

## RESEARCH ARTICLE

 View Article Online  
View Journal | View Issue

 Cite this: *Inorg. Chem. Front.*, 2023, **10**, 824

# Optimizing the pore space of a robust nickel–organic framework for efficient C<sub>2</sub>H<sub>2</sub>/C<sub>2</sub>H<sub>4</sub> separation†

 Xiuping Liu,<sup>‡a</sup> Yue Li,<sup>‡b</sup> Chunlian Hao,<sup>id b</sup> Weidong Fan,<sup>id \*b</sup> Wei Liu,<sup>a</sup> Jingquan Liu<sup>id a</sup> and Yijun Wang<sup>\*a</sup>

The separation of acetylene (C<sub>2</sub>H<sub>2</sub>) from ethylene (C<sub>2</sub>H<sub>4</sub>) is an important but challenging process in industry because of their similar physical properties and kinetic molecular sizes. Here, we presented a robust nickel–organic framework (UPC-22) with intrinsic hydrogen bonds and one-dimensional functionalized channels, offering efficient purification of C<sub>2</sub>H<sub>4</sub>. UPC-22 exhibits excellent chemical stability at various pH values from 1 to 11 and a high C<sub>2</sub>H<sub>2</sub>/C<sub>2</sub>H<sub>4</sub> selectivity of 4.8 at 273 K. Actual breakthrough experiments further demonstrate that UPC-22 is a promising potential adsorbent for C<sub>2</sub>H<sub>2</sub>/C<sub>2</sub>H<sub>4</sub> separation with a C<sub>2</sub>H<sub>4</sub> productivity of 1.07 mmol g<sup>-1</sup>. Grand canonical Monte Carlo simulation and density functional theory indicate that the unsaturated Ni<sup>II</sup> sites and uncoordinated carboxylate groups with an additional contribution from π···π packing between aromatic rings provide stronger multipoint interactions with C<sub>2</sub>H<sub>2</sub> over C<sub>2</sub>H<sub>4</sub>. This study offers practical guidance to fabricate durable materials for C<sub>2</sub>H<sub>2</sub>/C<sub>2</sub>H<sub>4</sub> separation in real industrial scenarios.

 Received 12th November 2022,  
Accepted 12th December 2022

DOI: 10.1039/d2qi02398a

[rsc.li/frontiers-inorganic](https://rsc.li/frontiers-inorganic)

## Introduction

Ethylene (C<sub>2</sub>H<sub>4</sub>), as one of the most important chemical feedstocks, is widely used to manufacture various chemicals and polymers. More than 170 million tons of C<sub>2</sub>H<sub>4</sub> are produced annually through petroleum cracking and ethane dehydrogenation.<sup>1</sup> During the C<sub>2</sub>H<sub>4</sub> production, trace amounts of acetylene (C<sub>2</sub>H<sub>2</sub>, about 1%) are always mixed with the resultant C<sub>2</sub>H<sub>4</sub>-containing gases, which can cause catalyst poisoning and hinder further utilization of C<sub>2</sub>H<sub>4</sub> in the chemical and polymer industries.<sup>2</sup> Therefore, the purification of C<sub>2</sub>H<sub>4</sub> is considered to be one of the most critical industrial processes.<sup>3</sup> However, the similar physical properties and molecular sizes of C<sub>2</sub>H<sub>2</sub> and C<sub>2</sub>H<sub>4</sub> also make their separation quite challenging. Currently, industrial technologies for C<sub>2</sub>H<sub>2</sub>/C<sub>2</sub>H<sub>4</sub> separation, including partial hydrogenation and solvent extraction, are very costly and energy-intensive.<sup>4–6</sup> In contrast, adsorptive

separation based on porous materials has attracted extensive attention in academia and industry because of its high efficiency and low-energy consumption.<sup>7–11</sup>

Metal–organic frameworks (MOFs) exhibit excellent application prospects in adsorption and separation because of their designable structures and tunable pore sizes/functionalities.<sup>12–18</sup> Recently, MOFs have attracted increasing attention for their potential applications in C<sub>2</sub> hydrocarbon separation (C<sub>2</sub>H<sub>2</sub>/C<sub>2</sub>H<sub>4</sub>, C<sub>2</sub>H<sub>4</sub>/C<sub>2</sub>H<sub>6</sub>, and C<sub>2</sub>H<sub>2</sub>/C<sub>2</sub>H<sub>6</sub>, *etc.*).<sup>19–25</sup> To improve the separation performance of MOFs, several strategies have been proposed, including pore size customization, pore surface functionalization, open metal sites (OMSs), *etc.* Since the first porous MOF (M'MOF) for C<sub>2</sub>H<sub>2</sub>/C<sub>2</sub>H<sub>4</sub> separation was reported in 2011, researchers have taken considerable effort to implement some porous MOFs to achieve their efficient separation.<sup>26–29</sup> For example, Li *et al.* achieved high C<sub>2</sub>H<sub>2</sub>/C<sub>2</sub>H<sub>4</sub> selectivity through NbU-8 with ultra-microporous building units and –OH groups, which was attributed to the supramolecular interaction between the framework and C<sub>2</sub>H<sub>2</sub> molecules.<sup>30</sup> The C–H···O/N hydrogen-bonding interaction between MOFs and gas molecules plays a significant role in the selective adsorption of gas molecules.<sup>31</sup> A special Cu-MOF (NbU-1) synthesized by Zhou *et al.* showed one of the highest kinetic separation efficiencies of C<sub>2</sub>H<sub>2</sub>/C<sub>2</sub>H<sub>4</sub> through the cooperation of Cu···C≡C interactions and Lewis-basic sites forming the H–C≡C–H···N (pyridyl) hydrogen bond.<sup>32</sup> Sun *et al.* reported that ZNU-3 with intrinsic hydrogen bonding

<sup>a</sup>School of Materials Science and Engineering, Linyi University, Linyi, Shandong 276000, China. E-mail: wangyijun@lyu.edu.cn

<sup>b</sup>School of Materials Science and Engineering, China University of Petroleum (East China), Qingdao, Shandong, 266580, China. E-mail: wdfan@upc.edu.cn

 †Electronic supplementary information (ESI) available: Simulation details, SEM images, TG curves, IR spectrum, and gas adsorption results. CCDC 2167452. For ESI and crystallographic data in CIF or other electronic format see DOI: <https://doi.org/10.1039/d2qi02398a>

‡These authors contributed equally.

exhibited excellent  $C_2H_2$  separation performance in the presence of  $C_2H_4$ ,  $C_2H_6$ , and  $CO_2$  due to the synergistic hydrogen bonding of carboxylate groups and  $\pi \cdots \pi$  packing interactions.<sup>33</sup> Therefore, an effective method to achieve special recognition for  $C_2H_2$  is to introduction of particular functional sites, such as OMSSs, functional groups, and hydrogen-bonding acceptors.

