

MOF Pore Design

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Capture and Separation of SO₂ Traces in Metal–Organic Frameworks via Pre-Synthetic Pore Environment Tailoring by Methyl Groups

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Abstract: Herein, we report a pre-synthetic pore environment design strategy to achieve stable methyl-functionalized metal–organic frameworks (MOFs) for preferential SO₂ binding and thus enhanced low (partial) pressure SO₂ adsorption and SO₂/CO₂ separation. The enhanced sorption performance is for the first time attributed to an optimal pore size by increasing methyl group densities at the benzenedicarboxylate linker in [Ni₂(BDC-X)₂DABCO] (BDC-X = mono-, di-, and tetramethyl-1,4-benzenedicarboxylate/terephthalate; DABCO = 1,4-diazabicyclo[2,2,2]octane). Monte Carlo simulations and first-principles density functional theory (DFT) calculations demonstrate the key role of methyl groups within the pore surface on the preferential SO₂ affinity over the parent MOF. The SO₂ separation potential by methyl-functionalized MOFs has been validated by gas sorption isotherms, ideal adsorbed solution theory calculations, simulated and experimental breakthrough curves, and DFT calculations.

Introduction

The emission of the toxic gas sulfur dioxide (SO₂) represents one of the most serious pollutions and continues

to threaten human health and poses various environment issues.^[1–4] Although a large fraction ($\approx 95\%$) of SO₂ is removed from flue gases by established desulfurization technologies such as limestone scrubbing,^[1,5] the residual SO₂ still remains in flue gas and can damage other gas scrubbers.^[6,7] Developing new technologies based on solid adsorbents for trace SO₂ removal could be a possibility in view of process economy and energy efficiency.^[8–11] Given the highly corrosive nature of SO₂, many materials are sensitive to SO₂ and thus relatively limited studies have been performed on ionic liquids,^[12] zeolite,^[13] porous organic cages,^[14] and metal–organic frameworks (MOFs).^[15–21] Among them, MOFs seem most promising due to their outstanding features including reticular synthesis, tunable structure, and high porosity.^[22–25] Up to now, there is still a small number of MOFs reported for SO₂ adsorption^[26–28] when compared to CO₂ and CH₄ sorption. Less effort was even given to targeted trace SO₂ removal, that is, high SO₂ uptake at low partial pressure. In general, the capacity of trace SO₂ removal is quantified by the SO₂ uptake amount at a partial pressure of 0.1 bar or even 0.01 bar. So far, two main strategies for the enhanced SO₂ affinity have been proposed on MOFs. One is open metal sites within the MOF structure for M–SO₂ interactions.^[29,30] The other one is polar amino groups in the framework as sites for hydrogen-bonding interactions with SO₂.^[31,32] In addition, it has been recently pointed out that small micropore diameters in the range of approximately 4 to 8 Å could be advantageous for low-pressure SO₂ uptake.^[33]

MOFs with methyl-functionalized linkers could be a good candidate for tailoring micropore diameters to the optimal range and at the same time having moderate non-covalent van der Waals (vdW) interactions with SO₂ molecules for sufficient SO₂ affinity but still facile (desorption) regeneration. Methyl-functionalized MOFs have been shown to display enhanced CO₂ uptake affinity,^[34,35] but were not explored for SO₂ sorption and separation to the best of our knowledge. We propose that MOFs with an already feasible topology could be tuned in their pore diameter for an efficient SO₂ separation through methyl-functionalization. At the same time, methyl groups increase the hydrophobicity and can shield the reactive metal–linker bonds to increase the stability of MOFs towards moisture.^[25,36]

To the best of our knowledge, there are no reports on the use of methyl groups to increase SO₂ affinity and SO₂/CO₂ selectivity. Herein, we systematically study the methyl-functionalized BDC linker in pillar-layered [Ni₂(BDC-X)₂DABCO] {BDC-X = monomethyl (X = M), 2,5-dimethyl (X = DM), and tetramethyl (X = TM) 1,4-benzenedicarbox-

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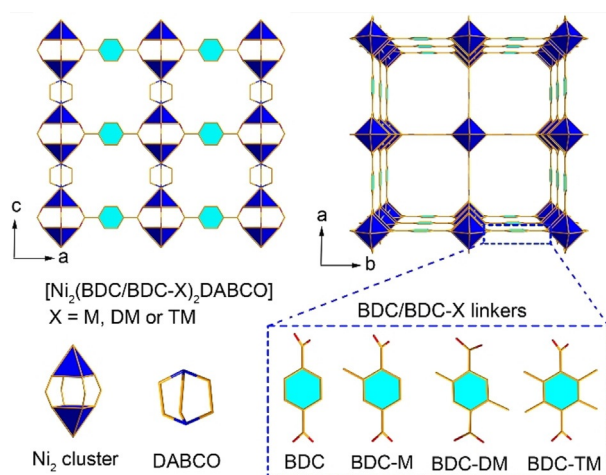


Figure 1. Top row: Sections of the packing diagram of DMOF showing the channel structures along the *b*- (and identical *a*-) axis and along the *c*-axis. Bottom row: The building blocks of the Ni_2 cluster, DABCO, and BDC/BDC-X in DMOF/DMOF-X. X represents the monomethyl (M), 2,5-dimethyl (DM), or 2,3,5,6-tetramethyl (TM) substituents. Hydrogen atoms are omitted for clarity.

ylate/terephthalate; DABCO = 1,4-diazabicyclo[2,2,2]octane} referred to as DMOF-X (Figure 1).^[37,38] DMOFs with different metals and linkers, mixed metals, and mixed linkers, including BDC-TM and Ni-DMOF-TM, were recently tested for SO_2 sorption with the focus on stability in humid conditions.^[25] The addition of methyl groups to the BDC linker yields isostructural DMOFs.^[39] The increased density of methyl groups in methyl-functionalized DMOF-X (X represents M, DM, and TM) is then correlated with the SO_2 adsorption and separation properties.

