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Investigating the non-idealities in adsorption of CO$_2$-bearing mixtures in cation-exchanged zeolites

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A R T I C L E  I N F O

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- Inhomogeneous distribution
- Congregation effects
- Real adsorbed solution theory

A B S T R A C T

Cation-exchanged zeolites have significant potential for capture of CO$_2$ from a wide variety of mixtures containing N$_2$, H$_2$, alkanes and alkenes. The strong coulombic interactions of CO$_2$ with extra-framework cations result in strong binding and selective capture. Published experimental data on mixture adsorption indicate that the Ideal Adsorbed Solution Theory (IAST) fails to provide accurate estimates of mixture adsorption equilibrium. The reasons for the quantitative failure of IAST estimates are investigated with the aid of Configurational-Bias Monte Carlo (CBMC) simulations of mixture adsorption. Computational snapshots indicate that the failure of the IAST is traceable to inhomogeneous distribution of adsorbates within the zeolite framework.

1. Introduction

Cation-exchanged zeolites are potent adsorbents for selective capture of CO$_2$ in natural gas purification, flue gas cleaning, and hydrogen purification processes [1–16]. Coulombic interactions of CO$_2$ with the extra-framework cations result in strong binding; the binding strength and selectivity can be tuned by appropriate choice of the extra-framework cations, and adjustment of the Si/Al ratios [3,13,17]. For the design and development of CO$_2$-capture technologies, that are normally conducted in fixed-bed adsorbers [18–20], the Ideal Adsorbed Solution Theory (IAST) of Myers and Prausnitz [21] is widely used for calculation of mixture adsorption equilibrium [2,8,15,17,22–26].

Briefly, in the IAST, the partial fugacities in the bulk fluid mixture are related to the mole fraction in the adsorbed phase $x_i = \frac{q_i}{q_i + q_j}$ by the analogue of Raoult’s law for vapor-liquid equilibrium, i.e. $f_i = P_i x_i$; $i = 1, 2$ where $P_i$ is the pressure for sorption of every component $i$, which yields the same spreading pressure, $\pi$ for each of the pure components, as that for the mixture:

$$\frac{\pi A}{RT} = \int_0^{P_f} \frac{q_i^A(f)}{f} df = \int_0^{P_f} \frac{q_i^B(f)}{f} df$$

(1)

The units of $\frac{\pi A}{RT}$, also called the adsorption potential [23,27–29], are mol kg$^{-1}$. If the pure component adsorption $q_i^A(f)$ isotherm is described by, say, the dual-site Langmuir-Freundlich isotherm $q_i^A(f) = q_{i,\text{max}} \frac{h_{i,A} f^m_{i}}{1 + h_{i,A} f^m_{i}} + q_{i,u} \frac{h_{i,u} f^m_{i}}{1 + h_{i,u} f^m_{i}}$, each of the integrals in Eq. (1) can be evaluated analytically. For specified partial fugacities in the bulk fluid phase, $f_i$, these constraints may be solved simultaneously, to yield the set of values of the adsorbed phase mole fractions, $x_i$, and $P_f$, all of which must satisfy Eq. (1). The corresponding values of the integrals using these values of $P_f$ as upper limits of integration must yield the same value of $\frac{\pi A}{RT}$ for each component.

A number of experimental data on mixture adsorption equilibrium reveal the IAST does not provide accurate estimates of component loadings, and adsorption selectivities, especially for operations at high guest occupancies [27,29]. As illustration, Fig. 1a,b,c present comparisons of experimental data on adsorption selectivity with IAST estimates for CO$_2$/CH$_4$ and CO$_2$/N$_2$ mixtures in NaX (trade name = 13X) and LTA-5A zeolites. The IAST selectivity estimates are about an order of magnitude higher than those determined experimentally. The experimental data for selectivity of adsorption of CO$_2$/C$_3$H$_8$ mixtures in 13X, ZSM-5 (Si/Al = 15), and H-MOR zeolites show that the selectivity decreases with increased mole fraction of CO$_2$ in the bulk gas mixture, $y_i = \frac{h_i}{h_i^{m} f_i^{m}}$. On the other hand, the IAST predicts the selectivity to increase, albeit slightly, with the mole fraction of CO$_2$ in the bulk gas.
2. CBMC simulations of mixture adsorption in cation-exchanged FAU zeolites