Based on the above considerations, we constructed a novel nickel-MOF UPC-22 ( $[Ni_3(\mu_3-OH)_2(HATTCA)(H_2O)_4]_n$ ,  $H_3ATTCA = 2\text{-amino-[1,1':3,1'-terphenyl]-4,4',5'-tricarboxylic acid}$ ), featuring multiple types of pores and specific pore space forming stronger host-guest interactions. UPC-22 not only has excellent thermal and chemical stability, but also has two types of optimized functional channels with OMSSs,  $-NH_2$ , and uncoordinated carboxylate groups. Breakthrough experiments show that UPC-22 can efficiently separate  $C_2H_4$  from the  $C_2H_2/C_2H_4$  mixture. Grand canonical Monte Carlo (GCMC) simulation and density functional theory (DFT) reveal that the unsaturated  $Ni^{II}$  sites and hydrogen bonding from carboxylate groups play a significant role in  $C_2H_4$  purification.

## Results and discussion

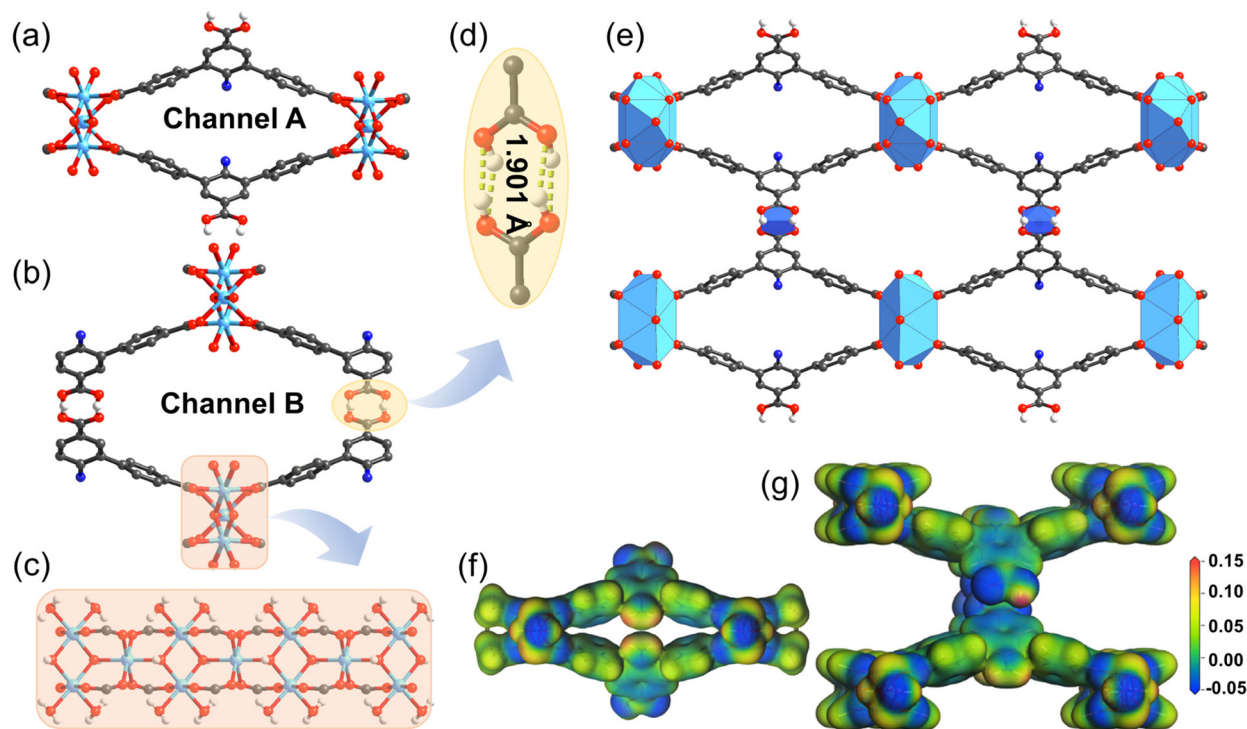
### Crystal structure of UPC-22

Conventional rod-shaped UPC-22 crystallizes in an orthorhombic system with the  $I2b2$  space group (Fig. S1 and Table S1<sup>†</sup>). The  $Ni^{2+}$  ions in the framework adopt an octa-

hedral geometry with oxygen atoms from carboxylate and  $H_2O$ , which are then arranged into 1D metal chains (Fig. 1c). Adjacent chains are connected by ligands into two-dimensional sheets. Only two of the three carboxylate groups of each  $H_3ATTCA$  ligand are coordinated to the nickel ions, and the other are protonated and hydrogen-bonded to the adjacent ligand (Fig. 1d). These hydrogen bond arrays connect the layers into a three-dimensional framework with one-dimensional channels. The length of hydrogen bonds (1.901 Å) is largely shorter than the sum of the van der Waals radii of the H and O atoms (2.6 Å), indicating that a strong hydrogen bonding exists (Fig. 1d). There are two rhombic channels in UPC-22 (Fig. 1e): the smaller channel A (Fig. 1a) with approximate dimensions of  $2.8 \times 16 \text{ \AA}^2$  and the larger channel B (Fig. 1b) with the dimensions of  $6.5 \times 15 \text{ \AA}^2$ . Furthermore, there are many open  $Ni^{2+}$  sites and carboxylate groups, which can be regarded as active sites around the rhombic channels and provide a stronger binding affinity for  $C_2H_2$  than  $C_2H_4$ .

### Stability of UPC-22

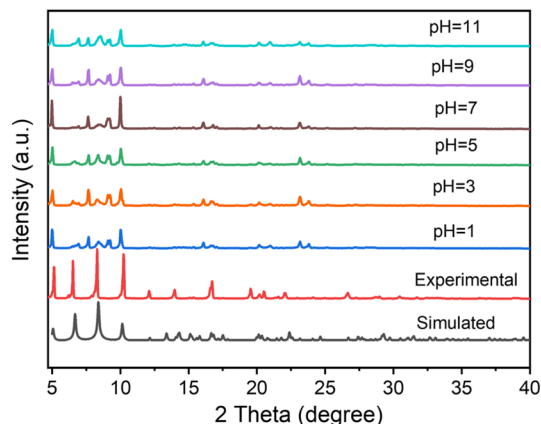
The stability of the adsorbent plays a significant role in practical application. Therefore, we evaluated the thermal and chemical stability of UPC-22. Thermogravimetric analysis (TGA) confirmed the thermal stability of the as-synthesized UPC-22 (Fig. S2<sup>†</sup>). When heated to 150 °C, the loss of guest water molecules was observed. Up to 375 °C, a substantial decline in quality was observed, and the structure began to col-