Results and Discussion

The pillar-layered $[\text{Ni}_2(\text{BDC})_2\text{DABCO}]$ DMOF is composed of dinuclear nickel paddlewheel units, $[\text{Ni}_2(\text{OOC-})_4]$ bridged by BDC linkers to form 2D regular square layers, which are further pillared by DABCO linkers to result in a 3D framework (Figure 1). Thus, two kinds of channels exist in this DMOF structure. One is the wide square channel with $\approx 7.5 \times 7.5 \text{ \AA}^2$ along the *c*-axis (Figure 1, top-right), while the other is

a more narrow rectangular aperture with $\approx 5.6 \times 6.9 \text{ \AA}^2$ along the *a*- and *b*-axis (Figure 1, top-left).^[37] The introduction of four methyl groups with the tetramethylterephthalate linker minimizes the pore width range of DMOF from $\approx 6\text{--}8 \text{ \AA}$ down to $\approx 5\text{--}7 \text{ \AA}$ in DMOF-TM (as determined from Ar sorption, Figure S11, SI). This agrees with the pore widths along the *c*-axis and *a/b*-axis in the DMOF-TM crystal structure of $\approx 4.9 \times 4.9 \text{ \AA}^2$ and $\approx 4.5 \times 6.7 \text{ \AA}^2$, respectively.^[39] In BDC-TM, the tetramethylphenyl group also rotates out of the plane of the carboxylate groups, due to the steric effect of the methyl groups (Figure S1 and S2, SI).

The PXRD patterns of methyl-functionalized DMOF-X match with that of the parent DMOF, indicating their isostructural frameworks (Figure S3, SI). The solution $^1\text{H NMR}$ spectra (Figure S5–S8, SI) of the digested DMOF and methyl-functionalized DMOF-X confirmed the expected 2:1 molar ratio of BDC/BDC-X to DABCO linker according to the formula of $[\text{Ni}_2(\text{BDC}/\text{BDC-X})_2\text{DABCO}]$, being consistent with the results from elemental analysis (see Section S3, SI). Compared to DMOF, a trend of gradual reduction of particle size with increased methylation to DMOF-TM was observed from SEM analysis (Figure S9, SI), attributed to an increased nucleation and reduced growth rate relative to each other with the increased number of methyl groups. From N_2 and Ar sorption isotherms at 77 and 87 K (Figure S11 and S12, SI), respectively, the Brunauer-Emmett-Teller (BET) surface area and pore volume of DMOF and DMOF-X decreased with the increasing number of methyl groups (Table 1), which fill the pores and limit the accessible surface area.

The SO_2 sorption isotherm of DMOF shows a slight S-shape (relatively low SO_2 affinity, see below) with the steep uptake setting in at 0.04 bar (Figure 2b). The SO_2 uptake of DMOF-X at 293 K sets in at decreasingly lower pressure (Figure 2b) with increasing number of methyl groups. At 0.01 bar, the SO_2 uptake of DMOF was recorded as 0.25 mmol g^{-1} , while DMOF-M, DMOF-DM, and DMOF-TM showed already an increased uptake of 0.46, 1.00, and 3.79 mmol g^{-1} (Table 1, Figure 2b). Particularly, the SO_2 uptake of DMOF-TM (3.79 mmol g^{-1}) at 0.01 bar exceeds most of the current top-performing MOFs (Figure S13 and Table S6, SI), such as Mg-MOF-74 (3.03 mmol g^{-1}), SIFSIX-1-Cu (3.43 mmol g^{-1}), SIFSIX-3-M (2.43 and 1.68 mmol g^{-1} for M = Ni and Zn, respectively) and $\text{NH}_2\text{-MIL-125(Ti)}$

Table 1: Porosity characteristics of DMOF and DMOF-X and the results of SO_2 adsorption at 293 K.

Material	BET-surface area ^[a] (from N_2/Ar) [$\text{m}^2 \text{ g}^{-1}$]	Total pore volume ^[b] (from N_2/Ar) [$\text{cm}^3 \text{ g}^{-1}$]	Pore width ^[c] [Å]	SO_2 uptake (293 K) [mmol g^{-1}] at:			SO_2/CO_2 selectivity ^[d] at SO_2/CO_2 molar ratio:		
				0.01 bar	0.1 bar	0.97 bar	0.01	0.1	0.5
DMOF ^[37]	2050 ^[39] /–	0.80 ^[39] /–	7.5, 5.6×6.9 ^{[37][e]}	–	–	9.97 (298) ^[17]	–	–	–
DMOF	1956/1843	0.76/0.67	$\approx 6\text{--}8$	0.25	7.21	13.09	18	36	92
DMOF-M	1557/1586	0.63/0.59	$\approx 6\text{--}8$	0.46	6.40	12.15	27	38	81
DMOF-DM	1343/1281	0.52/0.56	$\approx 6\text{--}8$	1.00	5.70	10.40	50	40	31
DMOF-TM	900/1079	0.43/0.42	$\approx 5\text{--}7$	3.79	6.43	9.68	134	169	253
DMOF-TM ^[39]	894 ^[39] /–	0.39 ^[39] /–	4.5 ^{[39][e]}	–	–	≈ 4.9 (298) ^[25]	–	–	–

[a] Obtained from five adsorption points in the pressure range $0.001 < p/p_0 < 0.05$. [b] Derived at $p/p_0 = 0.9$. [c] Pore widths from pore size distribution are measured by Ar sorption at 87 K. [d] See Section 5.2 in the SI for the CO_2 sorption data. [e] From X-ray structure.

