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Stepwise customizing pore environments of C_2H_2-selective frameworks for one-step C_2H_4 acquisition from ternary mixtures

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ABSTRACT

One-step purification of C_2H_4 from ternary $C_2H_2/C_2H_4/C_2H_6$ mixture is crucial but challenging since the primary physical properties of C_2H_4 all fall between C_2H_2 and C_2H_6. Hence, we report an effective approach for purifying C_2H_4 through stepwise customizing pore environments on C_2H_2-selective materials. Utilizing **SIFSIX-1-Cu** as a prototype material, we incorporated one or two methoxyl groups onto 4,4′-bipyridine to obtain isomorphic framework **SIFSIX-1-Cu-OMe** and **SIFSIX-1-Cu-(OMe)$_2$** respectively. As expected, pore sizes gradually decrease, while C_2H_6 binding sites increase. Ultimately, the C_2H_6/C_2H_4 (10/90) selectivity gradually increases from 1.18 (**SIFSIX-1-Cu**) to 1.27 (**SIFSIX-1-Cu-OMe**) and finally to a remarkably high value of 1.79 (**SIFSIX-1-Cu-(OMe)$_2$**). As anticipated, **SIFSIX-1-Cu-(OMe)$_2$** can achieve one-step acquisition of polymer-grade C_2H_4 (≥99.95 %) from $C_2H_2/C_2H_4/C_2H_6$ (1/90/9) mixture with high productivity of 6.82 L/kg. Furthermore, theoretical calculations indicate that the pore surface of **SIFSIX-1-Cu-(OMe)$_2$** is beneficial to preferentially capture C_2H_2 and C_2H_6, and thus realizes one-step purification of C_2H_4.

1. Introduction

As the most important chemical raw material, ethylene (C_2H_4) is widely used in the preparation of basic chemicals such as polyethylene, vinyl chloride and styrene [1–4]. Naphtha or ethane thermal cracking is the main method to produce C_2H_4, but impurities such as acetylene (C_2H_2) and ethane (C_2H_6) are inevitably present in the product [5,6]. The current industry standard for separation involves the utilization of low temperature and high pressure technology to remove C_2H_6, followed by catalytic hydrogenation or solvent extraction to eliminate C_2H_2, which is not only energy-consuming but also environmentally unfriendly [7–9]. Therefore, it is imperative to develop an efficient and energy-saving separation method to realize the one-step purification of C_2H_4 from ternary mixture of $C_2H_2/C_2H_4/C_2H_6$.

Metal-organic frameworks (MOFs) have become the star materials for purifying C_2H_4 due to their tunable frameworks and customizable pore structures. In recent years, MOFs have made significant progress in binary gas mixuture separation such as C_2H_2/C_2H_4 [10–14] and C_2H_4/C_2H_6 separation [15–18]. Regarding the ternary $C_2H_2/C_2H_4/C_2H_6$ mixture, the molecule size and quadrupole moment of C_2H_4 (4.2 Å and 1.5×10^{-26} esu·cm^2) are intermediate between those of C_2H_2 (3.3 Å and 7.2×10^{-26} esu·cm^2) and C_2H_6 (4.4 Å and 0.65×10^{-26} esu·cm^2), which not only eliminates the possibility of molecular sieving, but also presents a challenge to the one-step purification of C_2H_4 through thermodynamic separation [19,20]. At present, only several examples, which have stronger binding sites for C_2H_2 and C_2H_6 simultaneously compared with C_2H_4, can realize one-step C_2H_4 acquisition from ternary $C_2H_2/C_2H_4/C_2H_6$ mixture [21–26]. However, rationally designing an adsorbent with high selectivity for both C_2H_2/C_2H_4 and C_2H_6/C_2H_4 are extremely difficult. In contrast, pore engineering strategies based on C_2H_2-selective or C_2H_6-selective MOFs, such as ligand functionalization, offers greater potential for achieving one-step C_2H_4 acquisition from a mixture of C_2-hydrocarbons. Some successful instances, which introduce the C_2H_2 binding sites into C_2H_6-selective MOFs to enhance C_2H_2/C_2H_4 selectivity, have been reported [27,28]. Noteworthy, MOFs which show inverse adsorption of C_2H_6 and C_2H_4 are uncommon. Therefore, engineering the pore of a C_2H_6-selective material for one-step acquisition of C_2H_4 from $C_2H_2/C_2H_4/C_2H_6$ mixture is of great difficulty and not