**Fig. 1** Crystal structure of UPC-22. (a) and (b) The different channels of the framework in UPC-22; (c) the infinite secondary building units (iSBUs) comprised of one-dimensional (1D) nickel(II) chains; (d) view of the connection of the ligand by hydrogen bonds; (e) the three-dimensional framework with one-dimensional channels along the  $b$ -axis; (f) and (g) electrostatic potential (ESP) onto the pore surface of Ni-MOF mapped onto the  $0.05 \text{ e}^- \text{ \AA}^{-3}$  electron density isosurfaces. Ni, O, N and C are represented by green, red, blue, and gray, respectively.

lapse, which was consistent with the result of variable temperature powder X-ray diffraction (PXRD; Fig. S3<sup>†</sup>). The PXRD of bulk crystalline samples was conducted to examine the purity and chemical stability (Fig. 2). The chemical stability was determined by soaking UPC-22 samples in solutions of different pH values. There are no obvious peak changes in the

PXRD patterns; thus, UPC-22 can retain its structural integrity over 24 h in water in different acidic/basic aqueous solutions (pH, 1–11). The high stability of UPC-22 can be attributed to the stable multicore nickel metal chain and the strong Ni–O bond with a length of 2.034–2.093 Å. In a word, thermal and chemical stability in acidic, basic, and neutral aqueous solutions makes UPC-22 an extraordinary adsorbent.



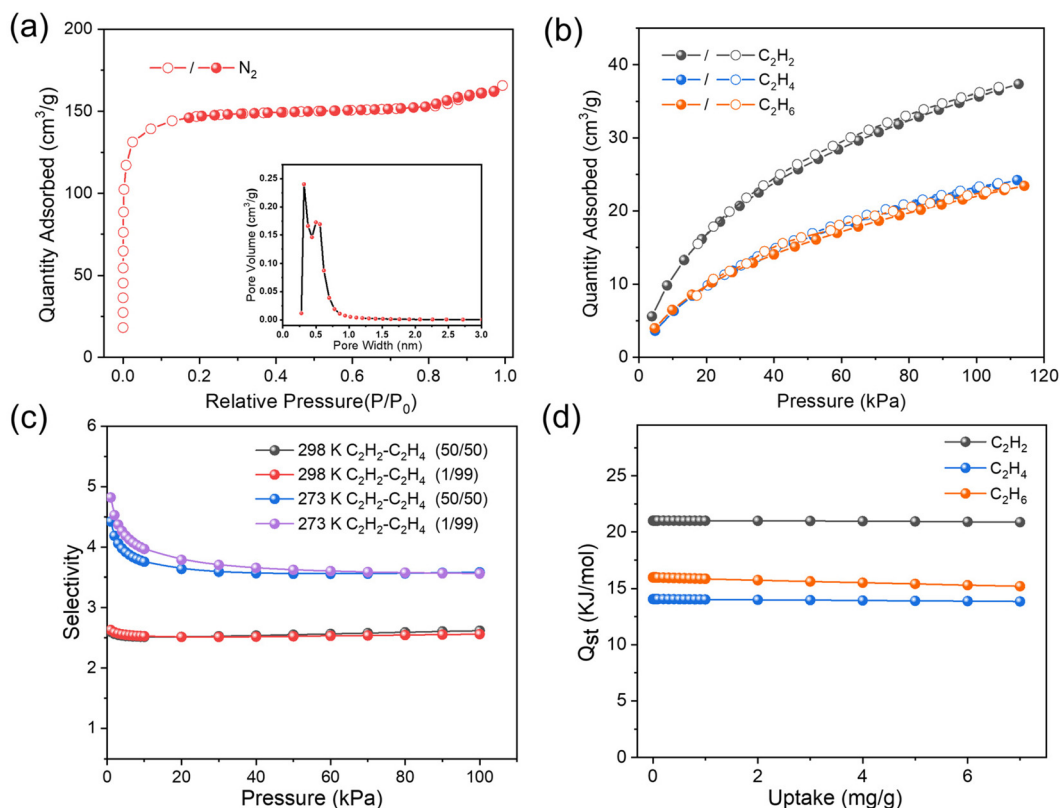
**Fig. 2** PXRD patterns of UPC-22 simulated from X-ray crystal diffraction data, experimental and samples sustained in a solution of a given pH, respectively.

### Permanent porosity

The permanent porosity of activated UPC-22 was measured using the N<sub>2</sub> sorption isotherm at 77 K. As shown in Fig. 3a, UPC-22 with a typical reversible type-I N<sub>2</sub> adsorption isotherm shows a saturated uptake of 165.6 cm<sup>3</sup> g<sup>-1</sup>, revealing the permanent porosity of the microporous material. The corresponding Brunauer–Emmett–Teller (BET) surface area and total pore volume are 486.3 m<sup>2</sup> g<sup>-1</sup> and 0.26 cm<sup>3</sup> g<sup>-1</sup>, respectively. In addition, there are two pore systems of around 3.8 Å and 6.5 Å (Fig. 3a), which is consistent with the single crystal data.

### Adsorption and separation of C<sub>2</sub> hydrocarbons

Considering the two types of rhombic channels decorated with carboxylate O atoms as hydrogen bond acceptors and dense open Ni<sup>II</sup> sites, we further investigated the adsorption performance of UPC-22 for C<sub>2</sub>H<sub>2</sub>, C<sub>2</sub>H<sub>4</sub>, and C<sub>2</sub>H<sub>6</sub>. As shown in Fig. 3b and Fig. S5,<sup>†</sup> the single adsorption isotherms of C<sub>2</sub>H<sub>2</sub>, C<sub>2</sub>H<sub>4</sub>,



**Fig. 3** (a) The N<sub>2</sub> adsorption isotherm in UPC-22 at 77 K and the pore size distribution for UPC-22. (b) The C<sub>2</sub>H<sub>2</sub>, C<sub>2</sub>H<sub>4</sub>, and C<sub>2</sub>H<sub>6</sub> adsorption isotherms in UPC-22 at 298 K. (c) Adsorption selectivities of UPC-22 calculated by the IAST method for the mixtures of C<sub>2</sub>H<sub>2</sub>/C<sub>2</sub>H<sub>4</sub> at 273 K and 298 K. (d) Isothermic heats of adsorption of C<sub>2</sub>H<sub>2</sub>, C<sub>2</sub>H<sub>4</sub>, and C<sub>2</sub>H<sub>6</sub>.

