


Cite this: *RSC Adv.*, 2019, 9, 1882

# Absorption and thermodynamic properties of CO<sub>2</sub> by amido-containing anion-functionalized ionic liquids†

Yanjie Huang, Guokai Cui,  Huiyong Wang, Zhiyong Li and Jianji Wang \*

In this contribution, two kinds of amido-containing anion-functionalized ionic liquids (ILs) were designed and synthesized, where the anions of these ILs were selected from deprotonated succinimide (H-Suc) and o-phthalimide (Ph-Suc). Then, these functionalized ILs were used to capture CO<sub>2</sub>. Towards to this end, solubility of CO<sub>2</sub> in the ILs was determined at different temperatures and different CO<sub>2</sub> partial pressures. Based on these data, chemical equilibrium constants of CO<sub>2</sub> with the ILs were derived at different temperatures from the “deactivated IL” model. The other thermodynamic properties such as reaction Gibbs energy, reaction enthalpy, and reaction entropy in the absorption were also calculated from the corresponding equilibrium constant data at different temperatures. It was shown that these anion-functionalized ILs exhibited high CO<sub>2</sub> solubility (up to 0.95 mol CO<sub>2</sub> mol<sup>-1</sup> IL) and low energy desorption, and enthalpy change was the main driving force for CO<sub>2</sub> capture by using such ILs as absorbents. In addition, the interactions of CO<sub>2</sub> with the ILs were also investigated by <sup>1</sup>H NMR, <sup>13</sup>C NMR, and FT-IR spectroscopy.

Received 20th September 2018

Accepted 7th January 2019

DOI: 10.1039/c8ra07832g

rsc.li/rsc-advances

## 1. Introduction

In recent decades, the excessive accumulation of carbon dioxide (CO<sub>2</sub>) in the atmosphere has attracted widespread concern due to the greenhouse effect.<sup>1</sup> In order to solve this problem, carbon capture and storage (CCS) through sustainable and green methods has become a hot topic in recent decades.<sup>2</sup> Although aqueous alkanolamine solutions have been used in industry for nearly a century as a kind of chemical absorbent for CO<sub>2</sub> in flue gas from power plants through the formation of ammonium carbamate, the main disadvantage of this process is the high energy consumption for the regeneration and recycling of the absorbent, which accounts for 30% of the energy of the power plant.<sup>3,4</sup> Thus, alternative CCS methods for highly efficient and reversible capture of CO<sub>2</sub> are desired.

In recent years, considerable attention has been focused on using ionic liquids (ILs), especially functionalized ILs, as a kind of competitive alternative green absorbent for CO<sub>2</sub> capture. These liquid materials provide some unique advantages such as reduced volatilization and improved regeneration.<sup>5–9</sup> In light of the reaction mechanism of CO<sub>2</sub> in alkanolamine solutions and

the outstanding properties of ILs, Davis *et al.*<sup>10</sup> first reported imidazolium ILs with amino-grafted cation for the chemical absorption of CO<sub>2</sub>. Since the anion plays a key role in carbon capture, worldwide researchers have developed many kinds of task-specified ILs with the functionalized anions such as amino acids,<sup>11–14</sup> azolates,<sup>15–20</sup> phenolates,<sup>7,21–23</sup> and acetate.<sup>24</sup> Compared with conventional ILs, these anion-functionalized ILs typically have high CO<sub>2</sub> absorption capacity and selectivity. It is highly encouraged that novel kinds of other anion-functionalized ILs should be developed and used in CCS process.

Thermodynamic properties of CO<sub>2</sub> – functionalized IL systems are essential to guide the design of new functionalized ILs for CO<sub>2</sub> capture. Up to now, great efforts have been devoted to the studies on the thermodynamic properties of CO<sub>2</sub> chemical absorption by functionalized ILs. For instance, Brennecke *et al.*<sup>25,26</sup> proposed “deactivated IL” model and “two-reaction” model to analyze the thermodynamic properties of CO<sub>2</sub> in amine-functionalized ILs. Wang *et al.*<sup>27</sup> reported that anion-functionalized [P<sub>66614</sub>][p-AA] and [P<sub>66614</sub>][p-ANA] had higher absorption capacity and lower reaction enthalpy because of entropic effects. Hu *et al.*<sup>28</sup> systematically studied the thermodynamic properties of CO<sub>2</sub> capture in low-viscous fluorine-substituted phenolic ILs through the “deactivated IL” model. Thus, it is very important to expand the thermodynamic studies of different types of functionalized ILs.

In this work, we designed and synthesized two kinds of amido-containing anion-functionalized ILs (see Fig. 1) for CO<sub>2</sub> capture. Solubility of CO<sub>2</sub> in these functionalized ILs was

Henan Key Laboratory of Green Chemistry, Collaborative Innovation Center of Henan Province for Green Manufacturing of Fine Chemicals, Key Laboratory of Green Chemical Media and Reactions, Ministry of Education, School of Chemistry and Chemical Engineering, Henan Normal University, Xinxiang, Henan 453007, China. E-mail: jwang@htu.cn

† Electronic supplementary information (ESI) available: NMR and IR data of the acylamido-based ILs, Tables S1 and S2, Fig. S1 and Scheme S1. See DOI: 10.1039/c8ra07832g