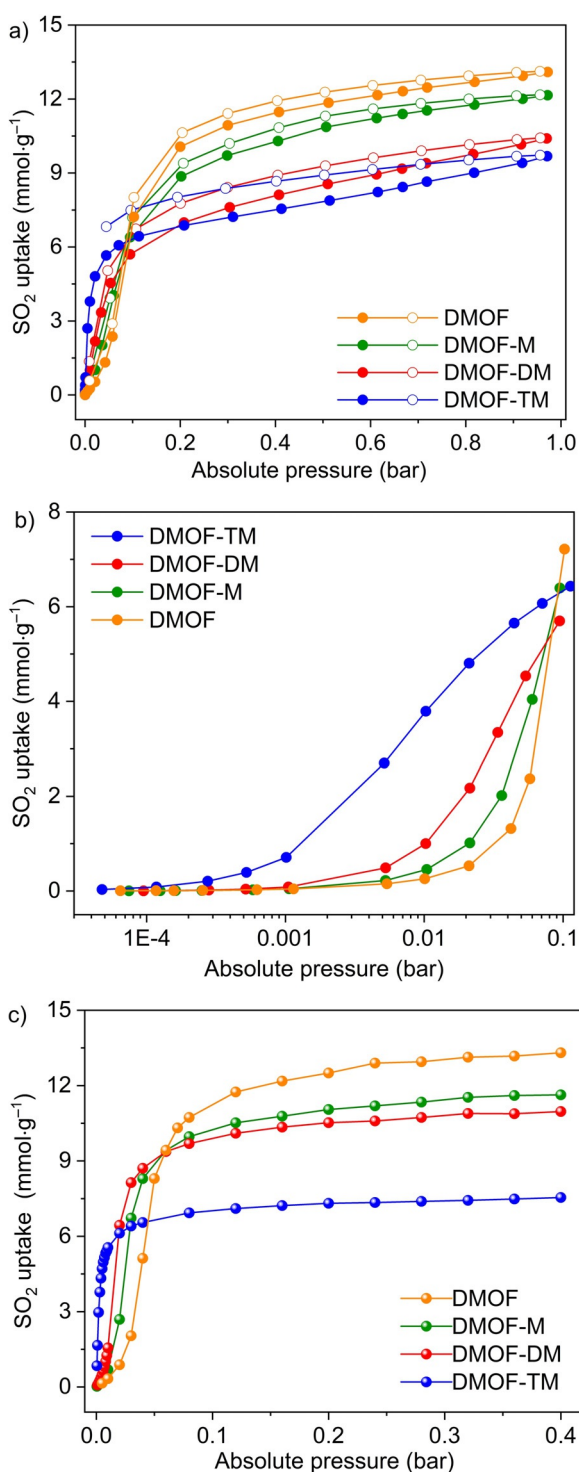


Figure 2. a) SO₂ sorption isotherms of DMOF and DMOF-X at 293 K between 0 and 0.97 bar.; b) The enlarged SO₂ adsorption at low pressure of 0–0.1 bar for better clarity of the onset of steep uptake; c) Monte Carlo simulated isotherms of SO₂ adsorption on DMOF and DMOF-X between 0 and 0.4 bar (low pressure) and 293 K.

(3.0 mmol·g⁻¹), and is only slightly lower than that of SIFSIX-2-Cu-i (4.16 mmol·g⁻¹)^[31,40] and MIL-160 (4.2 mmol·g⁻¹).^[31] The latter two feature polar groups (SiF₆²⁻ and a furan ring, respectively) together with optimal micropore widths of

approximately ≈ 5 Å (see below). As the pressure increased to 0.1 bar, SO₂ uptake of DMOF-TM rapidly rose up to 6.43 mmol·g⁻¹ accounting for $\approx 66\%$ of the SO₂ uptake (9.68 mmol·g⁻¹ at 0.97 bar). The observed high SO₂ uptake of DMOF-TM at low pressure (<0.1 bar) meets a prerequisite of potential adsorptive flue-gas desulfurization processes. The SO₂ uptake at ≈ 1 bar shows a reasonable linear relation relative to the BET surface area and pore volume (Figure 3). The SO₂ capacity at 0.97 bar was expectedly decreased with increasing density of methyl groups in DMOF, which can be attributed to the gradually decreased pore volume and BET surface area (Table 1 and Figure 3).