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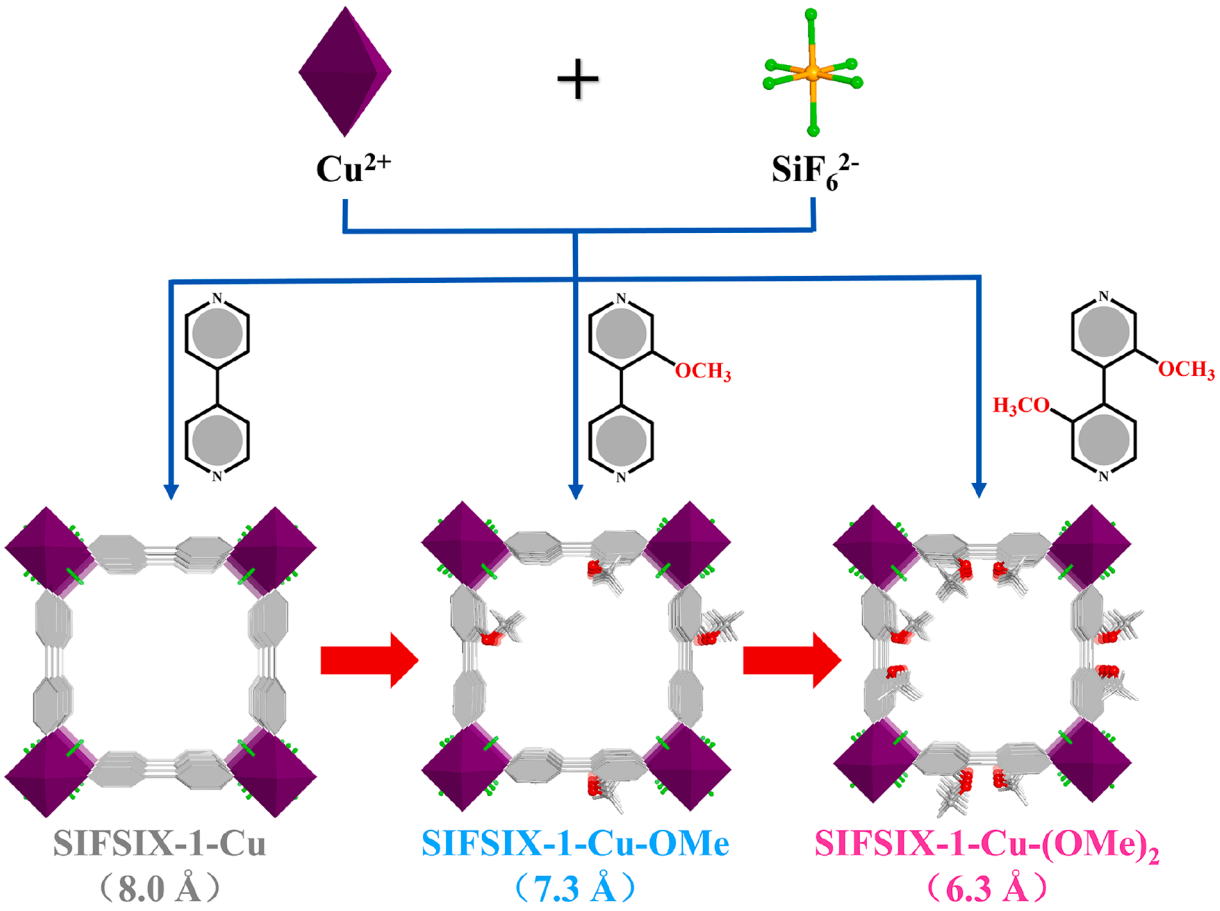

Fig. 1. Structural description of **SIFSIX-1-Cu**, **SIFSIX-1-Cu-OMe** and **SIFSIX-1-Cu-(OMe)$_2$**. Colour code: Cu (purple), Si (orange), F (green), C (grey), N (blue), O (red) and H (white).

feasible. In view of the fact that C_2H_2 has more π-electrons and smaller molecule size, it is observed that most reported MOFs exhibit a stronger affinity towards C_2H_2 compared with C_2H_4, which can realize the efficeint separation of C_2H_2/C_2H_4. Considering the easy availability, C_2H_2-selective MOFs may be used as the prototype materials for pore engineering. However, such examples are rarely reported, because it is extremely difficult to achieve preferential adsorption of C_2H_6 over C_2H_4 while maintain high C_2H_2/C_2H_4 selectivity [29].

The anion-pillared fluorinated hybrid materials, which demonstrate specific recognition of C_2H_2 due to the strong interactions between the C_2H_2 and electronegative F atoms, exhibit benchmark separation capability for C_2H_2/C_2H_4 [30–34]. More importantly, the pore dimension and environment can be fine-tuned by pore engineering strategies [35–40]. Therefore, they are a kind of promising adsorbents whose pore structures can be tailored to preferentially capture C_2H_2 and C_2H_6. For example, the typical SIFSIX material, **SIFSIX-1-Cu**, not only can be easily synthesized from inexpensive feedstocks with a stable framework, but also shows exceptional C_2H_2 adsorption capacity as well as high C_2H_2/C_2H_4 selectivity. As we know, C_2H_6 has higher polarizability and more hydrogen atoms compared with C_2H_4 (44.7×10^{-25} vs 42.52×10^{-25} cm^3). Therefore, by enlarging the non-polar/inert pore surfaces or introducing multiple O/N binding sites on the suitable pore walls, more supramolecular interactions (C-H…π interactions or C-H…O/N interactions) can be formed between C_2H_6 and the framework, which enables preferential adsorption of C_2H_6 over C_2H_4 [41–45].

