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Publication Date
2018-04-23

DOI
10.1021/acs.inorgchem.8b00138

Peer reviewed
Enhancement of CO₂ uptake and selectivity in a metal-organic framework by incorporation of thiophene functionality

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Keywords: Carbon dioxide, metal-organic framework, thiophene, carboxylate, zinc, binding site, breakthrough
Abstract

The complex $[\text{Zn}_2(\text{tdc})_2\text{dabco}]$ ($\text{H}_2\text{tdc} = \text{thiophene-2,5-dicarboxylic acid}; \text{dabco} = 1,4\text{-diazabicyclooctane}$) shows a remarkable increase in CO$_2$ uptake and CO$_2$/N$_2$ selectivity compared to the non-thiophene analogue $[\text{Zn}_2(\text{bdc})_2\text{dabco}]$ ($\text{H}_2\text{bdc} = \text{benzene-1,4-dicarboxylic acid}; \text{terephthalic acid}$). CO$_2$ adsorption at 1 bar for $[\text{Zn}_2(\text{tdc})_2\text{dabco}]$ is 67.4 cm$^3$·g$^{-1}$ (13.2 wt.%) at 298 K and 153 cm$^3$·g$^{-1}$ (30.0 wt.%) at 273 K. For $[\text{Zn}_2(\text{bdc})_2\text{dabco}]$ the equivalent values are 46 cm$^3$·g$^{-1}$ (9.0 wt.%) and 122 cm$^3$·g$^{-1}$ (23.9 wt.%), respectively. The isosteric heat of adsorption for CO$_2$ in $[\text{Zn}_2(\text{tdc})_2\text{dabco}]$ at zero coverage is low (23.65 kJ·mol$^{-1}$), ensuring facile regeneration of the porous material. The enhancement by the thiophene group on the separation of CO$_2$/N$_2$ gas mixtures has been confirmed by both ideal adsorbate solution theory (IAST) calculations and dynamic breakthrough experiments. The preferred binding sites of adsorbed CO$_2$ in $[\text{Zn}_2(\text{tdc})_2\text{dabco}]$ have been unambiguously determined by in situ single crystal diffraction studies on CO$_2$-loaded $[\text{Zn}_2(\text{tdc})_2\text{dabco}]$, coupled with quantum chemical calculations. These studies unveil the role of the thiophene moieties in the specific CO$_2$ binding via an induced dipole interaction between the CO$_2$ and the sulfur center, confirming that enhanced CO$_2$ capacity in $[\text{Zn}_2(\text{tdc})_2\text{dabco}]$ is achieved without the presence of open metal sites. The experimental data and the theoretical insights suggest a viable strategy for improvement of adsorption properties of already known materials through incorporation of S-based heterocycles within their porous structures.
Introduction