The SO₂ adsorption isotherms at 273 and 293 K were used to determine the isosteric enthalpy of SO₂ adsorption ($-\Delta H_{\text{ads}}$) by virial analysis (Figure S14–S17, SI).^[41] The $-\Delta H_{\text{ads}}$ values of methyl-functionalized DMOFs were obviously higher than the parent DMOF and increase with the number of methyl groups (Figure 4). Further, the $-\Delta H_{\text{ads}}$ values follow the uptake at low pressure (<0.05 bar). Grand-canonical-Monte Carlo (GCMC) simulations for a series of small-pore MOFs have shown a good correlation of the SO₂ uptake at reduced pressures (0.05 bar) and the heat of adsorption.^[42]

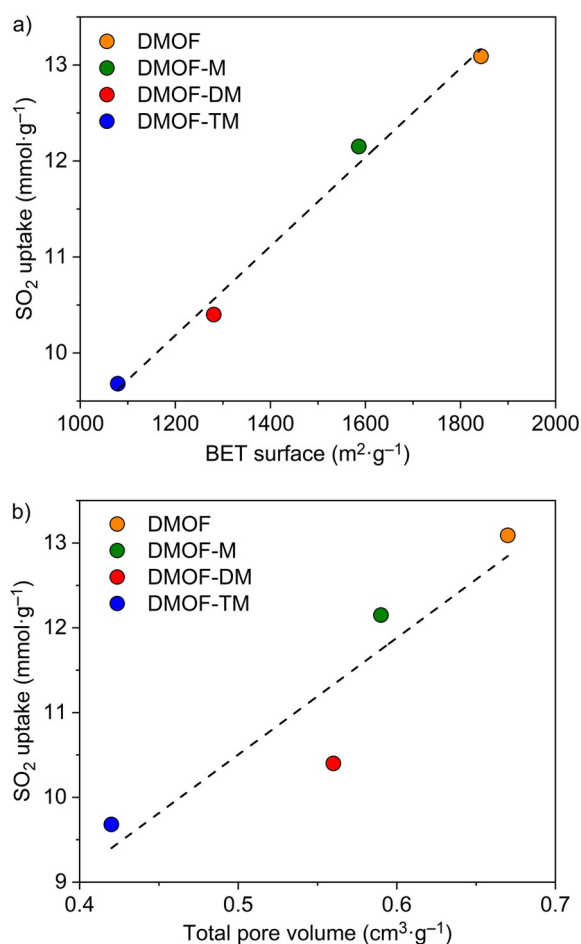


Figure 3. SO₂ uptake (0.97 bar, 293 K) vs. a) BET-surface area and b) total accessible pore volume (both determined by Ar adsorption at 87 K). The dashed trend lines are a guide to the eye.

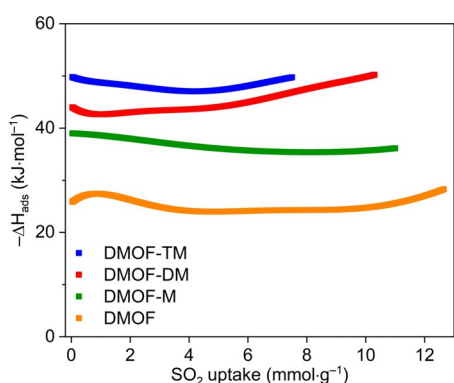


Figure 4. Isothermic enthalpy of adsorption of SO_2 on DMOF and DMOF-X materials from fitting the adsorption isotherms of SO_2 at 273 and 293 K by virial analysis (Figure S14–S17, SI).

At the low pressure of 0.01 bar and 0.1 bar the uptake in the DMOFs is clearly independent of the total surface area or pore volume (Figure 2b). Instead, if the SO_2 uptake at these pressures is normalized by the surface area, the surface-specific SO_2 uptake is obtained and can be plotted against the pore limiting diameter (PLD; Figure 5). The PLD is the smallest diameter of a pore, channel, or aperture in a framework. The maximum of surface-specific SO_2 uptake at low pressure for DMOF-TM at its PLD of $\approx 4.5 \text{ \AA}$ points to this value as an optimal pore diameter. The value of $\approx 4 \text{ \AA}$ agrees with the kinetic diameter of SO_2 (4.1 \AA).^[43] In a pore of width of $\approx 4 \text{ \AA}$ the SO_2 molecule can have multiple dispersive interactions with the surface. It is obviously an advantage for adsorbent structures to provide Connolly surfaces at a distance of the length of the adsorbed molecule which can then interact at several points with the accessible surface.^[44] The Connolly surface is the probe-accessible surface.

Monte Carlo simulations of SO_2 adsorption at 0–0.4 bar and 293 K were performed on DMOF and DMOF-X using the Cassandra software with standard UFF/UFF4MOF force field parameters.^[45] Through the simulated adsorption isotherms the trend of enhanced SO_2 affinity by methyl-

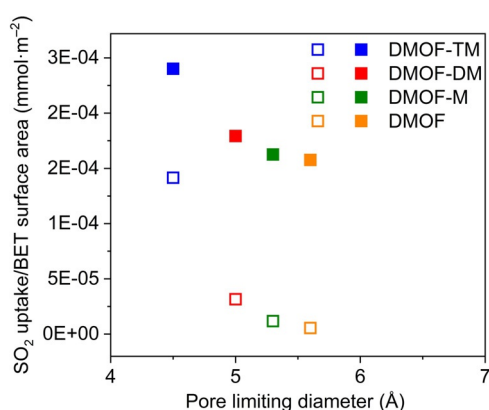


Figure 5. Surface-specific SO_2 uptake at 0.01 bar (open symbols) and 0.1 bar (closed symbols; 293 K), which is the uptake at this pressure divided by the BET-surface area vs. the pore limiting diameter (PLD). The PLD of DMOF-M and DMOF-DM was determined from their DFT-optimized structures (see Section S8.2, Figure S43, SI).

functionalized DMOF-X with increased density of methyl groups was well reproduced within the simulations (Figure 2c), despite the fact that the simulated isotherms slightly overestimated the uptake, the most for DMOF-DM (Figure S48, SI). Differences to the experiment occur due to the neglect of structure degradation and possible structure flexibility in the simulations (see the calculation details in the Supporting Information Section S8.2, S9 and Figure S45, S46). Also, the choice of force field influences the simulation results (Figure S47 documents the effect of different force fields on the simulated adsorption isotherm of DMOF-TM). Individual parametrization of the host–guest interactions may therefore contribute to further improve the simulation data.