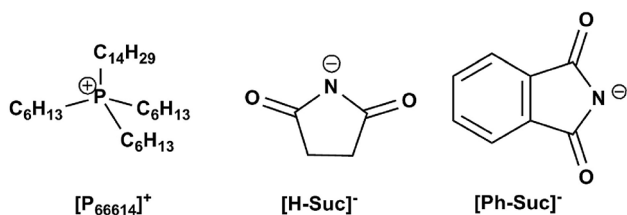


Fig. 1 Chemical structures of ILs used in this work for CO<sub>2</sub> capture.

determined at different temperatures and different CO<sub>2</sub> partial pressures. From these data, the equilibrium constants for the reaction of CO<sub>2</sub> with these ILs were calculated from a modified “deactivated IL” model as a function of temperature. Then, the Gibbs energy, enthalpy and entropy change were reported for the process of CO<sub>2</sub> capture. It was shown that high CO<sub>2</sub> absorption capacity and low energy consumption regeneration of the ILs could be achieved by these anion-functionalized ILs. From the viewpoint of chemical thermodynamic, enthalpy change is the main driving force for CO<sub>2</sub> capture by using such ILs as absorbents.

## 2. Experimental section

### 2.1. Materials

CO<sub>2</sub> and N<sub>2</sub> were purchased from Beijing Oxygen Plant Specialty Gases Institute Co., Ltd. with a purity of 99.999% and 99.9993%, respectively. Trihexyl(tetradecyl)phosphonium bromide ([P<sub>66614</sub>][Br], 97%) and *o*-phthalimide (Ph-Suc, 98%) were obtained from J&K Scientific, while succinimide (H-Suc) was supplied by Sigma-Aldrich. An anion-exchange resin (Amersep 900 OH) was purchased from Alfa Aesar. All these substances were used as received.

### 2.2. Preparation of the ionic liquids

Anion-functionalized ILs were simply produced through the neutralization of different kinds of acylamides and an ethanol solution of trihexyl(tetradecyl)phosphonium hydroxide ([P<sub>66614</sub>][OH]) at room temperature according to the procedures described in literature,<sup>29,30</sup> where [P<sub>66614</sub>][OH] was prepared from [P<sub>66614</sub>][Br] by anion-exchange method using ethanol as the solvent.<sup>31</sup> In a typical synthesis of [P<sub>66614</sub>][H-Suc], equimolar H-Suc was added to the ethanol solution of [P<sub>66614</sub>][OH], and the mixture was then stirred at room temperature for 24 h. Then, ethanol and water were evaporated at 333 K under reduced pressure. The as-prepared [P<sub>66614</sub>][H-Suc] was dried with P<sub>2</sub>O<sub>5</sub> under vacuum at 333 K for 24 h to remove possible residual moisture before use. The chemical structures of these ILs were confirmed by <sup>1</sup>H NMR, <sup>13</sup>C NMR and FT-IR spectra, and the data were listed in the ESI.†

### 2.3. Determination of CO<sub>2</sub> solubility

Solubility data of CO<sub>2</sub> in these ILs were measured by gravimetric method.<sup>32</sup> In a typical measurement, CO<sub>2</sub> was bubbled through about 1.0 g IL loaded in a glass container with an inside diameter of 12 mm, and the gas flow rate monitored by gas

rotameter was about 60 ml min<sup>-1</sup>. The glass container was partly immersed in a water bath which was maintained at the given temperature with temperature uncertainty of ± 0.1 K. During gas absorption, weight of the sample was determined at regular intervals by an electronic balance with an accuracy of ± 0.1 mg until it became constant. At this stage, the adsorption equilibrium of CO<sub>2</sub> in the IL was reached, and the solubility of CO<sub>2</sub> in the IL could be calculated. For the absorption of CO<sub>2</sub> under different partial pressure, CO<sub>2</sub> was diluted by N<sub>2</sub> gas and the given partial pressure was produced by controlling the flow rate ratio of CO<sub>2</sub> and N<sub>2</sub>.

### 2.4. Characterization of the ionic liquids

<sup>1</sup>H NMR and <sup>13</sup>C NMR spectra were determined on a Bruker spectrometer (400 MHz) in DMSO-d<sub>6</sub> with tetramethylsilane (TMS) as the standard. FT-IR spectra were recorded using a Nicolet 470 FT-IR spectrometer. The structures of ([P<sub>66614</sub>][H-Suc] and [P<sub>66614</sub>][Ph-Suc]) before and after CO<sub>2</sub> absorption were confirmed by NMR and FT-IR spectroscopy. The water contents in these ILs after drying, determined with Karl Fischer Titration (Mettler Toledo DL32, Switzerland), was lower than 0.1 wt%. The residual halide content, as determined by combining a Br<sup>-</sup> selective electrode (Shanghai Precision & Scientific Instrument Co. Ltd.) with a saturated calomel electrode (Shanghai Precision & Scientific Instrument Co. Ltd.), was less than 0.0005 mol per kilogram.