Carbon dioxide (CO₂) release poses one of the biggest anthropogenic impacts to the environment. While broad implementation of low-carbon fuels and strategies will reduce CO₂ release, power plants, cement and steel production represent major industries that will continue to generate exhausts which require effective purification to remove CO₂ as well as other harmful gases.¹ CO₂ sequestration through selective adsorption is viewed as one of the most promising approaches due to its simple implementation, the absence of hazardous materials, tunable selectivity and low energy costs.² Thus, porous materials, such as metal-organic frameworks (MOFs), with the highest CO₂ adsorption capacity at relatively low partial pressures (< 5 bar) are valuable targets for such applications.³-¹⁰ High adsorption selectivity and high uptake under ambient conditions may be enhanced in porous materials by the incorporation of specific binding sites at the pore surface. The main strategies for the incorporation of CO₂-binding centers into MOF structures have been via the incorporation of basic centers such as amines functioning as Lewis bases,¹¹-¹⁵ and adsorption at coordinatively unsaturated metal cations as Lewis acid sites.¹⁶-²¹ The former strategy is a development of the traditional approach of CO₂ capture by amines to form carbamates, and shows high uptakes and very good adsorption selectivity even under humid conditions, but also, significantly, increases the energy cost for regeneration of the adsorbate. The latter strategy employs CO₂ binding through the interaction to vacant metal sites. Despite a number of advantages such as moderate energy penalty for regeneration and tunability of the adsorption sites, such materials often only function under strictly anhydrous conditions as water competes effectively for binding at the unsaturated metal sites. Also the open metal sites usually reach saturation rapidly and thus lose their activity in selective guest binding. Since each strategy has its particular disadvantages, the development of porous materials with high adsorption selectivity, appreciable CO₂ uptake under ambient conditions, capable of working under humid environments and possessing a low regeneration penalty requires new approaches based on other types of inter- and supra-molecular interactions. With a handful of exceptions,¹⁹,²²-³² weak van der Waals and supramolecular interactions have not been widely considered as a driving force for specific CO₂ binding which could result in appreciable adsorption selectivity and improved storage capacity. We demonstrate herein that the incorporation of thiophene moieties with polarizable sulfur heteroatoms, capable of induced dipole-dipole interactions, results in a remarkable increase of the CO₂ binding affinity of the microporous MOF, [Zn₂(tdc)₂dabco]. This increases both the storage capacity and selectivity of the framework at ambient conditions by as much as 50%,
comparing thiophene with phenyl functionalization, and also maintains the heat of adsorption at a low level to minimize penalty costs for regeneration. The enhanced CO₂ binding property of the thiophene-containing MOF has also been confirmed by fixed-bed breakthrough separation of a CO₂/N₂ mixture. More importantly, adsorbed CO₂ molecules within [Zn₂(tdc)₂dabco] have been directly observed and quantified by in situ single crystal diffraction experiments, revealing the preferential host-guest binding interaction in the pores. The mechanism of MOF-CO₂ binding has also been studied by quantum chemical calculations, giving detailed insights on the role of the sulfur atoms in the CO₂ supramolecular binding. These results provide a new viable strategy underpinning the development of MOF materials with improved uptake and selectivity for CO₂.

Materials and Methods

All chemicals were of analytical grade and were used without additional purification. DMF was dried over the activated molecular sieves (3Å) prior to use.

Synthesis of [Zn₂(tdc)₂dabco]-4DMF (1). To a mixture of Zn(NO₃)₂·6H₂O (120 mg, 404 µmol) and thiophene-2,5-dicarboxylic acid (H₂tdc) (47 mg, 273 µmol) in DMF (5.3 ml) was added dabco (23 mg, 205 µmol) in DMF (4.0 ml) dropwise under rigorous stirring to avoid the formation of any precipitate. The resulting clear solution was heated at 100 °C for 20 h. The colorless block-shaped crystals were collected and washed with DMF. Yield: 0.093 mg (78% based on H₂tdc). Elemental analyses. Calculated for [Zn₂(tdc)₂dabco]·4DMF·H₂O: C, 40.3; H, 5.2; N, 9.4; S, 7.2. Found: C, 40.4; H, 5.0; N, 9.2; S, 7.4.

Thermogravimetric analysis. Calculated for 4DMF: 33.4%. Found: 30.5%. FT-IR (KBr): 1667 cm⁻¹ (νC=O of DMF).

Synthesis of [Zn₂(tdc)₂bpe]-2DMF (2) and [Zn₂(tdc)₂bpp]-2DMF (3) was carried out using a similar procedure starting from Zn(NO₃)₂·6H₂O (250 mg, 842 µmol), H₂tdc (145 mg, 843 µmol) and either 1,2-bis(4-pyridyl)ethane (bpe) (75 mg, 408 µmol) or 1,3-bis(4-pyridyl)propane (bpp) (84 mg, 424 µmol). The corresponding solids were dissolved in DMF (10 ml) with rigorous stirring and sonification. An unknown precipitate was removed from the reaction solution by centrifugation and the clear solution heated at 100 °C for 40 h. Block-shaped crystals of the product were collected and washed in DMF. The yields are 236 mg (69%) for 2 and 263 mg (73%) for 3. Elemental analyses. Calculated for [Zn₂(tdc)₂bpe]-2DMF: C, 45.0; H,
Found: C, 45.0; H, 3.9; N, 7.0; S, 7.8. Calculated for [Zn₂(tdc)₂bpp]·2DMF: C, 45.7; H, 4.0; N, 6.9; S, 7.9. Found: C, 45.3; H, 3.9; N, 6.8; S, 7.5. Thermogravimetric analysis for 2. Calculated for 2DMF: 18.3%. Found: 17.8%. Thermogravimetric analysis for 3. Calculated for 2DMF: 18.0%. Found: 17.4%. FT-IR (KBr): 2, 1675 cm⁻¹; 3, 1666 cm⁻¹ (νC=O of DMF).