In this work, we report an example of stepwise customizing pore environments on the C_2H_2-selective materials to enable one-step purification of C_2H_4 from ternary mixture of $C_2H_2/C_2H_4/C_2H_6$. Stepwise introduction of one and two methoxyl (–OCH_3) groups into **SIFSIX-1-Cu**, results in decreasing pore size from 8.0 Å (**SIFSIX-1-Cu**) to 7.3 Å (**SIFSIX-1-Cu-OMe**) and then to 6.3 Å (**SIFSIX-1-Cu-(OMe)$_2$**). At 298 K and 0.1 bar, **SIFSIX-1-Cu** shows almost equal adsorption amount of C_2H_6 and C_2H_4, and the adsorption difference as well as the C_2H_6/C_2H_4 uptake ratio are only 1.7 cm^3/g and 117 % respectively. With the progressive augmentation of the number of modified –OCH_3 groups, these values gradually enhance to 3.1 cm^3/g and 130 % (**SIFSIX-1-Cu-OMe**), and reach the maximum in **SIFSIX-1-Cu-(OMe)$_2$** (8.2 cm^3/g and 171 %) at 298 K and 0.1 bar. Furthermore, the difference of isosteric adsorption heats (ΔQ_{st}) for C_2H_4 and C_2H_6 decreases from 5.0 kJ/mol (**SIFSIX-1-Cu**) to 0.2 kJ/mol (**SIFSIX-1-Cu-OMe**). As anticipated, **SIFSIX-1-Cu-(OMe)$_2$** exhibits reverse-order adsorption of C_2H_6 and C_2H_4, accompanied with the ΔQ_{st} difference value of -2.2 kJ/mol. More importantly, the C_2H_6/C_2H_4 (10/90) IAST selectivity is significantly improve from 1.18 (**SIFSIX-1-Cu**) to 1.27 (**SIFSIX-1-Cu-OMe**), and finally reaches a remarkably high value of 1.79 (**SIFSIX-1-Cu-(OMe)$_2$**). Dynamic breakthrough experiments demonstrate that **SIFSIX-1-Cu** and **SIFSIX-1-Cu-OMe** cannot realize the one-step C_2H_4 purification from ternary $C_2H_2/C_2H_4/C_2H_6$ (1/90/9) mixture due to the simultaneous outflow of C_2H_4 and C_2H_6. In contrast, under the same condition, **SIFSIX-1-Cu-(OMe)$_2$** exhibits obviously C_2H_6/C_2H_4 separation with breakthrough time interval up to 14 min/g, and enables one-step access to polymer-grade C_2H_4 (≥99.95 %) from 1/90/9 $C_2H_2/C_2H_4/C_2H_6$ with a high productivity of 6.82 L/kg. Computational simulations reveal that the optimal pore surface of **SIFSIX-1-Cu-(OMe)$_2$** with suitable pore size and multiple O binding sites exhibits preferential affinity for capturing C_2H_2 and C_2H_6, thereby enabling the one-step purification of C_2H_4 from $C_2H_2/C_2H_4/C_2H_6$ mixture.

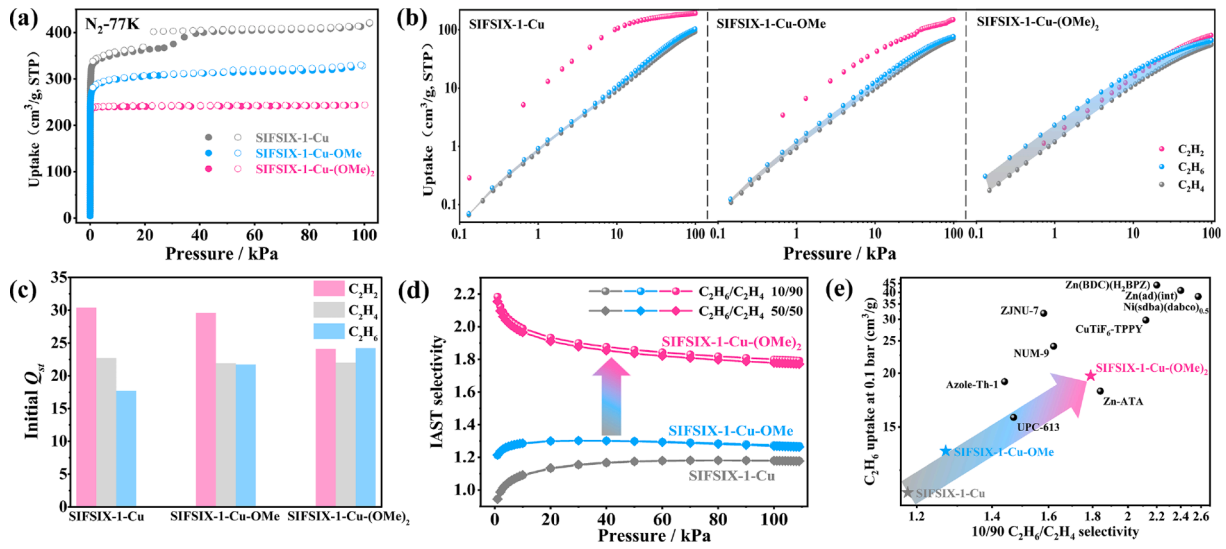

Fig. 2. Comparison of adsorption properties of **SIFSIX-1-Cu**, **SIFSIX-1-Cu-OMe** and **SIFSIX-1-Cu-(OMe)$_2$**. (a) N_2 adsorption isotherms at 77 K. (b) Gas adsorption isotherms of C_2H_2, C_2H_4 and C_2H_6 at 298 K. (c) Initial isosteric heat of adsorption (Q_{st}) of C_2H_2, C_2H_4, and C_2H_6. (d) The IAST selectivity of C_2H_6/C_2H_4 at 298 K. (e) Comparison of C_2H_6 uptake at 0.1 bar and 10/90 C_2H_6/C_2H_4 selectivity of these three materials and the reported famous MOFs that can realize one-step C_2H_4 purification from ternary C_2-gases mixture.

2. Experimental section

2.1. Materials synthesis

SIFSIX-1-Cu was prepared according to the reported literature [46]. An aqueous solution (3 mL) of $Cu(BF_4)_2{\cdot}6H_2O$ (1.00 mmol) and $(NH_4)_2{\cdot}SiF_6$ (1.00 mmol) was diffused to an ethylene glycol (3 mL) of 4,4′-bipyridine (2.00 mmol) in a rigid glass tube. After three days, purple single crystals were obtained.

An aqueous solution (3 mL) of $CuSiF_6$ (30 mg) was slowly diffused to a methanol (3 mL) of 3-methoxy-4,4′-bipyridine (20 mg) in a rigid glass tube. After a week, purple single crystals **SIFSIX-1-Cu-OMe** were obtained. Anal. Calcd (%) for the sample after adsorption: C, 36.59; H, 5.02; N, 7.76. Found: C, 37.12; H, 4.84; N, 7.75. It is observed that ca. eight water molecules are absorbed in activated **SIFSIX-1-Cu-OMe**.