The different SO_2 -adsorption behaviors of DMOF and DMOF-TM are demonstrated by simulation snapshots at different partial pressures (Figure 6) and by a movie (made with the iRASPA program)^[46] showing the consecutive filling with increasing pressure from 0 to 0.4 bar (40 kPa) (File DMOF2.mp4 in SI). It should be noted that in DMOF-TM SO_2 is preferentially located near the methyl groups of the BDC-TM linkers already at very low pressures, indicating favorable methyl– SO_2 interactions (see below). The pore filling is further enhanced by SO_2 – SO_2 dipole–dipole interactions between 0.04 and 0.4 bar. However, SO_2 distribution is sparse in DMOF at the same low-pressure regime (0.01–

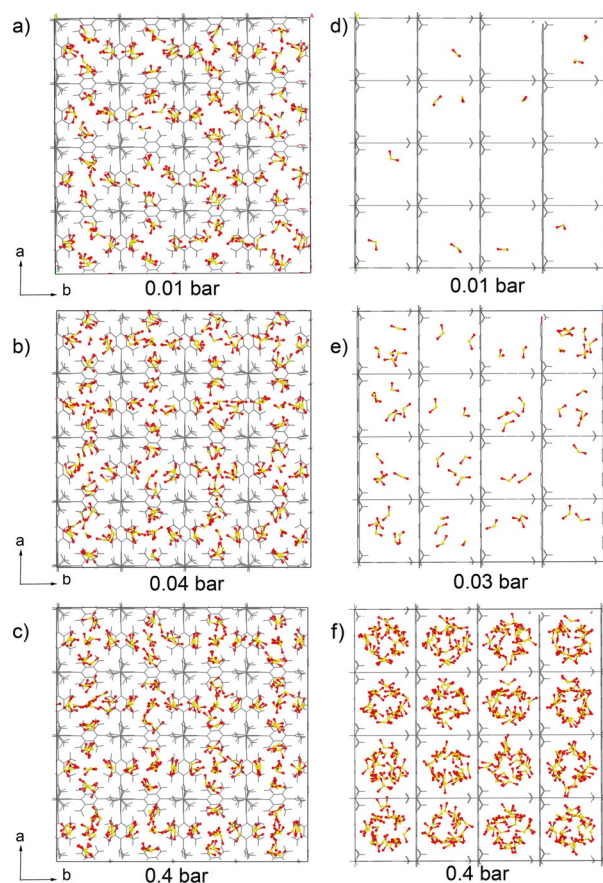


Figure 6. Monte Carlo simulation of SO_2 loading with snapshots at 0.01, 0.03, or 0.04 and 0.4 bar for DMOF-TM (a–c) and DMOF (d–f). See Figure S50, SI for a magnified image and the movie file DMOF2.mp4, SI for the full sequence.

0.04 bar, Figure 6d,e). The DMOF-SO₂ interactions are weaker (see below) and adsorption is mainly triggered by SO₂-SO₂ dipole-dipole interactions in which SO₂ molecules prefer to interact with already adsorbed SO₂ molecules (see below). The formation of SO₂ clusters finally fills the pores at 0.4 bar.

The single-component CO₂, N₂, and CH₄ adsorption isotherms for DMOF and DMOF-X were measured at 293 K (Figure S23, SI). The same attribute from the increasing density of methyl groups was also observed with enhanced low-pressure CO₂ and CH₄ adsorption but was not found for N₂ adsorption (Figure S23 and Table S2, SI). However, the increase of low-pressure SO₂ adsorption with the increase of methyl density was much steeper than that of CO₂ and CH₄ probably due to the high polarizability ($47.7 \times 10^{-25} \text{ cm}^3$) and high dipole moment (1.62 D) of SO₂.^[47] At the pressure of 0.97 bar, the uptake of CO₂ and CH₄ increased with the methyl groups density on DMOF-X (Table S2, SI), but the absolute specific amounts of CO₂ and CH₄ were still much lower compared to the SO₂ uptake. The difference in gas uptake, especially at low pressure, indicates the potential of DMOF-X for selective SO₂ adsorption from flue gases.

In order to evaluate the selectivity of SO₂ over CO₂, CH₄, and N₂ ideal adsorbed solution theory (IAST) calculations were performed for binary gas mixtures as a function of variable SO₂ molar fractions (from 0.01 to 0.5) at 1 bar and 293 K. Considering the trace SO₂ amount present in the flue gas, high SO₂ selectivity over these other gases is required for a realistic adsorptive gas desulfurization process. For a molar SO₂/CO₂ ratio of 10:90, the selectivity of DMOF was 35, while DMOF-M, -DM, and -TM afforded the increased selectivity of 38, 40, and 169 (Figure 7 and Table S6, SI). To the best of our knowledge, the SO₂/CO₂ selectivity value for DMOF-TM represents the highest value among all MOFs reported so far (Table S6, SI). Meanwhile, DMOF-TM also possesses a high SO₂/CH₄ and SO₂/N₂ selectivity of 725 and 1141, respectively, when the SO₂/CH₄ or SO₂/N₂ ratio is 10:90 (Figure S24, S25, SI).