**Synthesis of activated [Zn₂(tdc)₂dabco] (1a).** The as-synthesized compound 1 was heated at 90 °C in vacuo for 10 h. The sample weight loss was 30.3%. Elemental analyses. Calculated for [Zn₂(tdc)₂dabco]·H₂O: C, 36.0; H, 3.0; N, 4.7; S, 10.7. Found: C, 36.2; H, 3.0; N, 4.8; S, 10.9.

**Synthesis of [Zn₂(tdc)₂bpe] (2) and [Zn₂(tdc)₂bpp] (3):** The as-synthesized crystals of 2 or 3 were heated at 100 °C in vacuo for 6 h. The sample weight loss was found to be 18.4% for 2 and 17.7% for 3. Elemental analyses. Calculated for [Zn₂(tdc)₂bpe]: C, 44.0; H, 2.5; N, 4.3; S, 9.8. Found: C, 43.7; H, 2.4; N, 4.2; S, 9.5. Calculated for [Zn₂(tdc)₂bpp]·⅔H₂O: C, 44.1; H, 2.9; N, 4.1; S, 9.4. Found: C, 44.5; H, 2.7; N, 4.2; S, 9.0.

**Results and discussion**

**Synthesis and crystal structure analysis**

The coordination polymer [Zn₂(tdc)₂dabco]·4DMF (1) was prepared by solvothermal reaction of Zn(NO₃)₂, thiophene-2,5-dicarboxylic acid (H₂tdc) and dabco in hot DMF (100 °C) to give rectangular colorless stick-like single crystals. The stability of 1 was found to be very similar to many Zn(II) carboxylate MOFs. The crystalline material 1 is stable in organic media, but decomposes rapidly in water. The as-synthesized crystals 1 can be handled in air for several hours without any impact on crystallinity. Single crystal X-ray diffraction confirms that 1 crystallizes in tetragonal space group P4₂₁c and incorporates binuclear paddle-wheel nodes [Zn₂(OOCR)₄] (Fig. 1a) bound by four carboxylate groups of tdc²⁻ anions to form a slightly squeezed layer of square-grid topology with a corrugated overall structure (Fig. 1b). The remaining available coordination site at the square pyramidal Zn(II) cations are bound by N-donors of the dabco ligands, which connect [Zn₂(tdc)₂] layers into a 3D porous framework with a scaffold-like primitive cubic topology pcu (Fig. 1c). The rotation of the dabco ligands results, as expected, in severe disorder of the carbon atoms of the CH₂CH₂ moieties, and the rigid angular shape of the tdc²⁻ anion forces notable distortions of the paddle-wheel unit such that the Zn-Zn axis is twisted from the c crystallographic direction of the unit cell by ca. 16°. The van der Waals aperture of the channels running along the 4-fold axis is 5×8 Å corresponding to the
shape of the squeezed square window of the \([\text{Zn}_2(\text{tdc})_2]\) layer (Fig. 1d). These corrugated layers stack along the \(c\) direction in an alternating ABAB fashion, forming two different types of smaller windows across the 4-fold axis. The narrower window has van der Waals dimensions of 2.5×5 Å formed by two closely located \(\text{tdc}^{2-}\) moieties. The wider 3.5×5 Å window is formed by two \(\text{tdc}^{2-}\) arcs bent outwards from each other with an interatomic \(\text{S} \cdots \text{S}\) distance of 8.5 Å (Fig. 1e). It is worth noting that the slight tilting of the thiophene groups [\(i.e.,\) the orientation of the heteroatom (\text{vide supra})] results in two different types of pore environment (Fig. 1b). Regardless of this tilting, both types of channels have similar aperture and are set up for diffusion of gas molecules with potential interaction with the sulfur atoms of the thiophene moieties.