## 3. Results and discussion

### 3.1. Solubilities of CO<sub>2</sub> in the ionic liquids

At the beginning, solubility of CO<sub>2</sub> in these ionic liquids was measured at 308.15 K under atmospheric pressure. The results showed that up to 0.95 mol CO<sub>2</sub> per mol of IL could be achieved by these functionalized ILs, indicating good absorption performance of the absorbents. Thus, the solubility of CO<sub>2</sub> in these ILs was determined at 308.15 K, 313.15 K, 318.15 K, and 323.15 K under different CO<sub>2</sub> partial pressures. Table S1 and S2 (see ESI†) listed the solubility data of CO<sub>2</sub> in [P<sub>66614</sub>][H-Suc] and [P<sub>66614</sub>][Ph-Suc] at various temperatures and CO<sub>2</sub> partial pressures. For the sake of easy understanding, these data were shown in Fig. 2 and 3, respectively. It can be seen that the solubility of CO<sub>2</sub> in the ILs increased with increasing partial pressure in the range of low pressure. For instance, the solubility of CO<sub>2</sub> in [P<sub>66614</sub>][H-Suc] at 308.15 K was 0.61 mol CO<sub>2</sub> mol<sup>-1</sup> IL under 10 kPa of CO<sub>2</sub> partial pressure, while it increased to 0.95 mol CO<sub>2</sub> mol<sup>-1</sup> IL under 100 kPa of CO<sub>2</sub> partial pressure. However, Fig. 2 and 3 exhibited a nonlinear absorption trend with the increase of CO<sub>2</sub> partial pressure. This indicates that the absorption of CO<sub>2</sub> in these ILs was mainly carried out through chemical absorption. On the other hand, when the temperature increased from 308.15 K to 323.15 K, the molar ratio of CO<sub>2</sub> to [P<sub>66614</sub>][H-Suc] reduced from 0.61 to 0.14 under 10 kPa of CO<sub>2</sub> (Fig. 2). This result suggests that the captured CO<sub>2</sub> could be facilely released by mild heating. Thus, the CO<sub>2</sub> absorption process by these ILs was characterized by high CO<sub>2</sub> absorption capacity and low energy desorption.



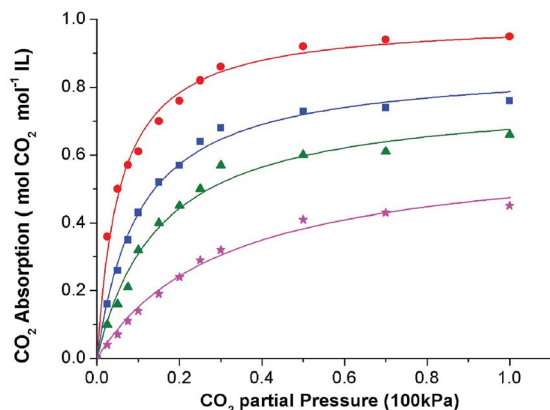


Fig. 2 The absorption isotherms of the  $\text{CO}_2$ -[P<sub>66614</sub>][H-Suc] system at different temperatures: 308.15 K, (●) 313.15 K, (■) 318.15 K, (▲) 323.15 K, (★) the curves were fittings from eqn (4).

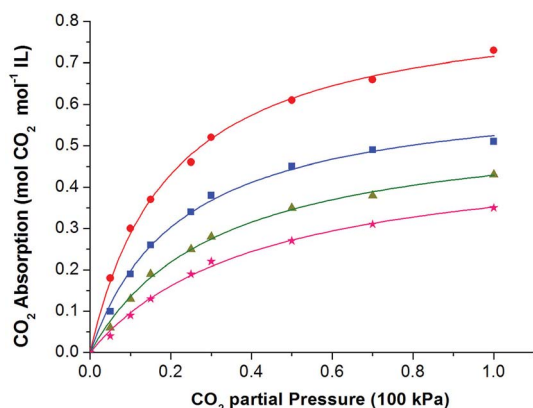


Fig. 3 The absorption isotherms of the  $\text{CO}_2$ -[P<sub>66614</sub>][Ph-Suc] system at different temperatures: 308.15 K, (●) 313.15 K, (■) 318.15 K, (▲) 323.15 K, (★) the curves were fittings from eqn (4).

### 3.2. Chemical absorption mechanism of $\text{CO}_2$ in the ionic liquids

The interaction between  $\text{CO}_2$  and [P<sub>66614</sub>][H-Suc] was studied by  $^1\text{H}$  NMR,  $^{13}\text{C}$  NMR, and FT-IR spectra, and the results were illustrated in Fig. 4. Comparing the  $^1\text{H}$  NMR spectrum of  $\text{CO}_2$ -IL with that of neat IL, it was found that the peak of  $2 \times \text{CH}_2$  in [H-Suc]<sup>−</sup> at  $\delta = 2.05$  ppm was shifted downfield to  $\delta = 2.24$  ppm after saturation of  $\text{CO}_2$  (Fig. 4a), indicating the strong interaction between  $\text{CO}_2$  and the anion of [P<sub>66614</sub>][H-Suc]. In the  $^{13}\text{C}$  NMR spectrum of  $\text{CO}_2$ -IL, a new peak appeared at 158.1 ppm after  $\text{CO}_2$  uptake, this could be attributed to the formation of carbamate carbonyl carbon in N- $\text{CO}_2$  interaction (Fig. 4b).<sup>15,33</sup> On the other hand, when 0.2 to 0.8 mol  $\text{CO}_2$  was absorbed by [P<sub>66614</sub>][H-Suc], a new characteristic peak at 1628  $\text{cm}^{-1}$  could be observed in the FT-IR spectrum of [P<sub>66614</sub>][H-Suc] (Fig. 4c), which belongs to the asymmetrical stretching vibration of N- $\text{CO}_2$  due to the chemical interaction between  $\text{CO}_2$  and the electronegative N atom in [H-Suc]<sup>−</sup> of the [P<sub>66614</sub>][H-Suc].<sup>34</sup>