An aqueous solution (3 mL) of $CuSiF_6$ (30 mg) was slowly diffused to a methanol (3 mL) of 3,3′-dimethoxy-4,4′-bipyridine (20 mg) in a rigid glass tube. After a week, purple single crystals **SIFSIX-1-Cu-(OMe)$_2$** were obtained. Anal. Calcd (%) for the sample after adsorption: C, 36.85; H, 5.15; N, 7.16. Found: C, 37.30; H, 4.92; N, 7.16. It is observed that ca. eight water molecules are absorbed in activated **SIFSIX-1-Cu-(OMe)$_2$**.

2.2. Gas sorption measurement

The gas adsorption isotherms were tested on a Micromeritics 3Flex surface area analyzer. Fresh samples were exchanged with ultra-dry methanol with a week. After that, **SIFSIX-1-Cu** was evacuated at room temperature for 24 h, **SIFSIX-1-Cu-OMe** and **SIFSIX-1-Cu-(OMe)$_2$** were activated by heating at 353 K for 10 h to completely remove the solvent molecules. The sorption curves of N_2 at 77 K, C_2H_2, C_2H_4 and C_2H_6 at different temperatures were collected in a liquid nitrogen bath, an ice-water bath and a water bath, respectively.

2.3. Breakthrough experiments

Dynamic breakthrough experiments were conducted on a homemade device. The activated sample, **SIFSIX-1-Cu** (1.2863 g), **SIFSIX-1-Cu-OMe** (0.8306 g) and **SIFSIX-1-Cu-(OMe)$_2$** (1.6648 g), were loaded into a stainless-steel column (4 mm internal diameter × 500 mm length), and a certain amount of silica wool was used to seal the end of the column. The columns were then activated with He gas (20 mL/min) at 60 ℃ (**SIFSIX-1-Cu**) or 80 ℃ (**SIFSIX-1-Cu-OMe** and **SIFSIX-1-Cu-(OMe)$_2$**) for 10 h. The gas mixture (C_2H_2/C_2H_4 = 1/99, *v/v*; C_2H_6/C_2H_4 = 10/90, *v/v*; $C_2H_2/C_2H_4/C_2H_6$ = 1/90/9, *v/v/v*) then flowed through the packed bed at a certain flow rate of 1 mL/min. The outlet gas was monitored by gas chromatography with a thermal conductivity detector (TCD). After a breakthrough experiment, samples were regenerated by purging with He gas (20 mL/min) at 60 ℃ (**SIFSIX-1-Cu**) or 80 ℃ (**SIFSIX-1-Cu-OMe** and **SIFSIX-1-Cu-(OMe)$_2$**) for 2 h.

3. Results and discussion

3.1. Structure analysis

SIFSIX-1-Cu, **SIFSIX-1-Cu-OMe** and **SIFSIX-1-Cu-(OMe)$_2$** were synthesized through diffusion using the corresponding pyridine ligand and $CuSiF_6$. Single-crystal X-ray diffraction (SCXRD) reveal that **SIFSIX-1-Cu-OMe** and **SIFSIX-1-Cu-(OMe)$_2$** possess isostructural structure with **SIFSIX-1-Cu**, which are in *P4/mmm* space group (Table S2). These compounds exhibit a two-dimensional (2D) *sql* layer constructed by the pyridine ligands and metal atoms, which are further connected by inorganic SiF_6^{2-} anionic to construct a 3D *pcu* pillar-layer framework with one-dimensional channels. As illustrated in Fig. 1, with the increase of the number of –OCH_3 groups, the pore size gradually decreases from 8.0 Å for **SIFSIX-1-Cu** to 7.3 Å for **SIFSIX-1-Cu-OMe** and further down to 6.3 Å for **SIFSIX-1-Cu-(OMe)$_2$**. More importantly, the incorporation of –OCH_3 groups within the pore walls of both **SIFSIX-1-Cu-OMe** and **SIFSIX-1-Cu-(OMe)$_2$** leads to a gradual increase in the number of O accessible sites compared to that of **SIFSIX-1-Cu**. Therefore, a suitable pore size combined with the presence of multiple supramolecular binding sites in the pore channel is expected to customize the pore environments that are more conducive to capturing C_2H_2 and C_2H_6, thereby achieving the one-step purification of C_2H_4 from a ternary mixture of $C_2H_2/C_2H_4/C_2H_6$.

3.2. Gas sorption measurements

The powder X-ray diffraction (PXRD) experiments indicate good phase purity of **SIFSIX-1-Cu**, **SIFSIX-1-Cu-OMe** and **SIFSIX-1-Cu-(OMe)$_2$** (Fig. S3). As shown in Figs. S4 and S5, the thermogravimetric analysis (TGA) and variable temperature (VT)-PXRD tests reveal that **SIFSIX-1-Cu-OMe** and **SIFSIX-1-Cu-(OMe)$_2$** exhibit exceptional