In a similar manner, two additional microporous zinc(II) thiophene-2,5-dicarboxylates \([\text{Zn}_2(\text{tdc})_2\text{bpe} \cdot 2\text{DMF (2)}\) and \([\text{Zn}_2(\text{tdc})_2\text{bpp} \cdot 2\text{DMF (3)}\) were synthesized using 1,2-bis(4-pyridyl)ethane (bpe) and 1,3-bis(4-pyridyl)propane (bpp) as N-donor bridging ligands, respectively. During the course of this work the synthesis and structure of 2 was reported.\(^{33}\) In 2 and 3 the structure of the \([\text{Zn}_2(\text{tdc})_2]\) corrugated layer remains unchanged compared to 1, and these layers are connected through longer N-donor linkers (Fig. 2). The elongation of the bridging ligand does open up the possibility for framework interpenetration, which is not possible for 1 incorporating shorter dabco ligands.\(^{34}\) As a result the structure 1 is a single non-interpenetrated net, while 2 and 3 show doubly-interwoven structures with \textbf{peu} topology. Despite the interpenetration, both 2 and 3 contain microporous volume filled with solvent molecules in the as-synthesized materials. We should also note that in spite of our numerous attempts to obtain similar structures with 4,4′-bipyridyl or trans-bis(4-pyridyl)ethylene bridging ligands we could not crystallize any product thus far. The problem could be related to steric constraint of substantially skewed \([\text{Zn}_2(\text{OOOCR})_4]\) paddle-wheel building units, which cannot be inter-connected by structurally rigid linear ligands. Dabco is an apparent exception due to its aliphatic nature and the formation of rather strong metal-ligand coordination bonds. The micropores of the as-synthesized materials 1-3 are filled by DMF solvent molecules which were located from the X-ray diffraction data. The FT-IR spectra and the chemical and thermogravimetric analyses confirm the nature and composition of the guest molecules. According to TGA data the DMF molecules can be removed by heating the material to 170–190 °C, while the irreversible thermolysis of the metal-organic framework takes place near 300 °C for 1 and 2, or 330 °C for 3.
The guest-free sample [Zn₂(tdc)₂dabco] (1a) was obtained by thermal activation of the as-synthesized crystals 1 in vacuo. Compared with the as-synthesized 1, the activated 1a is more susceptible to airborne moisture, but no sign of degradation of the X-ray powder diffraction pattern or gas adsorption properties was observed for 1a exposed to air for 1h. The crystalline material was sufficiently robust to sustain the activation procedure so we were able to characterize the solvent-free open structure 1a by single-crystal X-ray diffraction. The space group was found to be I4/mmm (tetragonal) and the local coordination of the metal cations as well as the overall pcu connectivity remains unchanged from 1 (Fig. 3a). The only notable difference is that the anionic tdc²⁻ linkers are more linear in the guest-free structure 1a, resulting in a higher symmetry and a more regular structure with rectangular channels of van der Waals aperture 6.5 × 6.5 Å (Fig. 3b). This straightening of the organic ligands results in an overall expansion of the guest-free structure 1a, compared to the solvated material 1. The total unit cell volume increases during the activation by ca. 3%. Notably, the structural changes between 1 and 1a are fully reversible as the guest free compound 1a shrinks back when placed in DMF solvent to re-form 1. It is worth noting that the analogous compound based on terephthalate bdc²⁻ bridging ligands [Zn₂(bdc)₂dabco]·x(solv) (4) features the same reversible structural changes upon the framework activation and re-solvation, though the degree of volume expansion/contraction of the unit cell in 4 is somewhat greater (3–5%) depending on the nature of the solvent.35,36

Gas adsorption studies
Activation of the interpenetrated compounds 2 and 3 was achieved by heating the compounds in vacuo at 100 °C for 6 h. The complete removal of the guest DMF molecules without framework collapse was confirmed by powder X-ray diffraction (PXRD), TGA, chemical analyses and IR spectroscopy. Some shift of the PXRD peaks to higher 2θ angles upon de-solvation of 3 indicates a shrinkage of the partially flexible framework. N₂ adsorption measurements for the activated samples at 77 K showed reversible type I isotherms, characteristic of microporous materials, with pore volumes of 0.19 and 0.20 cm³·g⁻¹ and BET surface areas of 447 and 407 m²·g⁻¹ for 2 and 3, respectively (See ESI). The relatively low porosity for these compounds is not surprising given the observed two-fold interpenetrated structures for these species.
The stability and permanent porosity of the guest-free compound 1a was confirmed by PXRD and gas adsorption measurements. The N$_2$ isotherm at 77 K reveals a type I reversible isotherm (Fig. 4) with a pore volume of 0.68 cm$^3$·g$^{-1}$ and BET surface area of 1553 m$^2$·g$^{-1}$. The pore volume is similar to the expected value of 0.63 cm$^3$·g$^{-1}$ calculated from the gravimetric density of the framework 1a (0.94 g·cm$^{-3}$) and its guest accessible volume (0.59 v/v) according to the PLATON SOLV routine.\(^{37}\) This is entirely consistent with the complete activation of the material and the overall stability of the porous structure under these conditions. The pore-size distribution, calculated from the N$_2$ isotherm, gives a sharp peak near 8 Å, which corresponds to the van der Waals diameter of the cubic cages in 1a (ca. 8–9 Å). The pore volume of 1a and its specific surface area are very close to those reported earlier for the terephthalate analogue [Zn$_2$(bdc)$_2$dabco] (4a) (0.75 cm$^3$·g$^{-1}$ and 1450 m$^2$·g$^{-1}$, respectively).\(^{38}\) Consistent with these surface area data, the H$_2$ adsorption for 1a (245 cm$^3$·g$^{-1}$ and 2.23 wt.% at 77K and 1 bar) is slightly higher than for 4a (2.0 wt.% under similar conditions).