The NMR and FT-IR spectra of [P<sub>66614</sub>][Ph-Suc] before and after the absorption of  $\text{CO}_2$  were showed in Fig. S1.† It can be seen that chemical shift of the protons in [Ph-Suc]<sup>−</sup> from  $\delta =$

7.30–7.46 to 7.43–7.47 ppm was observed after  $\text{CO}_2$  absorption, while typical carbon peak of C=O in [Ph-Suc]<sup>−</sup> moved from 185.0 ppm to 178.3 ppm, indicating the existence of chemical interaction between [Ph-Suc]<sup>−</sup> and  $\text{CO}_2$ . Moreover, the new characteristic peak at  $\delta = 157.9$  ppm after the absorption was attributed to the  $\text{CO}_2$  through the interaction of the  $\text{N} \cdots \text{CO}_2$ . No peak at about 1620  $\text{cm}^{-1}$  could be seen from FT-IR spectrum after  $\text{CO}_2$  capture, which is possibly covered by other peaks. However, the peaks at 1619 and 1588  $\text{cm}^{-1}$ , which were assigned to the five-membered cyclic imide anion of [P<sub>66614</sub>][Ph-Suc], was blue shifted to 1769 and 1720  $\text{cm}^{-1}$ , respectively, suggesting the interaction between  $\text{CO}_2$  and N atom in the anion.<sup>34</sup>

Based on the above solubility data and the spectroscopic investigation of the ILs before and after  $\text{CO}_2$  capture, the possible mechanisms of  $\text{CO}_2$  capture by [P<sub>66614</sub>][H-Suc] and [P<sub>66614</sub>][Ph-Suc] were proposed and shown in Schemes 1 and

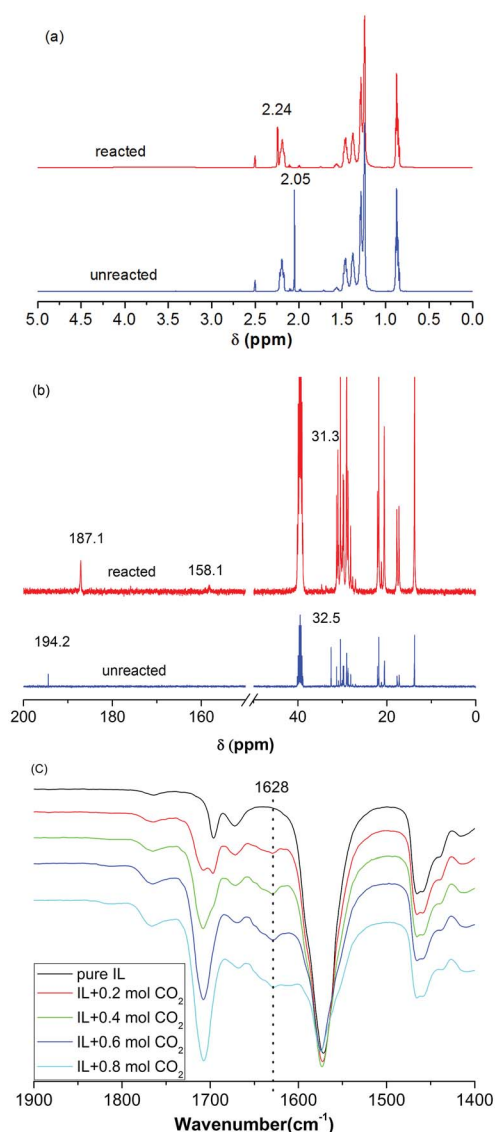
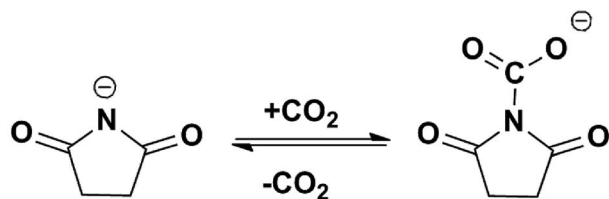


Fig. 4  $^1\text{H}$  NMR (a),  $^{13}\text{C}$  NMR (b) and FT-IR (c) spectra of [P<sub>66614</sub>][H-Suc] before and after the absorption of  $\text{CO}_2$ .





Scheme 1 Possible mechanism of CO<sub>2</sub> absorption by [P<sub>66614</sub>][H-Suc].

S1,<sup>†</sup> respectively, where the negatively charged N atom in the anions interacted with CO<sub>2</sub> and formed the complexes.

### 3.3. The recycling of ILs for CO<sub>2</sub> absorption

Considering the fact that recycling performance of CO<sub>2</sub> capture directly influences the application of ILs, we investigated CO<sub>2</sub> absorption–desorption cycles by using [P<sub>66614</sub>][H-Suc] as an example (Fig. 5). It can be seen that the high CO<sub>2</sub> absorption capacity and rapid absorption rate were remained during the 6 cycles, indicating that these amido-containing anion-functionalized ILs are highly recyclable.

### 3.4. Thermodynamic properties of CO<sub>2</sub> absorbed in the ionic liquids

Thermodynamic properties such as the absorption Gibbs energy, enthalpy and entropy change are of great importance for the evaluation of new absorbents in practical application<sup>35</sup> as well as for the understanding of thermodynamic driving force for the absorption.<sup>27</sup> For example, absorption enthalpy can reflect the binding strength between the gas and the active site on the absorbent, absorption entropy can be used to probe the change in microstructure of the absorption systems. Thus, the thermodynamic properties of CO<sub>2</sub> absorbed in these amido-containing anion-functionalized ILs were derived and analyzed. Usually, the absorption of CO<sub>2</sub> in ILs consists of two parts, the physical absorption and the chemical absorption.