and  $C_2H_6$  at 298 and 273 K were obtained, respectively. The results show that there are significant differences in the adsorption capacity of UPC-22 for  $C_2$  hydrocarbons. Compared with  $C_2H_4$  and  $C_2H_6$ , the type I curve of  $C_2H_2$  has a steeper upward trend, indicating a stronger host-guest interaction between  $C_2H_2$  and the framework. The  $C_2H_2$  uptake of UPC-22 under 1 bar is  $46.8 \text{ cm}^3 \text{ g}^{-1}$  at 273 K and  $37.4 \text{ cm}^3 \text{ g}^{-1}$  at 298 K. For  $C_2H_4$  and  $C_2H_6$ , the maximum adsorption capacities are relatively small, only  $29.2$  and  $28.6 \text{ cm}^3 \text{ g}^{-1}$  at 273 K and  $24.2$  and  $23.4 \text{ cm}^3 \text{ g}^{-1}$  at 298 K, respectively. The large adsorption capacity of  $C_2H_2$  with the uptake ratio of  $C_2H_2/C_2H_4$  is 1.55 at 298 K, which is greater than the reported values for the MOF-74 series (1.21–1.36),<sup>34</sup> ZJNU-115 (1.26),<sup>31</sup> ZJNU-119 (1.33),<sup>35</sup> and ZJNU-7 (1.4).<sup>15</sup> The great differences in the adsorption capacity between  $C_2H_2$ ,  $C_2H_4$ , and  $C_2H_6$  in UPC-22 revealed the large potential for one-step purification of  $C_2H_4$  and  $C_2H_6$ . Then, the adsorption enthalpies ( $Q_{st}$ ) of the three gases were calculated based on the Clausius-Clapeyron equation (Fig. 3d and Fig. S6†). The  $Q_{st}$  values for  $C_2H_2$ ,  $C_2H_4$ , and  $C_2H_6$  at zero loading are 21.1, 15.9, and 14.1  $\text{kJ mol}^{-1}$ , respectively. The  $Q_{st}$  of UPC-22 for  $C_2H_2$  is much higher than that for  $C_2H_4$  over the entire loading range, indicating that UPC-22 has a strong affinity for  $C_2H_2$ . For practical application, the moderate  $Q_{st}$  values of UPC-22 show that it can reduce the energy consumption of adsorbate recovery and adsorbent regeneration.

Inspired by the difference in the adsorption capacity and  $Q_{st}$  for  $C_2H_2$ ,  $C_2H_4$ , and  $C_2H_6$ , the ideal adsorption solution theory (IAST) calculations were used to evaluate the separation performance of  $C_2H_2/C_2H_4$  and  $C_2H_2/C_2H_6$  in UPC-22. As shown in Fig. 3c and Fig. S7,† the  $C_2H_2/C_2H_4$  adsorption selectivity decreased first and then remained constant, while the  $C_2H_2/C_2H_6$  selectivity showed an increasing trend. At the initial pressure, the corresponding IAST selectivity for  $C_2H_2/C_2H_4$  (v/v, 1 : 99) was 2.7 at 298 K and 4.8 at 273 K; the  $C_2H_2/C_2H_4$  selectivity for the molar ratio of 50 : 50 (v/v) at 298 K and 273 K was 2.6 and 4.4, respectively (Fig. 3c). Obviously, under

the ambient conditions, the  $C_2H_2/C_2H_4$  selectivity of UPC-22 is higher than that of most reported promising MOFs, such as MgMOF-74 (2.18),<sup>36</sup> FeMOF-74 (2.08),<sup>37</sup> BSF-1 (2.3),<sup>38</sup> NUM-9a (1.63),<sup>4</sup> NOTT-300 (2.17),<sup>39</sup> and NUM-12a (1.4),<sup>40</sup> but lower than that of some leading MOFs, such as SNNU-40 (4.5)<sup>41</sup> and ZJU-198 (7.2).<sup>42</sup> Furthermore, the  $C_2H_2/C_2H_6$  selectivity is 2.6 and 2.4 at 298 K, corresponding to the ratio of 50 : 50 (v/v) and 1 : 99 (v/v), respectively (Fig. S7†). The above results indicate that UPC-22 is a potential  $C_2H_2$ -selective material to purify  $C_2H_4$  and  $C_2H_6$ .

Encouraged by the above results, we further tested the actual separation performance of  $C_2H_2/C_2H_4$  and  $C_2H_2/C_2H_6$  under ambient conditions. The experimental breakthrough studies of  $C_2H_2/C_2H_4$  (50 : 50, v/v) and  $C_2H_2/C_2H_6$  (50 : 50, v/v) mixtures were performed using the fully degassed UPC-22 samples under a total flow of  $3 \text{ mL min}^{-1}$ . The breakthrough curves of the  $C_2H_2/C_2H_4$  and  $C_2H_2/C_2H_6$  mixtures are shown in Fig. 4. For  $C_2H_2/C_2H_4$  mixtures, owing to the low  $C_2H_4$  affinity of UPC-22, the breakthrough of  $C_2H_4$  occurred in the early stage, while  $C_2H_2$  was detected after about  $8 \text{ min g}^{-1}$  and the productivity was  $1.07 \text{ mmol g}^{-1}$  (Fig. 4a). UPC-22 can purify the  $C_2H_2/C_2H_4$  mixture into high-purity  $C_2H_4$  (99.99%) at 298 K with good cycling stability (Fig. S11†). The productivity of  $C_2H_4$  in the  $C_2H_2/C_2H_4$  mixture is higher than those of some promising MOFs, such as ZJU-HOF-1 ( $0.98 \text{ mmol g}^{-1}$ )<sup>43</sup> and ZnBAIm ( $0.3 \text{ mmol g}^{-1}$ ).<sup>44</sup> In addition, the breakthrough study was conducted with  $C_2H_2/C_2H_6$  under the same conditions (Fig. 4b). The penetration of  $C_2H_6$  was first detected, and the penetration time of  $C_2H_2$  was about  $7 \text{ min g}^{-1}$ .

GCMC and DFT calculations were further carried out to obtain preferential adsorption sites and gain some meaningful insights. First, the adsorption properties of UPC-22 for  $C_2H_2$  and  $C_2H_4$  at 298 K were investigated by GCMC simulations. There are three primary adsorption sites between  $C_2H_2$  and  $C_2H_4$  molecules and the channel surface (Fig. 5a, d and S9–S10†). The adsorbed gas molecules are preferentially located around the open  $Ni^{II}$  sites and uncoordinated carboxylate