The favorable interactions of methyl-functionalized DMOFs with SO₂ over the parent DMOF were elucidated by periodic dispersion-corrected DFT (DFT-D) calculations using Quantum Espresso.^[48] At least three main binding sites of SO₂ are present within the framework (Figure 8). The

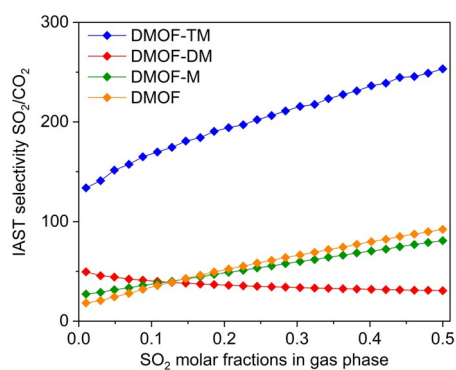


Figure 7. IAST selectivity of SO₂/CO₂ for DMOF-X series as a function of SO₂ molar fractions (0.1–0.5) at 1 bar and 293 K.

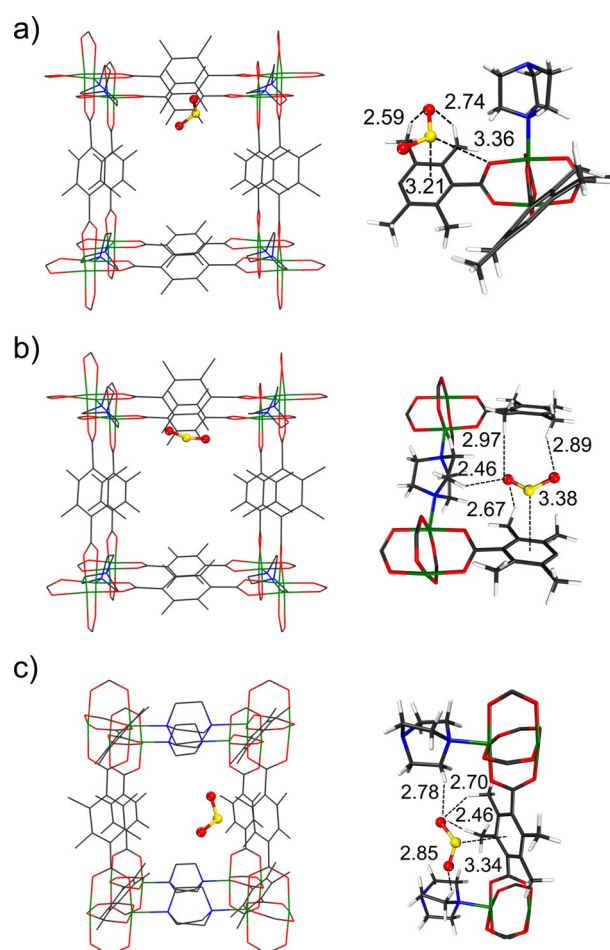


Figure 8. Periodic DFT-calculated SO₂ binding sites on optimized DMOF-TM (the distances are given in Å). Binding energy at site 1, a) $-58.0 \text{ kJ mol}^{-1}$; site 2, b) $-56.9 \text{ kJ mol}^{-1}$; site 3, c) $-61.0 \text{ kJ mol}^{-1}$. The respective sites in DMOF are shown in Figure S44, SI. The calculation details are given in Section S8.2, SI. Color code: S yellow; O red; N blue; Ni green; C gray; H light gray. Hydrogen atoms on framework images in left column are omitted for clarity.

adsorbed SO₂ within the pore surface of DMOF-TM is primarily stabilized by enhanced (C)H^(δ+)...^(δ-)O(S) interactions. The optimized H...O distances of 2.59–2.97 Å between methyl groups and SO₂ are significantly shorter than the sum of vdW radii of H and O atoms (3.05 Å). Multiple (C)H^(δ+)...^(δ-)O(S) interactions between DABCO and SO₂ contribute to structure stabilization with H...O distances of 2.46–2.97 Å (binding site 2 and 3, Figure 8b,c). Furthermore, the optimized (benzene)C...S distances are 3.21–3.38 Å, which are shorter than the analogous value (3.42 Å) in DMOF with SO₂. This indicates the enhanced strength of the benzene^(δ-)...^(δ+)S interactions, which are probably induced by the incorporation of electron-donating methyl groups. The calculated binding energies (-56.9 to $-61.0 \text{ kJ mol}^{-1}$) of SO₂ with DMOF-TM were significantly higher than those (-31.3 to $-31.8 \text{ kJ mol}^{-1}$) with DMOF at the three main binding sites for the first SO₂ molecule (Figure S44, SI). It should be noted that thermal and zero-point energy corrections are not included in this picture. To get an estimate of the zero-point energy contribution, we performed phonon computations for

SO₂-bound DMOF-TM (see SI section S8.2), obtaining 8.8 kJ mol⁻¹. With this value as a reference, the ZPE-corrected binding energies would range from ca. -48 to -52 kJ mol⁻¹. This is in agreement with the higher experimental $-\Delta H_{\text{ads}}$ values of SO₂ on DMOF-TM over DMOF (Figure 4). Subsequently, we explored the effect of increased SO₂ loading on the adsorption of DMOF-TM. DFT-D calculations showed that at least five SO₂ molecules could be trapped within the channel of DMOF-TM (Figure S45, S46). Four of them were primarily located in the proximity with BDC-TM linkers via noncovalent host-guest interactions and the other one was adsorbed at the center of the channel via SO₂-SO₂ dipole-dipole interactions with other, already adsorbed SO₂ molecules.