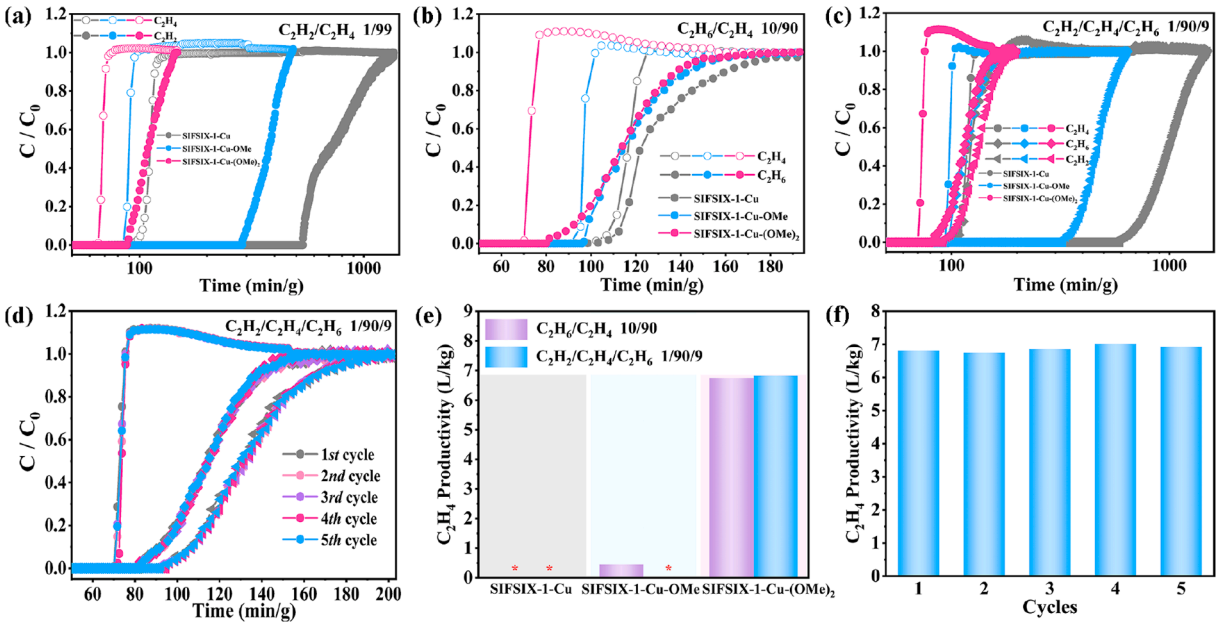

Fig. 3. Dynamic breakthrough experiments of **SIFSIX-1-Cu**, **SIFSIX-1-Cu-OMe** and **SIFSIX-1-Cu-(OMe)$_2$** at 298 K for (a) 1/99 C_2H_2/C_2H_4; (b) 10/90 C_2H_6/C_2H_4; (c) 1/90/9 $C_2H_2/C_2H_4/C_2H_6$. (d) Five cycles breakthrough experiments of **SIFSIX-1-Cu-(OMe)$_2$** for 1/90/9 $C_2H_2/C_2H_4/C_2H_6$. (e) Compare the C_2H_4 productivity calculated by binary C_2H_6/C_2H_4 (10/90) and ternary $C_2H_2/C_2H_4/C_2H_6$ (1/90/9) breakthrough experiments of the three materials. * represent that the material cannot achieve the one-step C_2H_4 purification. (f) The C_2H_4 productivity of multiple ternary $C_2H_2/C_2H_4/C_2H_6$ (1/90/9) cycles breakthrough experiments on **SIFSIX-1-Cu-(OMe)$_2$**.

thermal stability and can maintain their original structure at least to 453 K in air. Additionally, they demonstrate remarkable chemical stability (Fig. S6). Subsequently, the pore structure is examined by 77 K N_2 adsorption test. The experimental results demonstrate that the adsorption isotherms of three materials all exhibit the type-I curve, indicating their microporous characteristics (Fig. 2a). It is noteworthy that the corresponding Brunauer-Emmett-Teller (BET) surface area and pore volume gradually decrease from **SIFSIX-1-Cu** (1332 m^2/g, 0.65 cm^3/g) to **SIFSIX-1-Cu-OMe** (1130 m^2/g, 0.57 cm^3/g), and reach the value in **SIFSIX-1-Cu-(OMe)$_2$** (895 m^2/g, 0.38 cm^3/g). The pore size distribution obtained by density functional theory (DFT) is consistent with trend from the crystal structures (Fig. S7).

Single-component gas adsorption experiments of C_2H_2, C_2H_4 and C_2H_6 were conducted on **SIFSIX-1-Cu**, **SIFSIX-1-Cu-OMe** and **SIFSIX-1-Cu-(OMe)$_2$**. As shown in Fig. 2b, the maximum adsorption uptake of C_2H_2 is higher than that of C_2H_4 and C_2H_6 in all materials. Noteworthy, the difference of adsorption capacity for C_2H_6 and C_2H_4 is significantly increase from **SIFSIX-1-Cu** to **SIFSIX-1-Cu-OMe** and **SIFSIX-1-Cu-(OMe)$_2$**. At 298 K and 0.1 bar, the adsorption uptake of C_2H_6 (11.5 cm^3/g) is almost equal with C_2H_4 (9.8 cm^3/g) in **SIFSIX-1-Cu**, and the adsorption difference of C_2H_6 and C_2H_4 as well as the C_2H_6/C_2H_4 uptake ratio are only 1.7 cm^3/g and 117 %. In contrast, **SIFSIX-1-Cu-OMe** shows relatively higher C_2H_6 adsorption (13.5 cm^3/g) than C_2H_4 (10.4 cm^3/g), and the corresponding adsorption difference (3.1 cm^3/g) and uptake ratio of C_2H_6/C_2H_4 (130 %) are slightly larger than those of **SIFSIX-1-Cu**. As anticipated, **SIFSIX-1-Cu-(OMe)$_2$** exhibits extremely high adsorption amount of C_2H_6 (19.7 cm^3/g) at 298 K and 0.1 bar, about 1.7 times of **SIFSIX-1-Cu**, but only adsorbs C_2H_4 of 11.5 cm^3/g, resulting in the adsorption difference as high as 8.2 cm^3/g and an amazing C_2H_6/C_2H_4 uptake ratio of 171 % (Fig. S8). Moreover, such significant adsorption difference of C_2H_6 and C_2H_4 in **SIFSIX-1-Cu-(OMe)$_2$** can be maintained at multiple adsorption–desorption cycle experiments (Fig. S9).