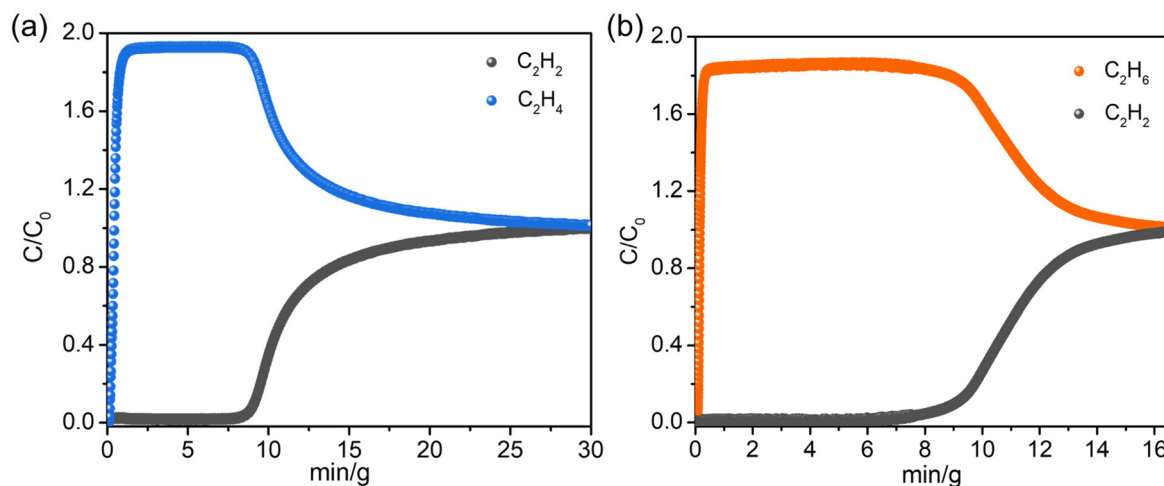
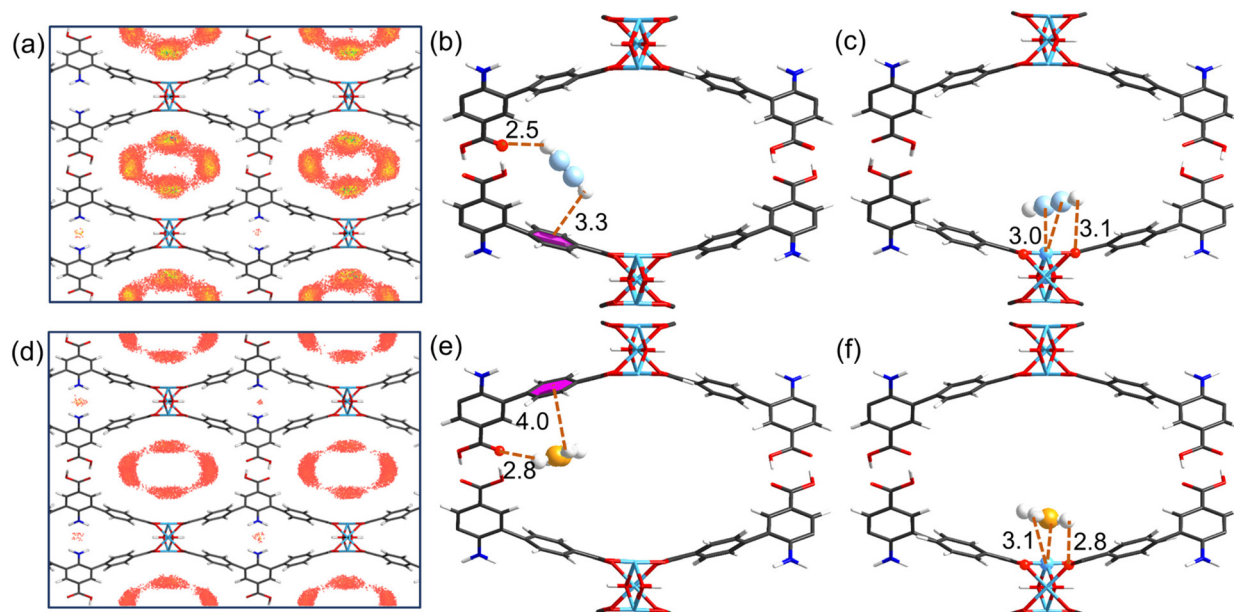


Fig. 4 Column breakthrough curves of UPC-22 for (a)  $C_2H_2/C_2H_4$  and (b)  $C_2H_2/C_2H_6$  mixtures at 298 K and 1 bar.



**Fig. 5** Results of the GCMC simulations showing preferential binding sites between the adsorbed molecule and UPC-22: (a)  $C_2H_2$  and (d)  $C_2H_4$  at 298 K and 30 KPa; binding sites of  $C_2H_2$  and  $C_2H_4$  in UPC-22 determined by DFT simulations (b–c) and (e–f).

groups in the larger channel B, whereas few near the amine groups of ligands in the channel A with a smaller size. DFT calculations were further conducted to obtain the optimized adsorption geometrical structures and the adsorption energy between  $C_2H_2/C_2H_4$  and the framework. The DFT calculated adsorption sites are in good agreement with the results of GCMC simulations (Fig. 5b, c, 5e, f and Fig. S11†). The adsorption energy of  $C_2H_2$  molecules on open  $Ni^{II}$  sites is larger than that of  $C_2H_4$ , with the corresponding values of 49.94 and 48.41  $\text{kJ mol}^{-1}$  (Fig. 5b and c), which are attributed to the synergistic effect of  $C-H\cdots O$  hydrogen bonds and stronger Coulomb attraction between open  $Ni^{II}$  sites and  $C\equiv C$  with  $\pi$  electrons. Another adsorption site of  $C_2H_2$  is the non-coordinating carboxylate group and benzene ring with an adsorption energy of 47.78  $\text{kJ mol}^{-1}$ , forming strong and multiple  $O_{-COO}\cdots H-C\equiv C-H\cdots\pi$  hydrogen bonds and van der Waals interactions with close distances of 2.5/3.3 Å (Fig. 5b). In contrast to  $C_2H_2$ , the adsorption energy of  $C_2H_4$  at this site (42.50  $\text{kJ mol}^{-1}$ ) is significantly lower with larger distances between  $C_2H_4$  and the framework (Fig. 5e). Moreover, the results of the electrostatic potential revealed that surface O atoms of non-coordinating carboxylate sites exhibited a strong negative potential, which could attractively interact with H atoms from  $C_2H_2$  and  $C_2H_4$  by forming strong  $C-H\cdots O$  hydrogen bonds (Fig. 1f, g and S12†). Furthermore, the adsorption energies of  $C_2H_2$  and  $C_2H_4$  at the  $-NH_2$  site in channel A are 47.91 and 37.12  $\text{kJ mol}^{-1}$  (Fig. S11†), respectively, indicating that  $-NH_2$  is a strong adsorption site, whereas only a few gas molecules are adsorbed (Fig. S9†) due to the small size of channel A ( $2.8 \times 16 \text{ \AA}^2$ ) hindering the entry of gas molecules. Thus, the synergy between OMSs/carboxylate sites and appropriate rhombic channels with aromatic  $\pi$ -electrons can create a

multi-binding environment to selectively capture  $C_2H_2$  from  $C_2H_4$  and  $C_2H_6$ .

## Conclusions

In conclusion, a novel robust MOF (UPC-22) containing two types of rhombic channels decorated with uncoordinated  $-COOH$  groups,  $-NH_2$  groups, and OMSs was successfully constructed by the hydrothermal method. UPC-22 exhibits a high selectivity toward  $C_2H_2/C_2H_4$  (2.7) under ambient conditions, outperforming most of the promising MOFs. Theoretical calculations reveal that the excellent separation performances are mainly attributed to the aromatic channels with abundant functional groups and OMSs that enable stronger interaction with  $C_2H_2$  molecules than that with  $C_2H_4$ . The high framework stability and dynamic breakthrough experiments demonstrate its application prospects in ethylene purification in the petrochemical industry.