The reported CO$_2$ adsorption measurements for 4a,\(^{39,40}\) as well as our data (see ESI) indicate rather moderate gas uptake of 9.0 wt.% (46 cm$^3$·g$^{-1}$) at 298K and 1 bar, and 23.9 wt.% (122 cm$^3$·g$^{-1}$) at 273 K and 1 bar. In contrast, CO$_2$ adsorption in 1a, which generally shows similar porosity as 4a, reveals a significant increase of ca 50% in uptake under the same conditions. The maximum CO$_2$ adsorption in 1a at 1 bar reaches as high as 13.2 wt% (67.4 cm$^3$·g$^{-1}$) at 298 K and 1 bar, and 30.0 wt% (153 cm$^3$·g$^{-1}$) at 273 K and 1 bar (Fig. 5). At a pressure of 0.15 bar, which is relevant to the flue gas processing, the CO$_2$ uptakes of 1a are 18.5 wt.% and 8.5 wt.% at 273 and 298 K, respectively.

The isosteric heat of adsorption for CO$_2$ in 4a at zero coverage, calculated from the isotherms at 273 and 298 K using the Clausius-Clapeyron equation is 19.52 kJ·mol$^{-1}$ consistent with literature data.\(^{41}\) The heat of the adsorption of CO$_2$ for 1a is noticeably higher at 23.65 kJ·mol$^{-1}$, reflecting presumably stronger binding of CO$_2$ to the thiophene ring. The modest adsorption enthalpy of 1a highlights the absence of the strong binding centers in 1a with open metal sites and active amines reported to increase the heat of adsorption to 35–45 kJ·mol$^{-1}$ and 50–100 kJ·mol$^{-1}$, respectively.\(^{5,6}\) Despite the negative impact to the selectivity,\(^{42}\) the low heat of the adsorption in 1a decreases the energy penalty for the regeneration of the porous material in a temperature-swing process.
Gas adsorption selectivity and gas separation studies

Together with the CO₂ uptake, the CO₂/N₂ adsorption selectivity is one of the most important parameters for the practical application of porous materials in the purification of the industrial exhausts.⁴³ The adsorption data (see ESI) allowed us to calculate the CO₂/N₂ selectivity factors for 1a and 4a at 298 K by three commonly used methodologies via i. the ratio of the adsorbed gas volume, ii. the ratio of the Henry’s constants, and iii. using ideal adsorbed solution theory (IAST). The selectivity, calculated as the ratio of the adsorbed gas volumes by 1a at 1 bar, is $V(\text{CO}_2)/V(\text{N}_2) = 15.1$ (Fig. 5). By considering a typical flue gas composition of 0.15 bar CO₂ and 0.75 bar N₂, the normalized³⁷ selectivity of adsorption at this composition can be calculated $S_{ads} = 11.4$. The corresponding numbers for 4a are $V(\text{CO}_2)/V(\text{N}_2) = 10.2$ and $S_{ads} = 9.4$. The Henry’s constants ($K_H$) were derived from the linear approximation of the low pressure part of the isotherms, and based on the obtained values of $K_H$ for 1a and 4a, and the selectivity factors at 298 K were calculated to be 12.5 and 8.9, respectively. The IAST⁴⁴ calculations for 1a resulted in a selectivity factor of 11.2 for an equimolar CO₂/N₂ mixture, while for 4a this factor is 9.2. Thus, comparison of the above selectivity factors for 1a and 4a concludes that substitution of a phenyl group to thiophene on going from 4a to 1a enhances the CO₂/N₂ adsorption selectivity by 20 to 50%, depending upon the methodology used. Finally, it is important to note that even though the obtained selectivity factors for 1a are lower than those for MOFs with strong CO₂ binding centers, a selectivity above 8 is high enough to be considered for practical applications.⁴⁵