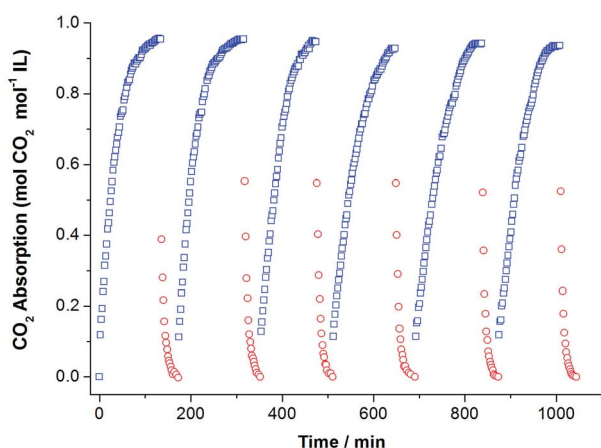
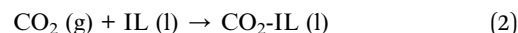


Fig. 5 Six consecutive CO<sub>2</sub> absorption–desorption cycles of [P<sub>66614</sub>][H-Suc]. The absorption of CO<sub>2</sub> was performed at 308.15 K and 1.0 bar under CO<sub>2</sub> (60 ml min<sup>-1</sup>). CO<sub>2</sub> desorption was carried out at 333.15 K and 1.0 bar under N<sub>2</sub> (60 ml min<sup>-1</sup>). Absorption, (□) desorption, (○).

Thus, the equations for physical CO<sub>2</sub> capture and chemical CO<sub>2</sub> capture can be expressed as follows:



where CO<sub>2</sub> (g) and CO<sub>2</sub> (l) in eqn (1) represent the CO<sub>2</sub> in gaseous and liquid states, respectively, while IL (l) and IL-CO<sub>2</sub> (l) in eqn (2) stand for the IL before and after CO<sub>2</sub> capture. Since our functionalized ILs are basic and they can interact chemically with acid CO<sub>2</sub> to form complex, IL-CO<sub>2</sub> (l) in eqn (2) may represent such a complex.

Inspired by the previous reports,<sup>25,26,28</sup> the CO<sub>2</sub> absorption isotherm data in Fig. 2 and 3 were fitted with the “deactivated IL” model developed by Brennecke and co-workers.<sup>25</sup> This model assumes that only 1 : 1 reaction takes place and less than 100% of the ionic liquids is allowed to react with CO<sub>2</sub>. The “deactivated IL” model can be expressed as follows:

$$Z = \frac{P_{\text{CO}_2}/H_m}{1 - P_{\text{CO}_2}/H_m} + \frac{K^0 \times P_{\text{CO}_2} \times C_3}{1 + K^0 \times P_{\text{CO}_2}} \quad (3)$$

where  $Z$  is the solubility expressed by molar ratio of CO<sub>2</sub> to ionic liquid.  $K^0$ ,  $P_{\text{CO}_2}$ , and  $H_m$  represent the equilibrium constant (dimensionless parameter), the CO<sub>2</sub> partial pressure in kPa, and the Henry's constant in kPa, respectively.  $C_3$  stands for the molar ratio of active ionic liquids to the total ionic liquids. The first term denotes the contribution from physical absorption, while the second term is the contribution from chemical absorption.

It is known that when the pressure of CO<sub>2</sub> is not higher than 100 kPa, the effect of CO<sub>2</sub> physical absorption by IL on the absorption isotherms can be ignored.<sup>25,26</sup> Considering the fact that our absorption isotherms of CO<sub>2</sub> in the amido-containing anion-functionalized ILs were determined under the pressure up to 100 kPa and the CO<sub>2</sub> absorption was mainly chemical, it is reasonable to ignore the CO<sub>2</sub> physical absorption term in the fitting of absorption isotherms. Therefore, the CO<sub>2</sub> absorption system by using these ILs as absorbents can be treated as an ideal chemical reaction system in the studied experimental temperature range, and the following equation of correlation between the solubility of CO<sub>2</sub> in these ILs and partial pressure of CO<sub>2</sub> could be obtained after simple derivation:

$$Z = \frac{K^0 \times P_{\text{CO}_2} \times C_3}{1 + K^0 \times P_{\text{CO}_2}} \quad (4)$$

First, the values of the experimental solubility of CO<sub>2</sub> in [P<sub>66614</sub>][H-Suc] and [P<sub>66614</sub>][Ph-Suc] were fitted to eqn (4) to obtain the values of chemical equilibrium constants at different temperatures, which were shown in the Table 1. It can be seen from Fig. 2 and 3 that the experimental solubility values of CO<sub>2</sub> in the studied ILs could be well correlated with the CO<sub>2</sub> partial pressure using eqn (4).