We first investigate CO$_2$(1)/C$_3$H$_8$(2) mixture adsorption in NaX zeolite, that has the Faujasite (FAU) topology consisting of cages of 786 Å$^3$ volume, separated by 7.3 Å 12-ring windows. Each unit cell of NaX zeolite has 106 Si, 86 Al, 86 Na$^+$ with Si/Al = 1.23. Two different CBMC simulation campaigns were conducted:

(i) The mole fraction of CO$_2$(1) in the bulk gas phase is held constant, $y_1 = 0.5$, and the bulk gas phase fugacity $f_1 = f_1 + f_2$ was varied, and

(ii) The mole fraction of CO$_2$(1) in the bulk gas phase, $y_1$ was varied from 0 to 1, keeping the bulk gas phase mixture fugacity $f_1 = f_1 + f_2$ constant at a value of 1 MPa.

The results of these two separate campaigns are presented in Fig. 2. In the Henry regime of adsorption, prevailing at $f_1 < 10$ kPa, the component loadings of CO$_2$ and C$_3$H$_8$ are nearly equal to each other (cf. Fig. 2a), and the CO$_2$(1)/C$_3$H$_8$(2) adsorption selectivity, $S_{ads}$ is close to unity (cf. Fig. 2b). With increasing values of the bulk gas phase fugacity $f_1$ above about 100 kPa, the adsorption becomes increasingly in favor of CO$_2$, due to strong Coulombic interactions with the extra-framework Na$^+$ cations. The IAST estimates for the adsorption selectivity are plotted as dashed lines in Fig. 2b. At $f_1 = 1$ MPa, the value of $S_{ads} ≈ 4$; the IAST estimate is a factor two higher than those determined from CBMC simulations.

The CBMC simulations for $f_1 = 1$ MPa, and varying mole fractions of CO$_2$(1) in the bulk gas phase, $y_1$, are shown in Fig. 2c. The CBMC simulations show that the adsorption selectivity decreases with increasing proportion of CO$_2$(1) in the bulk gas phase; see Fig. 2d. On the other hand, the IAST anticipates $S_{ads}$ to increase with increasing $y_1$. This trend is the same as that witnessed for the experimental data for CO$_2$(1)/C$_3$H$_8$(2) mixture adsorption in NaX zeolite; see Fig. 1d.

The failure of the IAST to provide quantitatively accurate estimates of component loadings, and adsorption selectivities is attributable to the inhomogeneous distribution of adsorbates in the pore space of NaX zeolite, caused by strong binding of CO$_2$ with the extra-framework cations. The inhomogeneous distribution is clearly visualized in the computational snapshot in Fig. 3 for $f_1 = 0.45$ MPa, and $f_2 = 0.55$ MPa. We note that the top left cage contains only CO$_2$, and there is no C$_3$H$_8$ present in that cage. One of the key assumptions of the IAST is that the distribution of adsorbates within the pore space is homogeneous; this assumption is violated causing the quantitative failure of the IAST.

Since the root cause of the failure of the IAST is the inhomogeneous distribution of adsorbates engendered by strong binding of CO$_2$ with the extra-framework cations, we should expect the non-ideality effects to be negligibly small in all-silica zeolites, with no extra-framework cations. In order to verify this, we performed CBMC simulations CO$_2$(1)/C$_3$H$_8$(2) mixture adsorption in all-silica FAU zeolite, with Si/Al → ∞, at 300 K and total fugacity $f_1 = 1$ MPa, with varying CO$_2$ in the mixture; see Fig. 1 d,e,f. There are several other examples of failures of the IAST estimations for mixture adsorption in a variety of cation-exchanged zeolites [4,30,31].

The primary objective of this communication is to gain some insights into the reasons for the failure of the IAST to match the experimental data, as witnessed in Fig. 1. Towards this end, Configurational-Bias Monte Carlo (CBMC) simulations on unary isotherms and mixture adsorption equilibrium were performed using the simulation methodology that is firmly established in the literature [6,7,32–34]. The force field information are taken from García-Sánchez et al. [35], and Dubbeldam et al. [36].