The potential of utilizing these MOFs for CO₂ separation has also been confirmed in breakthrough experiments in which an equimolar mixture of CO₂/N₂ was flowed over a packed bed of 1a at 298 K and 1.0 bar (Fig. 6). To validate the role of thiophene group in enhanced CO₂ binding, corresponding breakthrough experiment has also been conducted on the phenyl-functionalized material 4a under the same conditions. As predicted by the selectivity calculations, a complete separation has been achieved in both cases, with N₂ being the first to elute through the bed, whereas CO₂ was retained. On saturation, CO₂ breaks through from the bed and reaches saturation rapidly. As shown in Fig. 6, dimensionless breakthrough plots offer a direct comparison between 1a and 4a on the performance of separation of the CO₂/N₂ mixture. Significantly, 1a shows a pronouncedly better separation than 4a ($\Delta \tau = 130$ and 87 for 1a and 4a, respectively). Additionally, the enhanced CO₂ storage capacity by the thiophene functionalization in 1a has been confirmed by its notably delayed (almost a factor of 2) breakthrough of CO₂ ($\tau = 250$ and 143 for 1a and 4a, respectively). These results confirm the potential application of 1a on CO₂/N₂ separation.
Theoretical studies

Achieving such an outstanding affinity towards CO$_2$ in the absence of strong Lewis basic centers or coordinatively unsaturated metal sites prompted us to thoroughly investigate the nature of the CO$_2$ binding in 1a. The main difference between 1a and 4a is the chemical environment of the microporous surface as the channels in 1a are decorated by sulfur atoms from the thiophene-2,5-dicarboxylate linkers. In the absence of any stronger intermolecular interactions (such as donor-acceptor bonds or H-bonds) the CO$_2$ guest molecules have to interact with the porous host through somewhat weaker dipole-dipole interactions. The sulfur atom is more susceptible to polarization and thus for the induced dipole interactions with the quadrupole of CO$_2$. Comparison of [Zr$_6$O$_4$(OH)$_4$(bpdc)$_6$] with [Zr$_6$O$_4$(OH)$_4$(btdc)$_6$] (bpdc$_2^-$ = biphenyl-4,4’-dicarboxylate, btdc$_2^-$ = bithiophenedicarboxylate) shows, depending on the temperature, a 32 to 78% increase for the gravimetric CO$_2$ uptake for the latter thiophene-containing structure. It was suggested that differences in the electrostatic surface potentials for bpdc$_2^-$ and btdc$_2^-$ accounted for this difference, but no direct chemical explanation was given. In order to understand the role of the tdc$_2^-$ ligand in CO$_2$ adsorption in 1a, we undertook grand canonical Monte Carlo (GCMC) simulations (see ESI). These reveal unambiguously that CO$_2$ is preferentially adsorbed near the tdc$_2^-$ linker at low loading (Fig. 7a) and that thiophene plays a key role in the adsorption of CO$_2$ at low pressure. The CO$_2$⋅⋅⋅tdc$_2^-$ interaction was probed further by DFT simulations, which confirmed that the carbon-sulfur bond provides an excellent binding site for CO$_2$ (Fig. 7b,c), with calculated binding energies ranging from $-15.7$ to $-18.3$ kJ·mol$^{-1}$, ca. 3-10 kJ·mol$^{-1}$ stronger than reported binding energies for CO$_2$ with benzene-based moieties.$^{46-48}$ The shortest S⋅⋅⋅C interatomic distance in the energy-optimized thiophene⋅⋅⋅CO$_2$ complex is 3.51 Å (Fig. 7c), equal to the sum of the van der Waals radii of sulfur and carbon. The simulated heat of CO$_2$ adsorption in 1a (24.2 kJ·mol$^{-1}$) coincides with the experimental value (23.65 kJ·mol$^{-1}$), giving consistency between the theory and the experiment. The lower value of heat of adsorption of CO$_2$ for 4a (19.6 kJ·mol$^{-1}$)$^{39}$ calculated by DFT, suggests and generalizes the idea that the inclusion of thiophene-based ligands in MOFs provides a route to materials with an increased affinities for CO$_2$.