Furthermore, the isosteric heats of adsorption (Q_{st}) of C_2H_2, C_2H_4 and C_2H_6 are calculated based on the Virial equation to investigate the interaction between the framework and gas molecules (Figs. S12-S14). As shown in Fig. 2c, the initial Q_{st} of C_2H_2 is larger than that of C_2H_4 in all materials. Noteworthy, in **SIFSIX-1-Cu**, the initial Q_{st} of C_2H_4 (22.7 kJ/mol) is higher than that of C_2H_6 (17.7 kJ/mol), and the difference of isosteric adsorption heats (ΔQ_{st}) is 5.0 kJ/mol. For **SIFSIX-1-Cu-OMe**, although the Q_{st} order is the same as that of **SIFSIX-1-Cu**, in which C_2H_4 (21.9 kJ/mol) is higher than C_2H_6 (21.7 kJ/mol), the ΔQ_{st} is significantly reduced to 0.2 kJ/mol. As anticipated, **SIFSIX-1-Cu-(OMe)$_2$** shows a inversed Q_{st} order of C_2H_6 (24.2 kJ/mol) > C_2H_4 (22.0 kJ/mol) with a high difference (2.2 kJ/mol), indicating that **SIFSIX-1-Cu-(OMe)$_2$** has stronger affinity for C_2H_6 than that for C_2H_4.

Subsequently, we evaluate the separation potential of these materials through IAST selectivity. As expected, all three materials show outstanding IAST selectivity of C_2H_2/C_2H_4 mixture (Fig. S15). Regarding different ratios of C_2H_6/C_2H_4 mixture, the order of C_2H_6/C_2H_4 selectivity is **SIFSIX-1-Cu-(OMe)$_2$** > **SIFSIX-1-Cu-OMe** > **SIFSIX-1-Cu** (Fig. 2d). Especially, the 10/90 C_2H_6/C_2H_4 IAST selectivity is significantly improve from 1.18 (**SIFSIX-1-Cu**) to 1.27 (**SIFSIX-1-Cu-OMe**), and finally reach a remarkably high value of 1.79 (**SIFSIX-1-Cu-(OMe)$_2$**). As indicated in Fig. 2e, both C_2H_6 adsorption capacity at 298 K and 0.1 bar and 10/90 C_2H_6/C_2H_4 IAST selectivity gradually increase from **SIFSIX-1-Cu** (11.5 cm^3/g, 1.18) to **SIFSIX-1-Cu-OMe** (13.5 cm^3/g, 1.27), and reach the maximum in **SIFSIX-1-Cu-(OMe)$_2$** (19.7 cm^3/g, 1.79), which is also higher than some state-of-the-art materials capable of one-step purification of C_2H_4 from three-component C_2 hydrocarbon mixture, such as Azole-Th-1 (19.0 cm^3/g, 1.44) [47] and UPC-613 (15.7 cm^3/g, 1.47) [48], but lower than $CuTiF_6$-TPPY (29.8 cm^3/g, 2.12) [40] and Ni(sdba)(dabco)$_{0.5}$ (38.1 cm^3/g, 2.57) [49]. Based on the above results, by modifying one or two $-OCH_3$ groups into **SIFSIX-1-Cu**, the C_2H_6 adsorption capacity, C_2H_6/C_2H_4 uptake ratio and C_2H_6/C_2H_4 IAST selectivity could be stepwise improved. Therefore, **SIFSIX-1-Cu-(OMe)$_2$** may serve as a promising adsorbent that enables one-step purification of C_2H_4 from ternary $C_2H_2/C_2H_4/C_2H_6$ mixture.

3.3. Dynamic breakthrough experiments

To evaluate the actual separation performance, dynamic breakthrough experiments were performed on **SIFSIX-1-Cu**, **SIFSIX-1-Cu-OMe** and **SIFSIX-1-Cu-(OMe)$_2$**. As anticipated, all three materials can