The Supplementary Material accompanying this publication provides (a) details of experimental data and CBMC simulation data for mixture adsorption, (b) unary isotherm fits for all the guest/host combinations examined in this article, (c) details of the IAST, and Real Adsorbed Solution Theory (RAST) methodologies and calculations for mixture adsorption equilibrium, and (d) Wilson parameter fits for thermodynamic non-idealities.

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### Nomenclature

- $A$: surface area per kg of framework, m$^2$ kg$^{-1}$
- $b_i$: Langmuir-Freundlich parameter, Pa$^{-ν}$
- $C$: constant used in Eq. (3), kg mol$^{-1}$
- $f_i$: partial fugacity of species $i$, Pa
- $P_i$: total pressure of species $i$, Pa
- $P_i^t$: sorption pressure, Pa
- $q_i$: molar loading of species $i$, mol kg$^{-1}$
- $q_i^{sat}$: molar loading of species $i$ at saturation, mol kg$^{-1}$
- $Q_i$: total molar loading of mixture, mol kg$^{-1}$
- $Q_i^{sat}$: volumetric uptake of species $i$, Q$_i$ = $ρq_i$, mol m$^{-3}$
- $ΔQ$: separation potential, mol m$^{-3}$
- $R$: gas constant, 8.314 J mol$^{-1}$ K$^{-1}$
- $S_{ads}$: adsorption selectivity, dimensionless
- $T$: absolute temperature, K
- $x_i$: mole fraction of species $i$ in the adsorbed phase, dimensionless
- $y_i$: mole fraction of species $i$ in bulk fluid mixture, dimensionless
- $π$: spreading pressure, N m$^{-1}$
- $ρ$: framework density, kg m$^{-3}$

### Greek letters

- $ν$: Freundlich exponent, dimensionless
- $\Lambda_{ij}$: Wilson parameters, dimensionless
- $γ$: dimensionless
- $γ_i$: Langmuir-Freundlich parameter, Pa$^{-ν}$
- $y_i$: activity coefficient of component $i$ in adsorbed phase, dimensionless
- $y_i^{ads}$: activity coefficient of component $i$ in bulk fluid mixture, dimensionless
- $P_f$: total system pressure, Pa

### Superscripts

- $1$: referring to species 1
- $2$: referring to species 2
- $i$: components in mixture
- $j$: components in mixture
- $t$: referring to total mixture
- $0$: referring to pure component loading
- $sat$: referring to saturation conditions

### Subscripts

- $f$: fugacity
- $i$: referring to component $i$
- $s$: superscript referring to saturation conditions
- $t$: superscript referring to total mixture

### Data

- The Supplementary Material accompanying this publication provides (a) details of experimental data and CBMC simulation data for mixture adsorption, (b) unary isotherm fits for all the guest/host combinations examined in this article, (c) details of the IAST, and Real Adsorbed Solution Theory (RAST) methodologies and calculations for mixture adsorption equilibrium, and (d) Wilson parameter fits for thermodynamic non-idealities.
bulk gas phase; the results are presented in Fig. 4a. As anticipated, the IAST estimates of component loadings, and adsorption selectivities are in good agreement with CBMC data. Similar good agreement is also obtained for CO$_2$(1)/C$_2$H$_6$(2) mixture adsorption in all-silica FAU zeolite; see Fig. 4b.

From the data in Figs. 2 and 4, we must conclude that the accuracy of IAST estimates should also depend on the Si/Al ratio of cation-exchanged zeolites. To test this hypothesis Fig. 5 presents a comparison of CO$_2$/CH$_4$ adsorption selectivities determined from CBMC simulations at 300 K for all-silica FAU (Si/Al = \infty) with 192 Si, 0 Al, 0 Na$^+$ per unit
cell), NaY (Si/Al = 2.56 with 138 Si, 54 Al, 54 Na\(^+\) per unit cell), and NaX (Si/Al = 1.23 with 106 Si, 86 Al, 86 Na\(^+\) per unit cell) zeolites with IAST estimations. For all-silica FAU, the IAST estimates are in perfect agreement with CBMC simulations. The agreement of IAST estimates with CBMC simulated data becomes progressively worse with decreasing Si/Al ratios. This trend confirms our contention that the failure of IAST is due to the strong interactions of CO\(_2\) with extra-framework cations.

