concluded that the reaction is not instantaneous. When CO_2–MEA kinetics was studied, the rate constant at 308 K (9764 M s^-1) was close to the value reported by Hikita et al. ^19 (viz. 10,069 M s^-1). Thus, the procedure for kinetics measurements could be considered as validated.

5.3. Vapor–Liquid Equilibrium Measurements. In a vapor–liquid equilibrium (VLE) setup, the equilibrium solubility of CO_2 in NAG solution (100 mM) was measured at 303 K. The setup and procedure were described in our previous work.20 A glass apparatus consisting of an equilibrium cell, saturator, and gas reservoir was used. It was immersed in a water bath. The equilibrium cell (volume of 250 mL) was equipped with a conductivity probe and magnetic stirrer. Its inlet and exit ports were attached to the saturator and gas reservoir. The cell was filled with a CO_2-loaded solution, while the gas flow was realized by a blower. Reaching equilibrium was checked by the conductivity probe. After equilibrium was reached, the gas and liquid phases were analyzed by a CO_2 ion-selective electrode (Orion, U.S.A.). The error in measurements (<2%) was again found by the replication of a few trials under identical conditions. The variation in equilibrium partial pressure of CO_2 with the loading capacity of the solution was recorded.

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Notes
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■ NOMENCLATURE

| Symbol | Description |
|--------|-------------|
| A      | interfacial area, cm^2 |
| AmH    | amine used as an absorption activator in aq NAG (AmH) concentration of amine in liquid, M |
| AsH    | amino sugar (AsH) concentration of amino sugar in liquid, M |
| D_AsH  | diffusivity of amino sugar in liquid, m^2 s^-1 |
| D_CO2  | diffusivity of CO_2 in liquid, m^2 s^-1 |
| E      | enhancement factor due to the chemical reaction enhancement factor for an instantaneous reaction |
| E_h    | Hatta number |
| H_CO2  | solubility of CO_2 in liquid, kmol m^-3 kPa^-1 |
| H_W    | concentration of water, M |
| k_f    | forward rate constant for reaction between CO_2 and NAG, M^-1 s^-1 |
| k_r    | reverse rate constant for reaction between CO_2 and NAG, M^-1 s^-1 |
| k_amH  | deprotonation constant for amine |
| k_AmH  | deprotonation constant for amino sugar |
| k_H_2O | deprotonation constant for water |
| k_l    | liquid-side mass transfer coefficient, m^-1 |
| k_oh   | deprotonation constant for OH^- |
| m      | dimensionless solubility, mol mol^-1 |
| (NAG)  | initial concentration of NAG in liquid, M |
| (OH^-) | hydroxyl ion concentration, M |
| P_CO2  | partial pressure of CO_2 in bulk gas phase, kPa |
| P(i)   | partial pressure of solute gas at time t, kPa |
| P_final | final partial pressure of solute gas, kPa |
| P_initial | initial partial pressure of solute gas, kPa |
| (Promoter) | concentration of promoter in liquid, M |
| R_CO2  | absorption rate of CO_2, kmol m^-2 s^-1 |
| V_G    | volume of gas phase, cm^3 |
| V_L    | volume of liquid phase, cm^3 |

■ GREEK SYMBOLS

| Symbol | Description |
|--------|-------------|
| \( \rho \) | tabdensity of amino sugar solution, kg m^-3 |
| \( \mu \) | tabviscosity of amino sugar solution, mPa s |

■ REFERENCES

1. Blasko, A.; Bunton, C. A.; Bunel, S.; Ibarra, C.; Moraga, E. Determination of acid dissociation constants of anomers of amino sugars by 1H NMR spectroscopy. Carbohydr. Res. 1997, 298, 163–172.
2. Miyazaki, M.; Nishimura, S.; Yoshida, A.; Okubo, N. Metal complexes of D-glucosamine and its derivatives. VIII. Metal complexes of N-methyl-D-glucosamine and its related amino sugars. Chem. Pharm. Bull. 1979, 27, 532–535.
(3) Gómez-Díaz, D.; Navaza, J. M.; Sanjurjo, B.; Vázquez-Orgeira, L. Carbon dioxide absorption in glucosamine aqueous solutions. *Chem. Eng. J.* 2006, 122, 81–86.