Determination of the binding cites for adsorbed CO$_2$
We also sought to determine the preferred binding sites of adsorbed CO₂ molecules in the extended pore structure of 1a by \textit{in situ} synchrotron X-ray single-crystal diffraction. Desolvated sample of 1a shows complete retention of the framework structure and removal of the free guest solvent molecules from the pore (Fig. 8a). Two types of pores can be clearly observed and are denoted as α and β with a pore diameter of 7.1 Å and 7.8 Å (taking into consideration of van der Waal radii), respectively. The S centers of all thiophene groups point into pore α, whereas pore β is primarily functionalized with –CH moieties on the thiophene.

The desolvated 1a was then loaded with CO₂ at a pressure of 1.0 bar at 273 K and diffraction data collected at time \( t = 0.25, 1, \text{ and } 2 \) hours to capture the dynamic information of site population. It is worth mentioning that the kinetics of gas uptake in single crystals could be notably different to that of powder sample typically used in isotherm experiments. Analysis of the diffraction data indicates an absence of notable structural phase change of 1a upon CO₂ inclusion. Sequential Fourier difference map analysis of the diffraction data revealed the position of the adsorbed CO₂ molecules in all three structures (Fig. 8 b–d).

At the first dataset of CO₂-loaded 1a, only one binding site, (CO₂¹) was located within the pore α of 1a·(CO₂)₀.₄₀. CO₂¹ (occupancy = 0.20) is located near the \{Zn₂\} paddle-wheel stabilised by dipole interactions to the paddle-wheel and hydrogen bonds to the –CH groups (Fig. S6). Upon the second data collection, 1a·(CO₂)₁.₅₆, the occupancy of CO₂¹ increases to 0.43, accompanied by the appearance of a second binding site (CO₂²) with an occupancy of 0.352. CO₂² was located in pore β and is close to the thiophene group (Fig. S7). Interestingly, the CO₂–thiophene interatomic distance found in the X-ray diffraction data (3.49 Å) is highly consistent with that (3.51 Å) obtained in the DFT calculation. On additional equilibrium time (\( t = 2h \)), 1a·(CO₂)₁.₆₃, the occupancies of CO₂¹ and CO₂² drop slightly to 0.38 and 0.29, respectively, indicating a re-distribution of adsorbed CO₂ molecules. The rest of adsorbed CO₂ molecules fill into a third site (CO₂³) with an occupancy of 0.14 (Fig. S8). CO₂³ was found in pore α, forming intermolecular dipole interaction with CO₂¹ in a “T-shape” manner. Additional diffraction data collection at \( t > 2h \) yielded same crystal structures as 1a·(CO₂)₁.₆₃, indicating the presence of adsorption equilibrium. Thus, two out of the three CO₂ binding sites are found within the sulfur-rich pore α of 1a, confirming the critical role of this heteroatom functionalization in carbon dioxide adsorption. Indeed, the observation of direct host-guest interaction between the thiophene and CO₂² represents the first experimental evidence of CO₂ binding to a sulfur-rich functional group in MOFs.
Conclusions

Three isoreticular porous MOFs based on $[\text{Zn}_2(\text{OOCR})_4]$ paddle-wheels, connected through thiophene-2,5-dicarboxylate moieties and N-donor linkers (L) $[\text{Zn}_2(\text{tdc})_2\text{L}]$ have been synthesized and characterized. Apart from some structural distortions these frameworks are very similar to the prototypic Zn(II) terephthalate material $[\text{Zn}_2(\text{bdc})_2\text{dabco}]$ and has similar porosity in terms of pore size, volume and specific surface area. However, substitution of a phenyl group with thiophene substantially increases adsorption of CO$_2$ as well as CO$_2$/N$_2$ separation selectivity as evidenced by thorough gas isotherm measurements and breakthrough experiments. The thiophene-lined $[\text{Zn}_2(\text{tdc})_2\text{dabco}]$ possesses a very good CO$_2$ uptake under ambient condition even though it features neither basic amine functions nor open metal sites, which is reflected by a low isosteric heat of adsorption. The in situ synchrotron X-ray diffraction data and quantum chemical calculation confirm the role of the thiophene heterocycle and, particularly, sulfur atoms in binding CO$_2$ via induced dipole interactions. These results emphasize the feasibility of van der Waals interactions to effective CO$_2$ binding while maintaining low heat of adsorption within a hydrophobic porous material. More importantly, the incorporation of heterocycles into porous structures may represent a viable route to improving the adsorption properties of already known materials.

