

Cite this: *J. Mater. Chem. A*, 2024, **12**, 28032

# Aromatic pore surface with multiple adsorption sites for one-step C<sub>2</sub>H<sub>4</sub> acquisition from C<sub>2</sub>H<sub>6</sub>/C<sub>2</sub>H<sub>4</sub> mixture†

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Developing a C<sub>2</sub>H<sub>6</sub>-selective adsorbent for the efficient one-step purification of C<sub>2</sub>H<sub>4</sub> from C<sub>2</sub>H<sub>6</sub>/C<sub>2</sub>H<sub>4</sub> mixture is of great significance but is still challenging because of the extremely close physicochemical properties of C<sub>2</sub>H<sub>6</sub> and C<sub>2</sub>H<sub>4</sub>. We herein report a metal–organic framework Ni-3-F, which possesses an aromatic pore surface and shows high-density distribution of N/O/F atoms on its pore wall. Such a special pore environment provides the C<sub>2</sub>H<sub>6</sub> molecule with multitudinous binding sites. Adsorption experiments show that Ni-3-F exhibits a higher C<sub>2</sub>H<sub>6</sub> adsorption capacity than C<sub>2</sub>H<sub>4</sub> in the range of 273–313 K and delivers a high C<sub>2</sub>H<sub>6</sub>/C<sub>2</sub>H<sub>4</sub> (1/99) selectivity of 1.80 at 298 K. Practical breakthrough experiments show that Ni-3-F can achieve efficient C<sub>2</sub>H<sub>6</sub>/C<sub>2</sub>H<sub>4</sub> separation and realize a relatively high C<sub>2</sub>H<sub>4</sub> yield (27.14 L kg<sup>-1</sup>) at 298 K and 1 bar. Furthermore, according to its comparatively stable structure, Ni-3-F can maintain good separation performance at different temperatures (298–318 K), flow rates (1.05–2.95 mL min<sup>-1</sup>) and relative humidities (33–100%). Computational simulations reveal that the aromatic pore surface and multiple N/O/F sites comprehensively provide C<sub>2</sub>H<sub>6</sub> with more C–H⋯π and C–H⋯N/O/F supramolecular interactions, which allows Ni-3-F to preferentially adsorb C<sub>2</sub>H<sub>6</sub> over C<sub>2</sub>H<sub>4</sub>.

Received 22nd July 2024  
Accepted 26th August 2024

DOI: 10.1039/d4ta05086j

rsc.li/materials-a

## Introduction

As the most important raw material in petrochemical industry, ethylene (C<sub>2</sub>H<sub>4</sub>) has been widely used for producing polyethylene, vinyl chloride, polyvinyl chloride and other chemicals.<sup>1–3</sup> Until 2023, more than 200 million tons C<sub>2</sub>H<sub>4</sub> had been produced by cracking petroleum hydrocarbons or pyrolysing ethane at high temperature.<sup>4</sup> However, during the C<sub>2</sub>H<sub>4</sub> production process, C<sub>2</sub>H<sub>6</sub> is always inevitably produced as an impurity.<sup>5–7</sup> In order to obtain polymer-grade C<sub>2</sub>H<sub>4</sub> for its downstream applications, additional separation processes are required. Presently, in the industry, C<sub>2</sub>H<sub>4</sub> is generally purified *via* cryogenic distillation at high pressure and low temperature, which not only requires exceedingly high equipment investment and complex operation processes, but is also extremely energy-intensive.<sup>8–10</sup> The above purification technology cannot meet the requirements of sustainable and green development. Thus, a low-cost and high-efficiency separation method is urgently desired.

Adsorptive separation technology based on porous adsorbents has been deemed as a promising alternative. In recent years, with the boom in porous adsorbents, adsorptive separation technology has achieved rapid development and some significant separation processes, such as C<sub>3</sub>H<sub>8</sub>/C<sub>3</sub>H<sub>6</sub>,<sup>11–14</sup> C<sub>2</sub>H<sub>2</sub>/CO<sub>2</sub>,<sup>15–19</sup> H<sub>2</sub>/D<sub>2</sub>,<sup>20–22</sup> C<sub>3</sub>F<sub>6</sub>/C<sub>3</sub>F<sub>8</sub> and so on,<sup>23,24</sup> have been widely investigated. However, owing to the physical properties such as the molecular size, quadrupole moment and polarizability of C<sub>2</sub>H<sub>6</sub> (4.4 Å, 0.65 × 10<sup>-26</sup> esu cm<sup>2</sup> and 44.7 × 10<sup>-25</sup> cm<sup>3</sup>, respectively), which are extremely close to those of C<sub>2</sub>H<sub>4</sub> (4.2 Å, 1.5 × 10<sup>-26</sup> esu cm<sup>2</sup> and 42.52 × 10<sup>-25</sup> cm<sup>3</sup>, respectively), separating C<sub>2</sub>H<sub>6</sub>/C<sub>2</sub>H<sub>4</sub> mixture is thus extraordinarily challenging.<sup>25,26</sup> Furthermore, in order to directly acquire high-purity C<sub>2</sub>H<sub>4</sub> from C<sub>2</sub>H<sub>6</sub>/C<sub>2</sub>H<sub>4</sub> mixture, constructing a C<sub>2</sub>H<sub>6</sub>-selective adsorbent is of great significance.<sup>5,27–29</sup> According to the literature and our group's previous reports, designing porous materials with aromatic pores can efficiently enhance C<sub>2</sub>H<sub>6</sub> adsorption through multiple C–H⋯π interactions.<sup>27,30,31</sup> Moreover, in view of the more C–H bonds in the C<sub>2</sub>H<sub>6</sub> molecule, inserting more electronegative groups such as nitrogen, oxygen and fluorine atoms in the framework can provide more C–H⋯N/O/F supramolecular interactions, which are helpful in increasing the uptake of C<sub>2</sub>H<sub>6</sub>.<sup>32</sup> Therefore, if we prepare a porous adsorbent with an aromatic pore surface and a high-density distribution of N/O/F binding sites in the pore wall, it may effectively realize preferential ethane adsorption and achieve high-efficiency C<sub>2</sub>H<sub>4</sub> purification from C<sub>2</sub>H<sub>6</sub>/C<sub>2</sub>H<sub>4</sub> mixture.