Since the temperature range studied in this work is quite narrow, the reaction enthalpy and reaction entropy for the CO<sub>2</sub>





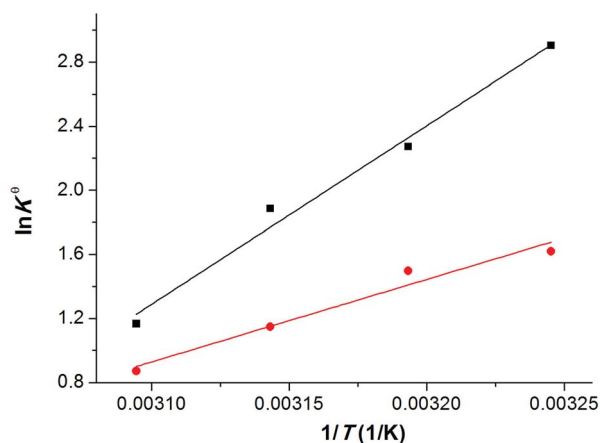
**Table 1** Equilibrium constants for CO<sub>2</sub> absorption in [P<sub>66614</sub>][H-Suc] and [P<sub>66614</sub>][Ph-Suc] at different temperatures

IL	Property	T (K)			
		308.15	313.15	318.15	323.15
[P <sub>66614</sub> ][H-Suc]	$K^0$	18.3 ± 1.4	9.7 ± 0.7	6.6 ± 0.8	3.2 ± 0.3
	$C_3$	1.00 ± 0.02	0.87 ± 0.02	0.78 ± 0.03	0.62 ± 0.03
	$r^2$	0.992	0.994	0.984	0.990
[P <sub>66614</sub> ][Ph-Suc]	$K^0$	5.1 ± 0.3	4.5 ± 0.3	3.2 ± 0.2	2.4 ± 0.2
	$C_3$	0.86 ± 0.02	0.64 ± 0.02	0.57 ± 0.02	0.50 ± 0.02
	$r^2$	0.998	0.996	0.997	0.996

absorption by the ILs could be determined by using the van't Hoff equation:

$$\ln K^0 = -\frac{\Delta H^0}{RT} + \frac{\Delta S^0}{R} \quad (5)$$

where  $\Delta H^0$  and  $\Delta S^0$  represent the enthalpy and entropy change for the chemical capture of CO<sub>2</sub> in kJ mol<sup>-1</sup> and kJ mol<sup>-1</sup> K<sup>-1</sup>, respectively.  $T$  is the thermodynamic temperature in K,  $R$  denotes the universal gas constant ( $R = 8.314 \text{ J mol}^{-1} \text{ K}^{-1}$ ). The relationship between the logarithms of the equilibrium constant ( $K^0$ ) and the reciprocal of temperature ( $1/T$ ) was shown in Fig. 6. It can be seen that the linear relationship is reasonable



**Fig. 6** Linear correlation between  $\ln K^0$  and  $1/T$ . [P<sub>66614</sub>][H-Suc], (■) [P<sub>66614</sub>][Ph-Suc], (●).

for the CO<sub>2</sub>-[P<sub>66614</sub>][H-Suc] and CO<sub>2</sub>-[P<sub>66614</sub>][Ph-Suc] systems. From the slope and intercept of the straight lines, the  $\Delta H^0$  and  $\Delta S^0$  values could be obtained, and the results were given in Table 2.

Then, the reaction Gibbs energy ( $\Delta G^0$ ) in kJ mol<sup>-1</sup> could be calculated by the following equations:

$$\Delta G^0 = -RT \ln K^0 \quad (6)$$

The resultant values of  $\Delta G^0$  were also collected in Table 2. It is clearly noted that  $\Delta H^0$  values for CO<sub>2</sub>-[P<sub>66614</sub>][H-Suc] and CO<sub>2</sub>-[P<sub>66614</sub>][Ph-Suc] systems are -92.7 kJ mol<sup>-1</sup> and -42.9 kJ mol<sup>-1</sup>, respectively. The negative values indicate that the capture of CO<sub>2</sub> is an exothermic process in [P<sub>66614</sub>][H-Suc] and [P<sub>66614</sub>][Ph-Suc] absorbents. Compared with the CO<sub>2</sub>-[P<sub>66614</sub>][Ph-Suc] system,  $\Delta H^0$  value of the CO<sub>2</sub>-[P<sub>66614</sub>][H-Suc] system is much lower, suggesting that the interaction between [P<sub>66614</sub>][H-Suc] and CO<sub>2</sub> is much stronger than that between [P<sub>66614</sub>][Ph-Suc] and CO<sub>2</sub>. It also implies that CO<sub>2</sub> is more likely difficult to desorb from CO<sub>2</sub>-[P<sub>66614</sub>][H-Suc] than CO<sub>2</sub>-[P<sub>66614</sub>][Ph-Suc], and more energy consumption is needed in the regeneration of [P<sub>66614</sub>][H-Suc]. We also calculated the gas-phase reaction enthalpies of [H-Suc]-CO<sub>2</sub> and [Ph-Suc]-CO<sub>2</sub> complexes using Gaussian 09 program<sup>36</sup> by DFT-D3(BJ) at the B3LYP/6-31++G(p,d) level. Although the calculated enthalpies were found to be only -38.4 and -24.3 kJ mol<sup>-1</sup> for [H-Suc]-CO<sub>2</sub> and [Ph-Suc]-CO<sub>2</sub> complexes, respectively, the order was in agreement with the experimental result.