(4) García-Abuín, A.; Gómez-Díaz, D.; Navaza, J. M.; Vidal-Tato, I. CO₂ capture by aqueous solutions of glucosamine in a bubble column reactor. *Chem. Eng. J.* 2010, 162, 37–42.

(5) Gómez-Díaz, D.; Navaza, J. M. Kinetics of carbon dioxide absorption into aqueous glucosamine solutions. *AIChE J.* 2008, 54, 321–326.

(6) García-Abuín, A.; Gómez-Díaz, D.; Navaza, J. M. Characterization of carbon dioxide capture by glucosamine: Liquid phase speciation and degradation. *J. Ind. Eng. Chem.* 2014, 20, 2272–2277.

(7) Yan, S.; He, Q.; Zhao, S.; Zhai, H.; Cao, M.; Ai, P. CO₂ removal from biogas by using green amino acid salts: Performance evaluation. *Fuel Process. Technol.* 2015, 129, 203–212.

(8) Mahajani, V. V.; Joshi, J. B. Kinetics of reactions between carbon dioxide and alkanolamines. *Gas Sep. Purif.* 1988, 2, 50–64.

(9) Versteeg, G. F.; van Dijck, L. A. J.; van Swaaij, W. P. M. On the kinetics between CO₂ and alkanolamines both in aqueous and nonaqueous solutions. An overview. *Chem. Eng. Commun.* 1996, 144, 113–158.

(10) Vaidya, P. D.; Kenig, E. Y. CO₂-alkanolamine reaction kinetics: A review of recent studies. *Chem. Eng. Technol.* 2007, 30, 1467–1474.

(11) Versteeg, G. F.; van Swaaij, W. P. M. Solubility and diffusivity of acid gases (carbon dioxide, nitrous oxide) in aqueous alkanolamine solutions. *J. Chem. Eng. Data* 1988, 33, 29–34.

(12) Vaidya, P. D.; Konduru, P.; Vaidyanathan, M.; Kenig, E. Y. Kinetics of carbon dioxide removal by aqueous alkaline amino acid salts. *Ind. Eng. Chem. Res.* 2010, 49, 11067–11072.

(13) Vaidya, P. D.; Mahajani, V. V. Kinetics of the reaction of CO₂ with aqueous formulated solution containing monoethanolamine, N-methyl-2-pyrrolidone, and diethylene glycol. *Ind. Eng. Chem. Res.* 2005, 44, 1868–1873.

(14) Littel, R. J.; Versteeg, G. F.; van Swaaij, W. P. M. Physical absorption into non-aqueous solutions in a stirred cell reactor. *Chem. Eng. Sci.* 1991, 46, 3308–3313.

(15) Doraiswamy, L. K.; Sharma, M. M. *Heterogeneous Reactions: Analysis, Examples and Reactor Design*, Vol. 2. John Wiley and Sons: New York, 1984.

(16) Ma’mun, S.; Kim, I. Selection and characterization of phase change solvent for carbon dioxide capture: Precipitating system. *Energy Procedia* 2013, 37, 331–339.

(17) Patil, M. P.; Vaidya, P. D. Characterization of the superior CO₂-capturing absorbent blend AMP/PZ/EGMEE/Water. *Int. J. Greenhouse Gas Control* 2019, 84, 29–35.

(18) Jiru, Y.; Eimer, D. A. A study of mass transfer kinetics of carbon dioxide in (monoethanolamine + water) in stirred cell. *Energy Procedia* 2013, 37, 2180–2187.

(19) Hikita, H.; Asai, S.; Ishikawa, H.; Honda, M. The kinetics of reactions of carbon dioxide with monoethanolamine, diethanolamine and triethanolamine by a rapid mixing method. *Chem. Eng. J.* 1977, 13, 7–12.

(20) Sutar, P. N.; Vaidya, P. D.; Kenig, E. Y. Activated DEEA solutions for CO₂ capture – A study of equilibrium and kinetic characteristics. *Chem. Eng. Sci.* 2013, 100, 234–241.