Cluster DFT-D calculations were performed with Gaussian 16^[49] to compare the difference in binding interactions between SO₂ and CO₂ on DMOF and DMOF-TM (Figure S41, S42, SI). Similar to periodic DFT-D results, structure optimizations of DMOF-TM with SO₂ yielded multiple noncovalent cooperative interactions (Figure S42, SI). The optimized H...O(S) (2.46–2.81 Å) distances in DMOF-TM models with SO₂ are shorter than those (2.60–2.88 Å) with CO₂. This supports the favorable binding interaction of DMOF-TM with SO₂ over CO₂, in line with the higher binding energies of DMOF-TM with SO₂ (Table S3, SI). Additionally, we performed frequency calculations for the cluster DFT models. The resulting adsorption enthalpies for DMOF and DMOF-TM models are in reasonable agreement with the experimental $-\Delta H_{\text{ads}}$ values (Table S3).

An attempt was made to localize the SO₂ in the pores of the DMOF-TM by powder XRD studies at low temperature (100 K). According to the approximate structural analysis, the SO₂ molecules are predominantly positioned in the largest cavity along the z-axis in the range of $x, y, z = 0, 0, 0-0.3$ and in the vicinity of two methyl groups of the same BDC-TM ligand molecule at approximately $x, y, z = 0, 0.38, 0.15$ (Section S11, SI).

The potential for SO₂ separation from other typical flue gases was investigated by breakthrough experiments and simulations with the ternary gas mixture of N₂/CO₂/SO₂ (84.9:15:0.1 v/v/v) at 293 K and 1 bar. From the experimental breakthrough curves (Figure S38 and S39), the immediate rise of N₂ and CO₂ could be clearly seen in both samples of DMOF and DMOF-TM. In contrast, their SO₂ retention time was significantly different. For DMOF-TM (Figure S39), SO₂ can be approximately retained for $\approx 346 \text{ min g}^{-1}$, but the SO₂ retention time in DMOF (Figure S38) was only $\approx 28 \text{ min g}^{-1}$. In addition, no significant loss in SO₂ retention time was found in the second and third run of the regenerated DMOF-TM (Figure 9a) with a comparable SO₂ uptake over the three runs (37 vs. 40 vs. 37 mg g⁻¹ in the first, second, and third run). However, for DMOF (Figure 9b), the total SO₂ loading in the second run was significantly reduced from 5.5 to 3 mg g⁻¹.

The simulated breakthrough curves have been calculated using the software 3P sim version 1.1.07, employing the “ideal adsorbed solution theory” (IAST) with data from fitted dual-site Langmuir SIPs isotherms.^[50] It has been verified that the outcome of the simulations, which were performed using a similar software, matches experimental breakthrough

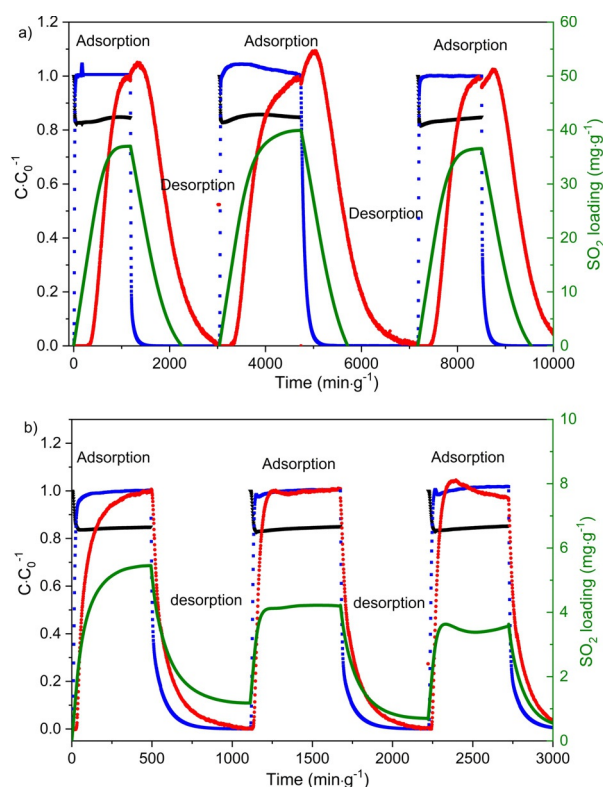


Figure 9. Three runs of adsorption and desorption in cycling breakthrough experiments of a DMOF-TM (a) and DMOF (b) sample (red: SO₂; blue: CO₂; black: N₂; green: SO₂ loading uptake; from a ternary gas mixture of N₂/CO₂/SO₂ with 84.9:15:0.1 v/v/v at 293 K and 1 bar).

studies if the separation is based on thermodynamic effects and not on kinetic-steric effects.^[51] The breakthrough simulation by the 3P software has already been demonstrated to enable a reliable estimate of the breakthrough onset time for SO₂ in gas mixtures.^[14,31] From the simulated breakthrough curves, the retention time of SO₂ in the outlet was gradually prolonged by increasing the density of methyl groups in DMOF, in which 6, 14, 63, and 333 min g⁻¹ were recorded for DMOF, DMOF-M, -DM, and -TM respectively (Figure S34–S37, SI). From the DMOF-TM, the immediate rise of N₂ and CO₂ in the outlet indicates the negligible N₂ and CO₂ adsorption. Thus, the high SO₂/CO₂ and SO₂/N₂ separation performance makes DMOF-TM promising for adsorptive gas desulfurization processes.