Furthermore, it can be seen from Table 2 that  $\Delta S^0$  has a negative value in the temperature range investigated, which indicates that the degree of disorder of the system becomes

**Table 2** Molar reaction enthalpy, molar reaction Gibbs energy, and molar reaction entropy for the CO<sub>2</sub> absorption by the amido-containing anion-functionalized ILs

IL	Property	T (K)			
		308.15	313.15	318.15	323.15
[P <sub>66614</sub> ][H-Suc]	$\Delta G^0$ (kJ mol <sup>-1</sup> )	-7.44	-5.92	-4.99	-3.13
	$\Delta H^0$ (kJ mol <sup>-1</sup> )	-92.7			
	$10^3 \Delta S^0$ (kJ mol <sup>-1</sup> K <sup>-1</sup> )	-276.8			
[P <sub>66614</sub> ][Ph-Suc]	$\Delta G^0$ (kJ mol <sup>-1</sup> )	-4.15	-3.90	-3.03	-2.34
	$\Delta H^0$ (kJ mol <sup>-1</sup> )	-42.9			
	$10^3 \Delta S^0$ (kJ mol <sup>-1</sup> K <sup>-1</sup> )	-125.2			



smaller due to the strong interaction of the IL with CO<sub>2</sub> molecules and the formation of CO<sub>2</sub>-anion complexes mentioned above. The values of  $\Delta G^0$  are negative under the experimental conditions (Table 2), this is a strong indication that CO<sub>2</sub> molecules are favourable to dissolve in the amido-containing anion-functionalized ILs. Moreover, considering the fact that  $\Delta G^0$ ,  $\Delta H^0$  and  $\Delta S^0$  are all negative, and absolute value of  $\Delta H^0$  is greater than  $T\Delta S^0$ , the sign of  $\Delta G^0$  is determined by that of  $\Delta H^0$ . Therefore, the enthalpy term is predominant for the favourable absorption of CO<sub>2</sub>.

## 4. Conclusion

Two kinds of amido-containing anion-functionalized ILs were synthesized, and evaluated for CO<sub>2</sub> capture by CO<sub>2</sub> solubility measurements at different temperatures and different CO<sub>2</sub> partial pressures. It was found that high CO<sub>2</sub> absorption capacity (up to 0.95 mol CO<sub>2</sub> mol<sup>-1</sup> IL) and low energy consumption regeneration of the ILs could be achieved by these anion-functionalized ILs. The interaction of negatively charged N atom in the anions with CO<sub>2</sub> and the formation of CO<sub>2</sub>-anion complexes were responsible for the high absorption capacity. Thermodynamically, reaction enthalpy was the main driving force for CO<sub>2</sub> capture. These results are useful for the design of new ionic liquid absorbents for capture of CO<sub>2</sub> from flue gas.

## Conflicts of interest

There are no conflicts to declare.

## Acknowledgements

This work was supported by the National Natural Science Foundation of China (No. U1704251, 21733011), the National Key Research and Development Program of China (No. 2017YFA0403101), the Science Foundation for Excellent Young Scholars of Henan Normal University (No. 15YQ002), and the 111 project (No. D17007). The DFT calculations were supported by the High Performance Computing Center of Henan Normal University.