ASSOCIATED CONTENT

Supplementary information available: the details of the analytical methods, X-ray single crystal experiments, CIF files, gas adsorption measurements, GCMC and DFT calculation, additional figures and plots. CCDC 1503063-1503066 and 1568882-1568885 contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from the Cambridge Crystallographic Data Center at http://www.ccdc.cam.ac.uk/data_request/cif.

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Competing financial interests

The authors declare no competing financial interests.
Acknowledgements

We thank EPSRC, ERC and University of Manchester for funding. NIIC team is grateful to the Russian Science Foundation (Grant 14-23-00013) and Federal Agency for Scientific Organizations for the financial support. We thank the University of Nottingham for HPC facilities. M.S. acknowledges the Russian Ministry of Science and Education for the award of a Russian Megagrant (14.Z50.31.0006). We are especially grateful to the Advanced Light Source for access to Beamline 11.3.1. The Advanced Light Source is supported by the Director, Office of Science, Office of Basic Energy Sciences, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231. The development of the gas cell used in this work was partially funded by the Center for Gas Separations Relevant to Clean Energy Technologies, an Energy Frontier Research Center funded by the U.S. Department of Energy, Office of Science, Basic Energy Sciences under Award # DE-SC0001015.

References


**Figure 1.** View of the structure of the as-synthesized [Zn₂(tdc₂)₂dabco]·4DMF (1). The view of the [Zn₂(OOCR)₄] paddle-wheels, connected by dabco ligands (a). The structure of the [Zn₂(tdc)₂] layer (b). Projection of the crystal structure of 1 along the 4-fold axis (c). The aperture of channels along the 4-fold axis (d). The aperture of channels across the 4-fold axis (e). Zn – green, S – yellow, O – red, N – blue, C – grey, hydrogen atoms are not shown.
Figure 2. Views of the single nets of \([\text{Zn}_2(\text{tdc})_2\text{bpe}]2\text{DMF (2)}\)\(^{28}\) (a) and \([\text{Zn}_2(\text{tdc})_2\text{bpp}]2\text{DMF (3)}\) (b). Zn – green, S – yellow, O – red, N – blue, C – grey, hydrogen atoms are not shown.
Figure 3. View of the crystal structure of the activated $[\text{Zn}_2(\text{tdc})_2\text{dabco}]$ (1a). Wireframe presentation viewed along the $[\text{Zn}_2(\text{tdc})_2]$ layers (a). Van der Waals model view along the 4-fold axis (b). Zn – green, S – yellow, O – red, N – blue, C – grey, hydrogen atoms are not shown.
Figure 4. N\textsubscript{2} (black squares) and H\textsubscript{2} (red circles) isotherms for [Zn\textsubscript{2}(tde)\textsubscript{2}dabco] (1a) at 77K. Adsorption – full symbols, desorption – open symbols. Inset: pore size distribution curve.
**Figure 5.** N$_2$ and CO$_2$ adsorption (full symbols) and desorption (open symbols) isotherms on [Zn$_2$(tdc)$_2$dabco] (1a) at 273 K and 298 K.
Figure 6. Dimensionless breakthrough curves for N₂/CO₂ mixture (1:1) for 1a (a) and 4a (b) at 25 °C and 1 bar.
Figure 7. Snapshot from GCMC simulation at low pressure in which the majority of CO$_2$ molecules were found to be located near to the thiophene ring (a). The DFT-optimized lowest-energy binding site for CO$_2$ viewed from above the tdc$^2$- fragment (b,c).
Figure 8. X-ray crystal structures for [Zn(tdc)2dabco] (1a) as a function of CO2 loading (projection along the c direction). The gas-free activated structure 1a featuring sulfur-rich (α) and sulfur-poor (β) channels, respectively (a). Views of the binding site for adsorbed CO2 molecules at gradually increased population of CO2 in the channels of 1a (b, c, d).
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