To investigate the stability of the DMOFs towards SO₂, all activated materials were exposed to dry SO₂ for 6 hours and to humid SO₂ for 6 hours (at 35 ppm SO₂ content with 75 % RH in the air atmosphere, see Section S6, Figure S26, SI). As expected, the increasing density of methyl groups gradually improved the structure stability, as seen from the evaluation of PXRD patterns and porosity measurements by N₂ sorption. The little changed PXRD patterns of all materials after dry and humid SO₂ exposure suggest the retention of crystallinity without noticeable phase transformation or decomposition (Figure S27, SI). The BET surface area and pore volume on DMOF-DM ($\approx 85\%$) and DMOF-TM ($\approx 90\%$) were also well retained after dry and humid SO₂ adsorption (Figure S30–S32, SI). DMOF-TM was reported to maintain some

crystallinity with a 50% decrease in surface area after 50 ppm SO₂/85% RH/1 day exposure but a complete loss in surface area after 100 ppm SO₂/85% RH/1 day exposure.^[25] However, for DMOF (Figure S28, SI), which has no methyl groups, the porosity was significantly reduced under the same SO₂ treatment conditions. For DMOF-M (Figure S29, SI) there was a significant porosity reduction under humid SO₂ exposure.

The regeneration ability of DMOF-TM was further tested by a recycling SO₂ adsorption experiment. Considering the $-\Delta H_{\text{ads}}$ values of DMOF-TM ($\approx 50 \text{ kJ mol}^{-1}$), we regenerated DMOF-TM by applying vacuum (below 10^{-3} mbar) at room temperature for 1 hour. Remarkably, the SO₂ uptake capacity of re-generated DMOF-TM can be retained for at least four runs of SO₂ adsorption at 0.97 bar and 293 K (Figure S33, SI).

The presence of vibrational modes of remaining adsorbed SO₂ in DMOF-TM under exposure of the SO₂-loaded MOF (see Section S10, SI) to air atmosphere (during 1–20 min) was probed by FT-IR spectra. Two sharp bands at 1331 and 1140 cm⁻¹, not present in pristine DMOF-TM and, hence, associated with the vibrational modes of SO₂ molecules, could be observed in SO₂-adsorbed DMOF-TM (Figure S52). The relative intensity of these bands gradually decreased and the bands almost disappeared after 20 min. At the same time, several vibrational modes corresponding to the DMOF-TM framework were changed upon SO₂ adsorption (Figure S53): There is (1) a blue-shift of the stretching modes of COO⁻ (BDC-TM) from 1593 cm⁻¹ and 1442 cm⁻¹ to 1597 cm⁻¹ and 1444 cm⁻¹; (2) a blue-shift of the phenyl bending mode of C=C (benzene of BDC-TM) from 1539 cm⁻¹ to 1542 cm⁻¹; (3) a blue-shift of the vibrational mode of -CH₃ (BDC-TM) from 3000 to 3005 cm⁻¹ as well as that of -CH₂ (DABCO) from 2943 to 2947 cm⁻¹. These blue-shifted bands, which we attribute to the interactions with the adsorbed SO₂ molecules, were re-established when the SO₂ bands had vanished after 20 min.

Conclusion

We have successfully developed a pre-synthetic rational pore environment tailoring strategy to achieve methyl-functionalized DMOFs with enhanced low-pressure SO₂ adsorption and IAST SO₂/CO₂ selectivity. The improved stability of methyl-functionalized DMOFs against the highly corrosive SO₂ was attributed to the increased steric hindrance and hydrophobicity induced by increasing density of methyl groups. Benefitting from the tunable pore size and chemistry, DMOF-M and DMOF-DM showed a high SO₂ capacity (12.1 and 10.4 mmol g⁻¹) at 1 bar, while DMOF-TM displayed a high SO₂ uptake at low pressure (3.79 mmol g⁻¹ at 0.01 bar) with a high IAST SO₂/CO₂ selectivity (169, for a molar ratio of SO₂/CO₂ at 10:90). As further demonstrated by the breakthrough simulations, the retention time of SO₂ was the longest on DMOF-TM compared to the other three DMOFs. The highly selective SO₂ adsorption by methyl-functionalized DMOFs, especially for DMOF-TM, was attributed to the multiple moderate non-covalent interactions of the small-

pore methyl-functionalized framework with SO₂ molecules, as confirmed by DFT calculations. The methylation-design strategy in our work should be also applicable to other isostructural frameworks for highly efficient gas sorption and separations. Also, the expected rotational freedom of the BDC-TM ligand in DMOF-TM at room temperature might be a factor which enhances the high affinity to SO₂ as the methyl groups could ensure a double weak contact with “bridging” SO₂ molecules.

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Conflict of Interest

The authors declare no conflict of interest.

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