## Experimental and computational section

### Materials and measurements

All materials were used in the commercially available form without further purification. The ligand 2-amino-[1,1:3,1-terphenyl]-4,4,5-tricarboxylic acid ( $H_3ATTCA$ ) was prepared according to previously published procedures.<sup>45</sup> The powder X-ray diffraction (XRD) data were obtained on an X-Pert PRO MPD diffractometer with  $Cu-K\alpha$  radiation. IR spectra were obtained on a Nexus FT-IR spectrometer using KBr pellets in

the frequency range of 4000–400  $\text{cm}^{-1}$ . Elemental analyses (C, H, and N) were performed on an instrument EA 1110 elemental analyzer. Thermo-gravimetric analysis (TGA) experiments were conducted from 40 to 900  $^{\circ}\text{C}$  on a Mettler Toledo TGA instrument with a heating rate of 10  $^{\circ}\text{C min}^{-1}$  under a  $\text{N}_2$  atmosphere. Low-pressure ( $<800$  torrs)  $\text{N}_2$ ,  $\text{C}_2\text{H}_2$ ,  $\text{C}_2\text{H}_4$ , and  $\text{C}_2\text{H}_6$  adsorption isotherms were obtained using a Micromeritics ASAP 2020 surface area and pore size analyzer. The Brunauer–Emmett–Teller (BET) surface area was calculated from  $\text{N}_2$  adsorption isotherms at 77 K. Pore size distribution data were also obtained from the  $\text{N}_2$  adsorption isotherms at 77 K based on a non-local density functional theory (NLDFT) model in the Micromeritics ASAP 2020 software package (assuming a slit pore geometry). The breakthrough experiments were performed on dynamic gas breakthrough equipment. The experiments were conducted using a stainless-steel column. The weight of UPC-22 packed in the columns was 0.6267 g. The mixed gas of  $\text{C}_2\text{H}_2/\text{C}_2\text{H}_4$  and  $\text{C}_2\text{H}_2/\text{C}_2\text{H}_6$  (50/50, v/v) was then introduced with a flow rate of 3  $\text{mL min}^{-1}$ . More details of breakthrough equipment are shown in the ESI.†

### Synthesis of UPC-22

$\text{H}_3\text{ATCA}$  (7.5 mg, 0.02 mmol) and  $\text{Ni}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$  (30 mg, 0.10 mmol) in 3 mL of DMF (*N,N*-dimethylformamide): $\text{H}_2\text{O}$  (v/v = 1:1) were ultrasonically dissolved in a Pyrex vial. The Pyrex vial was sealed, heated to 100  $^{\circ}\text{C}$  for 3 days, and then cooled to room temperature. The resulting light-green block crystals were washed multiple times with DMF prior to single-crystal X-ray diffraction analysis. Yield: about 72% based on nickel. Elemental analysis calcd (%) for UPC-22: C, 38.24 N, 2.12 H, 3.64; found: C, 38.31 N, 2.19 H, 3.56.

### Computational methods

In this work, the adsorption isotherms of pure  $\text{C}_2\text{H}_2$  and  $\text{C}_2\text{H}_4$  in UPC-22 were obtained using the Grand Canonical Monte Carlo (GCMC) method implemented in the Materials Studio code.<sup>46</sup> The site-site L–J potential was described with the L–J (12, 6) model, and the electrostatic interaction was calculated *via* the Coulomb law. The cutoff of 8 Å was employed for the L–J interactions. Density functional theory (DFT) was performed to provide the atomic partial charges and electronic potential of the UPC-22 framework and calculate the optimized structures and energies of the  $\text{C}_2\text{H}_2$  and  $\text{C}_2\text{H}_4$  interaction with fragmented clusters.<sup>47</sup> Generalized gradient approximation (GGA) with the Perdew–Burke–Ernzerhof (PBE) functional was used to do all-electron spin-unrestricted DFT calculations. DFT-D calculations were performed using the Grimme parameters for the van der Waals correction of gas adsorption. The details of all the calculations are given in the ESI.†

### Conflicts of interest

There are no conflicts to declare.

## Acknowledgements

This work was supported by the National Natural Science Foundation of China (NSFC, Grant No. 22108113, 22201305), the Natural Science Foundation of Shandong Province (ZR2020QB032), the Fundamental Research Funds for the Central Universities (22CX06024A), and the Outstanding Youth Science Fund Projects of Shandong Province (2022HWYQ-070).

## References

- 1 L. Li, R.-B. Lin, R. Krishna, H. Li, S. Xiang, H. Wu, J. Li, W. Zhou and B. Chen, Ethane/ethylene separation in a metal-organic framework with iron-peroxo sites, *Science*, 2018, **362**, 443–446.
- 2 Z. L. Ma, P. X. Liu, Z. Y. Liu, J. J. Wang, L. B. Li and L. Tian, Thermally and chemically stable copper(II) metal-organic framework with high performance for gas adsorption and separation, *Inorg. Chem.*, 2021, **60**, 6550–6558.
- 3 G.-D. Wang, Y.-Z. Li, W.-J. Shi, L. Hou, Y.-Y. Wang and Z. Zhu, One-step  $\text{C}_2\text{H}_4$  purification from ternary  $\text{C}_2\text{H}_6/\text{C}_2\text{H}_4/\text{C}_2\text{H}_2$  mixtures by a robust metal-organic framework with customized pore environment, *Angew. Chem., Int. Ed.*, 2022, e202205427.
- 4 S.-Q. Yang, F.-Z. Sun, P. Liu, L. Li, R. Krishna, Y.-H. Zhang, Q. Li, L. Zhou and T.-L. Hu, Efficient purification of ethylene from  $\text{C}_2$  hydrocarbons with an  $\text{C}_2\text{H}_6/\text{C}_2\text{H}_2$ -selective metal–organic framework, *ACS Appl. Mater. Interfaces*, 2021, **13**, 962–969.
- 5 Q. Hong, W. Wang, S. Chen, K. Chen, M. Liu, H.-X. Zhang and J. Zhang, Host–guest pore space partition in a boron imidazolate framework for ethylene separation, *Chem. Mater.*, 2022, **34**, 307–313.
- 6 C. Gu, J. Liu, J. Hu and D. Wu, Highly selective separations of  $\text{C}_2\text{H}_2/\text{C}_2\text{H}_4$  and  $\text{C}_2\text{H}_2/\text{C}_2\text{H}_6$  in metal–organic frameworks via pore environment design, *Ind. Eng. Chem. Res.*, 2019, **58**, 19946–19957.
- 7 B.-Y. Zhu, T. Zhang, C.-H. Li, J.-W. Cao, Z.-Q. Zhang, W. Qi, G.-Y. Wang, Z.-H. Rong, Y. Wang and K.-J. Chen, A (3,8)-connected metal–organic framework with bending dicarboxylate linkers for  $\text{C}_2\text{H}_2/\text{CO}_2$  separation, *Inorg. Chem.*, 2022, **61**, 4555–4560.
- 8 Y.-L. Peng, T. Pham, P. Li, T. Wang, Y. Chen, K.-J. Chen, K. A. Forrest, B. Space, P. Cheng, M. J. Zaworotko and Z. Zhang, Robust ultramicroporous metal–organic frameworks with benchmark affinity for acetylene, *Angew. Chem., Int. Ed.*, 2018, **57**, 10971–10975.
- 9 K. Su, W. Wang, S. Du, C. Ji and D. Yuan, Efficient ethylene purification by a robust ethane-trapping porous organic cage, *Nat. Commun.*, 2021, **12**, 3703.
- 10 C. Ji, K. Su, W. Wang, J. Chang, E.-S. M. El-Sayed, L. Zhang and D. Yuan, Tunable cage-based three-dimensional covalent organic frameworks, *CCS Chem.*, 2022, **4**, 3095–3105.