3. CBMC simulations of mixture adsorption in cation-exchanged LTA zeolite

We now investigate the accuracy of IAST estimates of CO\(_2\)(1)/C\(_3\)H\(_8\)(2) mixture adsorption in NaX zeolite at 300 K. The CBMC simulations show that the adsorption selectivity decreases with increasing proportion of CO\(_2\)(1) in the bulk gas phase; see Fig. 6b. On the other hand, the IAST anticipates \(S_{ads}\) to be practically independent of \(y_1\); this trend is similar to that witnessed in Fig. 1 e,f for the experimental data for CO\(_2\)(1)/C\(_3\)H\(_8\)(2) mixture adsorption in ZSM-5 (Si/Al = 15), and H-MOR.

Fig. 7 shows computational snapshots of the location of CO\(_2\)(1), and C\(_3\)H\(_8\)(2) molecules within the pore topology of LTA-4A zeolite. We note that the CO\(_2\) is almost exclusively located at the windows, or near the window entrance regions. Consequently, the competition between the adsorption of CO\(_2\) and C\(_3\)H\(_8\) is less severe than assumed in the homogenous distribution that is inherent in the IAST prescription. The preferential perching of CO\(_2\) at the window sites also manifests for other cage-window structures such as DDR, ERI, and CHA [23,37,38].
Modelling non-ideal mixture adsorption using the RAST

For quantifying the departures of the IAST from CBMC data, we use the Real Adsorbed Solution Theory (RAST)\([21,23,27–29,39]\), in which the partial fugacity of any component in the bulk fluid phase is related to the mole fraction \(x_i\) in the adsorbed phase by introduction of activity coefficients describing non-idealities in the adsorbed phase

\[
f_i = P_i x_i \gamma_i
\]

From the CBMC data on CO\(_2(1)/C_3H_8(2)\) mixture adsorption data in Fig. 2, the quantities \(f_i/P_i x_i, \text{CBMC}\) may be determined; these are plotted in Fig. 8a, b as function of (a) the mole fraction of CO\(_2\) in the adsorbed phase, \(x_{1,\text{CBMC}}\), and (b) the adsorption potential, \(\pi_A\). The plots show that appropriate models for the activity coefficient must also include the dependence on the adsorption potential\([21,23,27–29,39]\). The Wilson model, for example, may be written as

\[
\ln \gamma_i = \left(1 - \ln(x_1 + x_2) - \frac{x_1}{x_1 + x_2} \ln \frac{x_1}{x_1 + x_2} \right) \left(1 - \exp\left(-\frac{C_{21}}{RT}\right)\right)
\]

\[
\ln \gamma_2 = \left(1 - \ln(x_1 + x_2) - \frac{x_2}{x_1 + x_2} \ln \frac{x_2}{x_1 + x_2} \right) \left(1 - \exp\left(-\frac{C_{21}}{RT}\right)\right)
\]

In Eq. (3), \(C\) is a constant with the units kg mol\(^{-1}\). The introduction of \(1 - \exp\left(-\frac{C_{21}}{RT}\right)\) imparts the correct limiting behaviors \(\gamma_i \rightarrow 1\); \(f_i \rightarrow 0\) for the activity coefficients in the Henry regime. As pore saturation conditions are approached, this correction factor tends to unity, \(1 - \exp\left(-\frac{C_{21}}{RT}\right) \rightarrow 1\). The total mixture loading is given by

\[
q_i = q_1 + q_2 = \frac{x_1}{q_1^{\gamma_1} + \frac{x_2}{q_2^{\gamma_2}} + [-x_1 \ln(x_1 + x_2 \Lambda_1) - x_2 \ln(x_1 + x_2 \Lambda_2)]C \exp\left(-\frac{C_{21}}{RT}\right)}
\]

The set of Eqs. (1), (2), (3), and (4) must be solved simultaneously to obtain the values of the component loadings \(q_1\), and \(q_2\) for a specified set of values of \(f_1\), and \(f_2\).