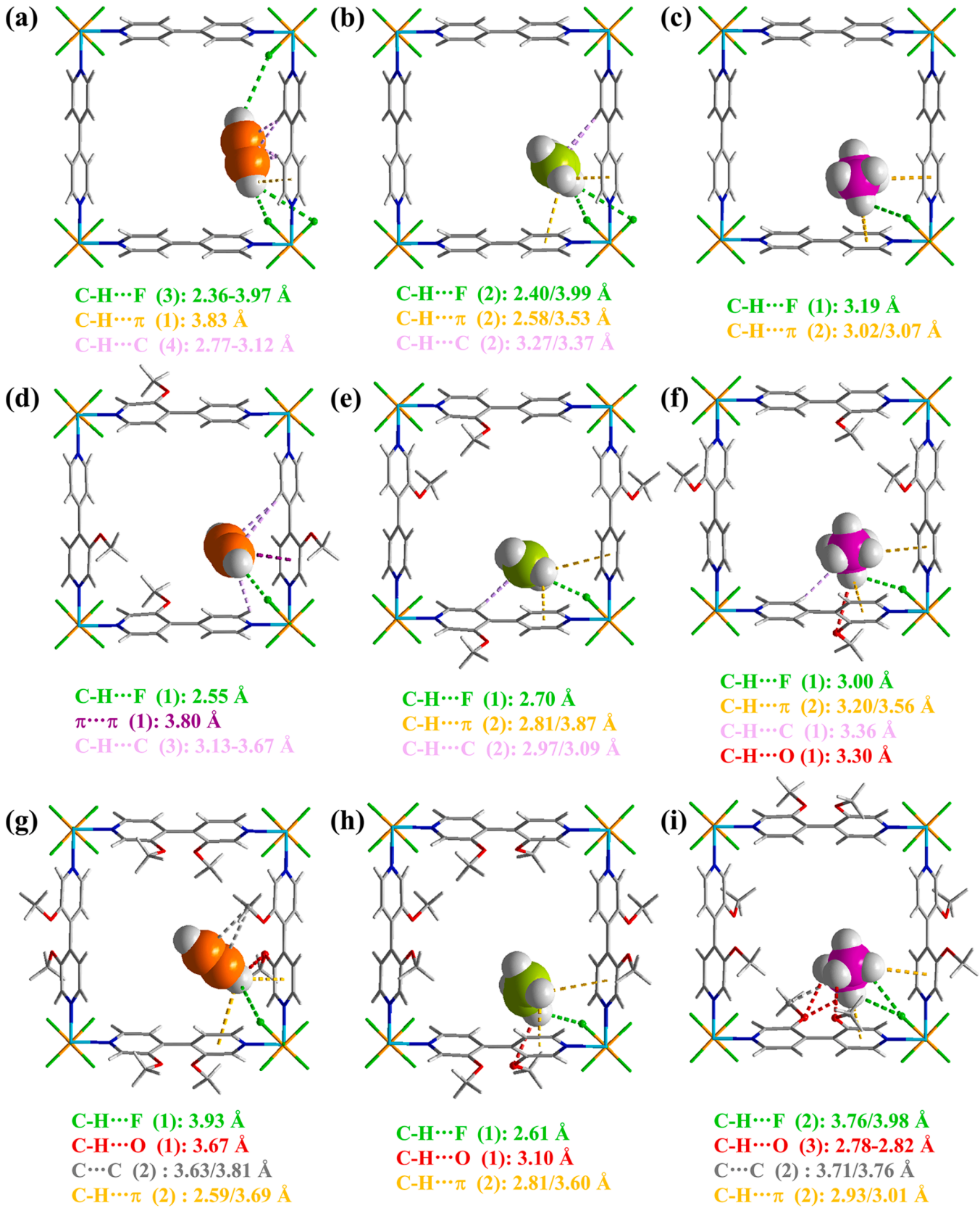

Fig. 4. The optimal gas adsorption sites by GCMC simulations. (a) C_2H_2; (b) C_2H_4; (c) C_2H_6 in **SIFSIX-1-Cu**. (d) C_2H_2; (e) C_2H_4; (f) C_2H_6 in **SIFSIX-1-Cu-OMe**. (g) C_2H_2; (h) C_2H_4; (i) C_2H_6 in **SIFSIX-1-Cu-(OMe)$_2$**.

efficiently separate C_2H_2/C_2H_4 (1/99) mixture. C_2H_4 breaks out first and C_2H_2 is also detected after a considerable time interval, suggesting that the framework has stronger interactions with C_2H_2 than C_2H_4 (Fig. 3a). Furthermore, a binary gas mixture of C_2H_6/C_2H_4 (10/90) was tested. As shown in Fig. 3b, C_2H_4 and C_2H_6 break out almost simultaneously and the purification of C_2H_4 cannot be achieved with **SIFSIX-1-Cu**. Meanwhile, for **SIFSIX-1-Cu-OMe**, C_2H_4 is detected at about 91 min and C_2H_6 flows at 97 min. However, only 0.45 L/kg of polymer-grade C_2H_4 (≥99.95 %) can be obtained. As anticipated, compared with **SIFSIX-1-Cu** and **SIFSIX-1-Cu-OMe**, the breakthrough time interval between C_2H_4 and C_2H_6 is sharply increase to 11 min in **SIFSIX-1-Cu-(OMe)$_2$**, and the polymer-grade C_2H_4 (≥99.95 %) productivity is up to 6.75 L/kg, which is nearly 15 times higher than that of **SIFSIX-1-Cu-OMe** (Fig. 3e). Furthermore, we investigated the separation ability of these three materials in ternary $C_2H_2/C_2H_4/C_2H_6$ (1/90/9) mixture. The experimental results show that C_2H_2 has the longest retention time on the breakthrough column in all materials, while **SIFSIX-1-Cu** and **SIFSIX-1-Cu-OMe** cannot realize one-step C_2H_4 purification from ternary gas mixture due to the simultaneous outflow of C_2H_4 and C_2H_6. In contrast, for **SIFSIX-1-Cu-(OMe)$_2$**, C_2H_4 is detected at 68 min, while C_2H_6 is not detected at outlet until 82 min, and the polymer-grade C_2H_4 (≥99.95 %) productivity is as high as 6.82 L/kg (Fig. 3c and 3e). The C_2H_4 productivity of **SIFSIX-1-Cu-(OMe)$_2$** is superior to some reported materials that can achieve C_2H_4 purification from $C_2H_2/C_2H_4/C_2H_6$ (1/90/9) mixture, such as UiO-66-CF_3 (3.49 L/kg) [50], LIFM-XYY-6 (3.20 L/kg) [28] and HIAM-210 (2.56 L/kg) [51]. Since the stability of material is crucial in practical industrial application, we further performed multiple cycle breakthrough experiments on **SIFSIX-1-Cu-(OMe)$_2$**. As indicated in Fig. 3d and 3f, the separation performance and the polymer-grade C_2H_4 (≥99.95 %) productivity from $C_2H_2/C_2H_4/C_2H_6$ (1/90/9) remain basically unchanged after five cycles, which shows the excellent recyclability of **SIFSIX-1-Cu-(OMe)$_2$**. In summary, compared to **SIFSIX-1-Cu** and **SIFSIX-1-Cu-OMe**, **SIFSIX-1-Cu-(OMe)$_2$** shows exceptional separation performance and ultra-high stability through the pore environment engineering, making it a potential material for purifying C_2H_4 from ternary C_2-gases mixtures in one step.