- 11 L. Li, C. Ji, W. Wang, F. Wu, Y.-X. Tan and D. Yuan, The effect of pore sizes on  $D_2/H_2$  separation conducted by MOF-74 analogues, *Inorg. Chem. Front.*, 2022, **9**, 1674–1680.
- 12 L.-N. Ma, L. Zhang, W.-F. Zhang, Z.-H. Wang, L. Hou and Y.-Y. Wang, Amide-functionalized In-MOF for effective hydrocarbon separation and  $CO_2$  catalytic fixation, *Inorg. Chem.*, 2022, **61**, 2679–2685.
- 13 X.-W. Gu, J.-X. Wang, E. Wu, H. Wu, W. Zhou, G. Qian, B. Chen and B. Li, Immobilization of lewis basic sites into a stable ethane-selective MOF enabling one-step separation of ethylene from a ternary mixture, *J. Am. Chem. Soc.*, 2022, **144**, 2614–2623.
- 14 G.-D. Wang, Y.-Z. Li, W.-F. Zhang, L. Hou, Y.-Y. Wang and Z. Zhu, Acetylene separation by a Ca-MOF containing accessible sites of open metal centers and organic groups, *ACS Appl. Mater. Interfaces*, 2021, **13**, 58862–58870.
- 15 Z. Jiang, L. Fan, P. Zhou, T. Xu, S. Hu, J. Chen, D.-L. Chen and Y. He, An aromatic-rich cage-based MOF with inorganic chloride ions decorating the pore surface displaying the preferential adsorption of  $C_2H_2$  and  $C_2H_6$  over  $C_2H_4$ , *Inorg. Chem. Front.*, 2021, **8**, 1243–1252.
- 16 S. Zou, Z. Di, H. Li, Y. Liu, Z. Ji, H. Li, C. Chen, M. Wu and M. Hong, Stable fluorinated hybrid microporous material for the efficient separation of  $C_2$ – $C_3$  alkyne/alkene mixtures, *Inorg. Chem.*, 2022, **61**, 7530–7536.
- 17 Z. Jiang, Y. Zou, T. Xu, L. Fan, P. Zhou and Y. He, An aromatic-rich cage-based MOF with inorganic chloride ions decorating the pore surface displaying the preferential adsorption of  $C_2H_2$  and  $C_2H_6$  over  $C_2H_4$ , *Dalton Trans.*, 2020, **49**, 3553–3561.
- 18 Z. Jiang, L. Fan, P. Zhou, T. Xu, J. Chen, S. Hu, D.-L. Chen and Y. He, A hydrostable cage-based MOF with open metal sites and Lewis basic sites immobilized in the pore surface for efficient separation and purification of natural gas and  $C_2H_2$ , *Dalton Trans.*, 2020, **49**, 15672–15681.
- 19 H. Cheng, Q. Wang, M. Ding, Y. Gao, D. Xue and J. Bai, Modifying a partial corn-sql layer-based (3,3,3,3,4,4)-c topological MOF by substitution of  $OH(-)$  with  $Cl(-)$  and its highly selective adsorption of  $C_2$  hydrocarbons over  $CH_4$ , *Dalton Trans.*, 2021, **50**, 4840–4847.
- 20 S. R. Acharya, A. Elias, K. Tan, S. Jensen, R.-B. Lin, B. Chen, M. D. Gross and T. Thonhauser, Identifying the gate-opening mechanism in the flexible metal–organic framework UTSA-300, *Inorg. Chem.*, 2022, **61**, 5025–5032.
- 21 Q.-L. Qian, X.-W. Gu, J. Pei, H.-M. Wen, H. Wu, W. Zhou, B. Li and G. Qian, A novel anion-pillared metal–organic framework for highly efficient separation of acetylene from ethylene and carbon dioxide, *J. Mater. Chem. A*, 2021, **9**, 9248–9255.
- 22 F.-Z. Sun, S.-Q. Yang, R. Krishna, Y.-H. Zhang, Y.-P. Xia and T.-L. Hu, Microporous metal–organic framework with a completely reversed adsorption relationship for  $C_2$  hydrocarbons at room temperature, *ACS Appl. Mater. Interfaces*, 2020, **12**, 6105–6111.
- 23 S. Geng, E. Lin, X. Li, W. Liu, T. Wang, Z. Wang, D. Sensharma, S. Darwish, Y. H. Andaloussi, T. Pham, P. Cheng, M. J. Zaworotko, Y. Chen and Z. Zhang, Scalable room-temperature synthesis of highly robust ethane-selective metal–organic frameworks for efficient ethylene purification, *J. Am. Chem. Soc.*, 2021, **143**, 8654–8660.
- 24 H.-J. Lv, J.-W. Zhang, Y.-C. Jiang, S.-N. Li, M.-C. Hu and Q.-G. Zhai, Micropore regulation in ultrastable  $[Sc_3O]$ -organic frameworks for acetylene storage and purification, *Inorg. Chem.*, 2022, **61**, 3553–3562.
- 25 Y.-Z. Li, H.-H. Wang, G.-D. Wang, L. Hou, Y.-Y. Wang and Z. Zhu, A  $Dy_6$ -cluster-based fcu-MOF with efficient separation of  $C_2H_2/C_2H_4$  and selective adsorption of benzene, *Inorg. Chem. Front.*, 2021, **8**, 376–382.
- 26 W. Fan, S. B. Peh, Z. Zhang, H. Yuan, Z. Yang, Y. Wang, K. Chai, D. Sun and D. Zhao, Tetrazole-functionalized zirconium metal-organic cages for efficient  $C_2H_2/C_2H_4$  and  $C_2H_2/CO_2$  separations, *Angew. Chem., Int. Ed.*, 2021, **60**, 17338–17343.
- 27 X. Zhang, M. Fu, H. Liu, Y. Wang, Y. Zou, L. Wang, C. Li, Y. Lu, L. Zhou and X. Cui, A copper-based metal–organic framework with a suitable pore environment for effective ethylene purification, *Inorg. Chem. Front.*, 2022, **9**, 2104–2108.
- 28 J. Zhao, Q. Li, X.-C. Zhu, J. Li and D. Wu, Highly robust tetranuclear cobalt-based 3D framework for efficient  $C_2H_2/CO_2$  and  $C_2H_2/C_2H_4$  separations, *Inorg. Chem.*, 2020, **59**, 14424–14431.
- 29 J. Wang, Y. Zhang, P. Zhang, J. Hu, R.-B. Lin, Q. Deng, Z. Zeng, H. Xing, S. Deng and B. Chen, Optimizing pore space for flexible-robust metal–organic framework to boost trace acetylene removal, *J. Am. Chem. Soc.*, 2020, **142**, 9744–9751.
- 30 Q. Li, N. Wu, J. Li and D. Wu, A highly connected trinuclear cluster based metal–organic framework for efficient separation of  $C_2H_2/C_2H_4$  and  $C_2H_2/CO_2$ , *Inorg. Chem.*, 2020, **59**, 13005–13008.
- 31 L. Fan, P. Zhou, X. Wang, L. Yue, L. Li and Y. He, Rational construction and performance regulation of an  $In(III)$ -tetraisophthalate framework for one-step adsorption-phase purification of  $C_2H_4$  from  $C_2$  Hydrocarbons, *Inorg. Chem.*, 2021, **60**, 10819–10829.
- 32 J. Li, L. Jiang, S. Chen, A. Kirchon, B. Li, Y. Li and H.-C. Zhou, Rational construction and performance regulation of an  $In(III)$ -tetraisophthalate framework for one-step adsorption-phase purification of  $C_2H_4$  from  $C_2$  Hydrocarbons, *J. Am. Chem. Soc.*, 2019, **141**, 3807–3811.
- 33 W.-Q. Sun, J.-B. Hu, Y.-J. Jiang, N. Xu, L.-Y. Wang, J.-H. Li, Y.-Q. Hu, S. Duttwyler and Y.-B. Zhang, Flexible molecular sieving of  $C_2H_2$  from  $CO_2$  by a new cost-effective metal organic framework with intrinsic hydrogen bonds, *Chem. Eng. J.*, 2022, **439**, 135745.
- 34 X. Cui, K. Chen, H. Xing, Q. Yang, R. Krishna, Z. Bao, H. Wu, W. Zhou, X. Dong, Y. Han, B. Li, Q. Ren, M. J. Zaworotko and B. Chen, Pore chemistry and size control in hybrid porous materials for acetylene capture from ethylene, *Science*, 2016, **353**, 141–144.