## References

- 1 J. E. Bara, D. E. Camper, D. L. Gin and R. D. Noble, *Acc. Chem. Res.*, 2010, **43**, 152–159.
- 2 G. Cui, J. Wang and S. Zhang, *Chem. Soc. Rev.*, 2016, **45**, 4307–4339.
- 3 J. F. Brennecke and B. E. Gurkan, *J. Phys. Chem. Lett.*, 2010, **1**, 3459–3464.
- 4 P. Mores, N. Scenna and S. Mussati, *Energy*, 2012, **45**, 1042–1058.
- 5 V. I. Pârvulescu and C. Hardacre, *Chem. Rev.*, 2007, **107**, 2615–2665.
- 6 X. Li, M. Hou, Z. Zhang, B. Han, G. Yang, X. Wang and L. Zou, *Green Chem.*, 2008, **10**, 879–884.
- 7 X. Luo, Y. Guo, F. Ding, H. Zhao, G. Cui, H. Li and C. Wang, *Angew. Chem., Int. Ed.*, 2014, **126**, 7173–7177.
- 8 F. Ding, X. He, X. Luo, W. Lin, K. Chen, H. Li and C. Wang, *Chem. Commun.*, 2014, **50**, 15041–15044.
- 9 M. Tao, J. Gao, W. Zhang, Y. Li, Y. He and Y. Shi, *Ind. Eng. Chem. Res.*, 2018, **57**, 9305–9312.
- 10 E. D. Bates, R. D. Mayton, I. Ntai and J. H. Davis, *J. Am. Chem. Soc.*, 2002, **124**, 926–927.
- 11 B. E. Gurkan, J. C. de la Fuente, E. M. Mindrup, L. E. Ficke, B. F. Goodrich, E. A. Price, W. F. Schneider and J. F. Brennecke, *J. Am. Chem. Soc.*, 2010, **132**, 2116–2117.
- 12 S. Saravanamurugan, A. J. Kunov-Kruse, R. Fehrmann and A. Riisager, *ChemSusChem*, 2014, **7**, 897–902.
- 13 S. Bhattacharyya and F. U. Shah, *ACS Sustainable Chem. Eng.*, 2016, **4**, 5441–5449.
- 14 M. Pan, R. Vijayaraghavan, F. Zhou, M. Kar, H. Li, C. Wang and D. R. MacFarlane, *Chem. Commun.*, 2017, **53**, 5950–5953.
- 15 C. Wang, X. Luo, H. Luo, D.-e. Jiang, H. Li and S. Dai, *Angew. Chem., Int. Ed.*, 2011, **123**, 5020–5024.
- 16 C. Wang, H. Luo, D.-e. Jiang, H. Li and S. Dai, *Angew. Chem., Int. Ed.*, 2010, **122**, 6114–6117.
- 17 X. Zhu, M. Song and Y. Xu, *ACS Sustainable Chem. Eng.*, 2017, **5**, 8192–8198.
- 18 B. Gurkan, B. F. Goodrich, E. M. Mindrup, L. E. Ficke, M. Massel, S. Seo, T. P. Senftle, H. Wu, M. F. Glaser, J. K. Shah, E. J. Maginn, J. F. Brennecke and W. F. Schneider, *J. Phys. Chem. Lett.*, 2010, **1**, 3494–3499.
- 19 S. Seo, M. Quiroz-Guzman, M. A. DeSilva, T. B. Lee, Y. Huang, B. F. Goodrich, W. F. Schneider and J. F. Brennecke, *J. Phys. Chem. B*, 2014, **118**, 5740–5751.
- 20 H. Tang and C. Wu, *ChemSusChem*, 2013, **6**, 1050–1056.
- 21 C. Wang, H. Luo, H. Li, X. Zhu, B. Yu and S. Dai, *Chem.-Eur. J.*, 2012, **18**, 2153–2160.
- 22 M. Vafaezadeh, J. Aboudi and M. M. Hashemi, *RSC Adv.*, 2015, **5**, 58005–58009.
- 23 M. Pan, N. Cao, W. Lin, X. Luo, K. Chen, S. Che, H. Li and C. Wang, *ChemSusChem*, 2016, **9**, 2351–2357.
- 24 F.-F. Chen, K. Huang, Y. Zhou, Z.-Q. Tian, X. Zhu, D.-J. Tao, D.-e. Jiang and S. Dai, *Angew. Chem., Int. Ed.*, 2016, **55**, 7166–7170.
- 25 B. F. Goodrich, J. C. de la Fuente, B. E. Gurkan, D. J. Zadigian, E. A. Price, Y. Huang and J. F. Brennecke, *Ind. Eng. Chem. Res.*, 2011, **50**, 111–118.
- 26 B. F. Goodrich, J. C. de la Fuente, B. E. Gurkan, Z. K. Lopez, E. A. Price, Y. Huang and J. F. Brennecke, *J. Phys. Chem. B*, 2011, **115**, 9140–9150.
- 27 X. Y. Luo, F. Ding, W. J. Lin, Y. Q. Qi, H. R. Li and C. M. Wang, *J. Phys. Chem. Lett.*, 2014, **5**, 381–386.
- 28 X.-M. Zhang, K. Huang, S. Xia, Y.-L. Chen, Y.-T. Wu and X.-B. Hu, *Chem. Eng. J.*, 2015, **274**, 30–38.
- 29 K. Fukumoto, M. Yoshizawa and H. Ohno, *J. Am. Chem. Soc.*, 2005, **127**, 2398–2399.
- 30 Y. Zhang, S. Zhang, X. Lu, Q. Zhou, W. Fan and X. Zhang, *Chem.-Eur. J.*, 2009, **15**, 3003–3011.
- 31 G. Cui, C. Wang, J. Zheng, Y. Guo, X. Luo and H. Li, *Chem. Commun.*, 2012, **48**, 2633–2635.



- 32 G. Cui, Y. Huang, R. Zhang, F. Zhang and J. Wang, *RSC Adv.*, 2015, 5, 60975–60982.
- 33 D. Xiong, G. Cui, J. Wang, H. Wang, Z. Li, K. Yao and S. Zhang, *Angew. Chem., Int. Ed.*, 2015, 54, 7265–7269.
- 34 S. Zhang, Y.-N. Li, Y.-W. Zhang, L.-N. He, B. Yu, Q.-W. Song and X.-D. Lang, *ChemSusChem*, 2014, 7, 1484–1489.
- 35 Y. Bian, S. Shen, Y. Zhao and Y.-n. Yang, *J. Chem. Eng. Data*, 2016, 61, 2391–2398.
- 36 M. J. Frisch, G. W. Trucks, H. B. Schlegel, G. E. Scuseria, M. A. Robb, J. R. Cheeseman, G. Scalmani, V. Barone, B. Mennucci, G. A. Petersson, H. Nakatsuji, M. Caricato, X. Li, H. P. Hratchian, A. F. Izmaylov, J. Bloino, G. Zheng, J. L. Sonnenberg, M. Hada, M. Ehara, K. Toyota, R. Fukuda, J. Hasegawa, M. Ishida, T. Nakajima, Y. Honda, O. Kitao, H. Nakai, T. Vreven, J. A. J. Montgomery, J. E. Peralta, F. Ogliaro, M. Bearpark, J. J. Heyd, E. Brothers, K. N. Kudin, V. N. Staroverov, T. Keith, R. Kobayashi, J. Normand, K. Raghavachari, A. Rendell, J. C. Burant, S. S. Iyengar, J. Tomasi, M. Cossi, N. Rega, J. M. Millam, M. Klene, J. E. Knox, J. B. Cross, V. Bakken, C. Adamo, J. Jaramillo, R. Gomperts, R. E. Stratmann, O. Yazyev, A. J. Austin, R. Cammi, C. Pomelli, J. W. Ochterski, R. L. Martin, K. Morokuma, V. G. Zakrzewski, G. A. Voth, P. Salvador, J. J. Dannenberg, S. Dapprich, A. D. Daniels, O. Farkas, J. B. Foresman, J. V. Ortiz, J. Cioslowski and D. J. Fox, *Gaussian 09 (Revision D.01)*, Gaussian, Inc., Wallingford CT, 2013.