3.4. Theoretical calculations

The optimal adsorption sites of C_2H_2, C_2H_4 and C_2H_6 on the three materials were determined by grand canonical monte carlo (GCMC) simulations, and the binding energies were evaluated based on dispersion-corrected density functional theory (DFT) calculations [52,53]. As shown in Fig. 4a-4c, in **SIFSIX-1-Cu**, we can clearly find that both C_2H_2 and C_2H_4 can form multiple C-H…F interactions, C-H…π interactions and C-H…C interactions with the framework, whereas only one C-H…F interaction and two C-H…π interactions can be noted for C_2H_6, The calculated static binding energies of three gases follow the tendency of C_2H_2 (−69.98 kJ/mol) > C_2H_4 (−51.36 kJ/mol) > C_2H_6 (−35.71 kJ/mol). After modification of the ligand with one –OCH_3 group, for C_2H_6, in addition to one C-H…F interaction, two C-H…π interactions and one C-H…C interaction with the pore surface, it can also form an additional C-H…O interaction with the –OCH_3 group compared with C_2H_2 and C_2H_4 (Fig. 4d-4f). The binding energy of C_2H_6 increases to −45.56 kJ/mol, but remains lower than that of C_2H_2 (−61.02 kJ/mol) and C_2H_4 (−49.28 kJ/mol). When the number of –OCH_3 group is increased to two, as anticipated, C_2H_6 not only forms two C-H…F interactions and two C-H…π interactions with the skeleton, but also forms extra three C-H…O interactions and two C…C interactions with the inserted –OCH_3 groups. It can be observed that increasing the number of –OCH_3 groups in the pore wall leads to more supramolecular interactions, especially C-H…O interactions, between C_2H_6 and the pore surface. In contrast, only one C-H…O interaction is produced between the introduced –OCH_3 groups and C_2H_4 (Fig. 4g-4i). Therefore, in **SIFSIX-1-Cu-(OMe)$_2$**, the insertion of –OCH_3 group results in more supramolecular interactions between C_2H_6 and the framework than C_2H_4, with the binding energy of C_2H_6 (−45.52 kJ/mol) > C_2H_2 (−43.27 kJ/mol) > C_2H_4 (−41.62 kJ/mol). The above results demonstrate that an optimal pore environment is tailored for **SIFSIX-1-Cu-(OMe)$_2$** through the synergistic effect of reduction in pore size and increase in O binding sites, which endow enhancing affinity towards C_2H_6 compared with C_2H_4. Therefore, **SIFSIX-1-Cu-(OMe)$_2$** realizes efficient one-step purification of C_2H_4 from a ternary $C_2H_2/C_2H_4/C_2H_6$ mixture.

4. Conclusions

In conclusion, we have successfully customized the pore environments of C_2H_2-selective materials through ligand functionalization to achieve one-step purification of C_2H_4 from a ternary $C_2H_2/C_2H_4/C_2H_6$ mixture. The O binding sites are continuously increased by stepwise modifying one and two –OCH_3 groups into C_2H_2-selective **SIFSIX-1-Cu**, resulting in significant improvements in the adsorption capacity of C_2H_6, the C_2H_6/C_2H_4 uptake ratio, as well as the C_2H_6/C_2H_4 IAST selectivity. Moreover, in comparison to **SIFSIX-1-Cu** and **SIFSIX-1-Cu-OMe**, which are incapable of achieving the purification of C_2H_4 from ternary C_2-hydrocarbons, **SIFSIX-1-Cu-(OMe)$_2$** can realize the one-step acquisition of polymer-grade C_2H_4 from a mixture of $C_2H_2/C_2H_4/C_2H_6$ (1/90/9) with significantly high productivity of 6.82 L/kg. Theoretical calculations further demonstrate that the pore surface of **SIFSIX-1-Cu-(OMe)$_2$** possesses multiple binding sites for C_2H_6, in contrast to C_2H_4. Consequently, **SIFSIX-1-Cu-(OMe)$_2$** exhibits good performance in purifying C_2H_4 from a mixture of $C_2H_2/C_2H_4/C_2H_6$. The present work represents a significant advancement in stepwise customizing pore environments on a C_2H_2-selective material, aiming to achieve one-step C_2H_4 purification from ternary C_2 hydrocarbon mixtures. This work provides novel insights into the development of C_2H_2/C_2H_6-selective MOFs for one-step acquisition of C_2H_4 from C_2-hydrocarbons.

CRediT authorship contribution statement

Shuixiang Zou: Conceptualization, Methodology, Software, Writing – original draft. **Cheng Chen:** Supervision, Writing – review & editing. **Zhengyi Di:** Supervision, Writing – review & editing. **Yuanzheng Liu:** Supervision, Writing – review & editing. **Hengbo Li:** Supervision, Writing – review & editing. **Yashuang Li:** Supervision, Writing – review & editing. **Rajamani Krishna:** Software, Supervision, Writing – review & editing. **Daqiang Yuan:** Software, Supervision, Writing – review & editing. **Mingyan Wu:** Resources, Funding acquisition, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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