- 35 P. Zhou, X. Wang, L. Yue, L. Fan and Y. He, A microporous MOF constructed by cross-linking helical chains for efficient purification of natural gas and ethylene, *Inorg. Chem.*, 2021, **60**, 14969–14977.
- 36 S. Xiang, W. Zhou, Z. Zhang, M. A. Green, Y. Liu and B. Chen, Open metal sites within isostructural metal-organic frameworks for differential recognition of acetylene and extraordinarily high acetylene storage capacity at room temperature, *Angew. Chem., Int. Ed.*, 2010, **49**, 4615–4618.
- 37 E. D. Bloch, W. L. Queen, R. Krishna, J. M. Zadrozny, C. M. Brown and J. R. Long, Hydrocarbon separations in a metal-organic framework with open iron(II) coordination sites, *Science*, 2012, **335**, 1606–1610.
- 38 Y. Zhang, L. Yang, L. Wang, S. Duttwyler and H. Xing, A microporous metal-organic framework supramolecularly assembled from a Cu<sup>II</sup> dodecaborate cluster complex for selective gas separation, *Angew. Chem., Int. Ed.*, 2019, **58**, 8145–8150.
- 39 S. Yang, A. J. Ramirez-Cuesta, R. Newby, V. Garcia-Sakai, P. Manuel, S. K. Callear, S. I. Campbell, C. C. Tang and M. Schröder, Supramolecular binding and separation of hydrocarbons within a functionalized porous metal-organic framework, *Nat. Chem.*, 2015, **7**, 121–129.
- 40 Q. Zhang, S.-Q. Yang, L. Zhou, L. Yu, Z.-F. Li, Y.-J. Zhai and T.-L. Hu, Pore-space partition through an embedding metal-carboxylate chain-induced topology upgrade strategy for the separation of acetylene/ethylene, *Inorg. Chem.*, 2021, **60**, 19328–19335.
- 41 Y. P. Li, Y. N. Zhao, S. N. Li, D. Q. Yuan, Y. C. Jiang, X. Bu, M. C. Hu and Q. G. Zhai, Ultrahigh-uptake capacity-enabled gas separation and fruit preservation by a new single-walled nickel-organic framework, *Adv. Sci.*, 2021, **8**, 2003141.
- 42 L. Zhang, K. Jiang, M. Jiang, D. Yue, Y. Wan, H. Xing, Y. Yang, Y. Cui, B. Chen and G. Qian, A highly stable amino-coordinated MOF for unprecedented block off N<sub>2</sub> adsorption and extraordinary CO<sub>2</sub>/N<sub>2</sub> separation, *Chem. Commun.*, 2016, **52**, 13568–13571.
- 43 X. Zhang, J.-X. Wang, L. Li, J. Pei, R. Krishna, H. Wu, W. Zhou, G. Qian, B. Chen and B. Li, A rod-packing hydrogen-bonded organic framework with suitable pore confinement for benchmark ethane/ethylene separation, *Angew. Chem., Int. Ed.*, 2021, **60**, 10304–10310.
- 44 D. Luo, Y.-L. Peng, M. Xie, M. Li, A. A. Bezrukov, T. Zuo, X.-Z. Wang, Y. Wu, Y. Y. Li, A. R. Lowe, M. a. Chorążewski, Y. Grosu, Z. Zhang, M. J. Zaworotko, X.-P. Zhou and D. Li, Improving ethane/ethylene separation performance under humid conditions by spatially modified zeolitic imidazolate frameworks, *ACS Appl. Mater. Interfaces*, 2022, **14**, 11547–11558.
- 45 W. Fan, H. Lin, X. Yuan, F. Dai, Z. Xiao, L. Zhang, L. Luo and R. Wang, Expanded porous metal-organic frameworks by SCSC: organic building units modifying and enhanced gas-adsorption properties, *Inorg. Chem.*, 2016, **55**, 6420–6425.
- 46 A. Gupta, S. Chempath, M. J. Sanborn, L. A. Clark and R. Q. Snurr, Object-oriented programming paradigms for molecular modeling, *Mol. Simul.*, 2003, **29**, 29–46.
- 47 B. Delley, From molecules to solids with the DMol<sup>3</sup> approach, *J. Chem. Phys.*, 2000, **113**, 7756–7764.