The continuous solid lines in Figs. 1, 2, and 6 represent RAST calculations in which the parameters in the Wilson model are obtained by fitting to match CBMC or experimental data on component loadings. As illustration of the influence of thermodynamic non-idealities on the separation performance in fixed beds, let us consider CO\(_2/C_3H_8\) separations in an adsorber packed with NaX zeolite operating at 300 K. Using the theory of shock waves for separations in fixed bed adsorbers\([8,19]\), the maximum amount of pure C\(_3H_8\) that can be recovered during the adsorption cycle is given by the separation potential, \(\Delta Q = Q_{C_3H_8}/(1 - \frac{1}{\rho \text{NaX}}) - Q_{C_3H_8}\). expressed in the units mol per L of adsorbent; for these calculations the crystal framework density of NaX zeolite is taken as \(\rho = 1421\) kg m\(^{-3}\). Fig. 9. presents a comparison of the
Fig. 4. CBMC simulations (symbols) of the component loadings for adsorption of (a) CO$_2$(1)/C$_3$H$_8$(2), and (b) CO$_2$(1)/C$_2$H$_6$(2) mixtures in all-silica FAU zeolite at 300 K and total fugacity $f_t = 1$ MPa. The $x$-axis represents the mole fraction of CO$_2$ in the bulk gas phase. The dashed line represent IAST estimates. All data inputs and computational details are provided in the Supplementary Material.

Fig. 5. Comparison CO$_2$/CH$_4$ adsorption selectivities determined from CBMC simulations 300 K for all-silica FAU (192 Si, 0 Al, 0 Na$^+$, Si/Al = $\infty$), NaY (138 Si, 54 Al, 54 Na$^+$, Si/Al = 2.56), and NaX (106 Si, 86 Al, 86 Na$^+$, Si/Al = 1.23) zeolites with IAST estimations. All data inputs and computational details are provided in the Supplementary Material.
IAST and RAST calculations of $\Delta Q$; for a total mixture fugacity, $f_t = 1$ MPa, the values of $\Delta Q$, are respectively 5.2, and 4 mol $L^{-1}$, respectively. Thermodynamic non-idealities reduce the productivity of pure C3H8 in a fixed bed adsorber by about 20%.

5. Conclusions

The following major conclusions emerge from the foregoing analysis of adsorption of CO2-bearing mixtures in cation-exchanged zeolites. The failure of the IAST to provide quantitatively accurate estimates of mixture adsorption, as witnessed in the experimental data in Fig. 1, is ascribable to inhomogeneous distribution of adsorbates within the zeolite pores. In NaX zeolite, the inhomogeneity is a direct consequence of strong binding of CO2 with extra-framework cations, leading congreation effects around cations. In LTA zeolites, CO2 locates preferentially at the window regions, causing an inhomogeneous distribution of adsorbates. In the RAST description of mixture adsorption, the chosen model for activity coefficients must also include the dependence on the adsorption potential $\pi_{A}RT$.

The overall conclusion to be drawn from this study is that thermodynamic non-idealities may have a significant influence of the separations in fixed bed adsorption devices. For CO2 capture applications with cation-exchanged zeolites, departures from idealities generally tend to reduce the separation effectiveness.
Fig. 7. Computational snapshots showing the location of CO$_2$ and C$_3$H$_8$ within the cages of LTA-4A zeolite at 300 K and total fugacity $f_t = 1$ MPa. The component partial fugacities are $f_1 = 0.85$ MPa, and $f_2 = 0.15$ MPa.

Fig. 8. Analysis of the non-idealities in CO$_2$(1)/C$_3$H$_8$(2) mixture adsorption in NaX zeolite at 300 K. Dependence of $f_i/P_i^0 x_i$ on (a) the mole fraction of CO$_2$ in the adsorbed phase as determined from CBMC simulations, $x_{1,\text{CBMC}}$, and (b) the adsorption potential, $(\pi A/RT)$. All data inputs and computational details are provided in the Supplementary Material.
Fig. 9. Comparison of IAST and RAST calculations of the separation potential, $\Delta Q = Q_1 - Q_2$ for separation of 50/50 CO$_2$(1)/C$_3$H$_8$(2) feed mixtures in NaX zeolite at 300 K.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.seppur.2018.06.009.

References