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† Electronic supplementary information (ESI) available: Experimental procedures. CCDC 2369828. For ESI and crystallographic data in CIF or other electronic format see DOI: <https://doi.org/10.1039/d4ta05086j>



Based on the above considerations, we herein employed a fluorinated organic ligand (3-fluoro-4-(pyridine-4-yl)benzoic acid) and constructed a novel quadruple interpenetrated MOF material (Ni-3-F). Benefiting from the high-density distribution of N/O/F atoms on its pore wall, Ni-3-F can provide multiple supramolecular bonding sites for C<sub>2</sub>H<sub>6</sub> molecule, which makes it preferentially adsorb C<sub>2</sub>H<sub>6</sub> rather than C<sub>2</sub>H<sub>4</sub>. At 298 K and 1 bar, Ni-3-F can adsorb 77.44 cm<sup>3</sup> g<sup>-1</sup> of C<sub>2</sub>H<sub>6</sub> but can only adsorb 65.13 cm<sup>3</sup> g<sup>-1</sup> of C<sub>2</sub>H<sub>4</sub>. Due to its different adsorption for C<sub>2</sub>H<sub>6</sub> and C<sub>2</sub>H<sub>4</sub>, Ni-3-F can efficiently capture C<sub>2</sub>H<sub>6</sub> and provide high-purity C<sub>2</sub>H<sub>4</sub> from the C<sub>2</sub>H<sub>6</sub>/C<sub>2</sub>H<sub>4</sub> mixture (1/99, v/v). At 298 K and 1 bar, Ni-3-F can provide 27.14 L kg<sup>-1</sup> of polymer-grade C<sub>2</sub>H<sub>4</sub> from the C<sub>2</sub>H<sub>6</sub>/C<sub>2</sub>H<sub>4</sub> mixture with a volume ratio of 1/99. More importantly, due to its high structural stability, Ni-3-F can even realize excellent C<sub>2</sub>H<sub>6</sub>/C<sub>2</sub>H<sub>4</sub> separation at high temperature (313 K), high flow rate (2.95 mL min<sup>-1</sup>) as well as high-humidity condition (100% relative humidity). Theoretical calculations show that Ni-3-F provides more supramolecular interactions with C<sub>2</sub>H<sub>6</sub> than C<sub>2</sub>H<sub>4</sub>, which is the key to realize efficient C<sub>2</sub>H<sub>6</sub>/C<sub>2</sub>H<sub>4</sub> separation.

## Experimental section

### Materials and physical measurements

All chemicals were purchased from suppliers and used directly without further purification. <sup>1</sup>H NMR spectra were recorded using a Bruker AVANCE III 400 (400 MHz) spectrometer. Single-crystal X-ray diffraction experiments were carried out on an XtaLAB Synergy R diffractometer. The powder X-ray diffraction (PXRD) data was recorded using a Rigaku MiniFlex600 X-ray diffractometer with Cu K $\alpha$  radiation ( $\lambda = 1.5406 \text{ \AA}$ ), scanning at 5° min<sup>-1</sup> in the range of 4–50°. The sample was heated in air to the expected temperature and stored for about 10 min to collect PXRD patterns at different temperatures. The thermogravimetric analysis curves was recorded on an NETZSCH-STA-449C unit at a heating rate of 10 °C min<sup>-1</sup> in a nitrogen atmosphere.

### Synthesis of ligand (3-fluoro-4-(pyridin-4-yl)benzoic acid)

The mixture of pyridin-4-ylboronic acid (3.7 g, 30 mmol), 4-bromo-3-fluorobenzoic acid (6.6 g, 30 mmol), Na<sub>2</sub>CO<sub>3</sub> (8.5 g, 80 mmol) and Pd(PPh<sub>3</sub>)<sub>4</sub> (2.4 g, 2.4 mmol) were dissolved in 130 mL H<sub>2</sub>O and 150 mL 1,4-dioxane and heated to 105 °C for 48 h under N<sub>2</sub> atmosphere. After the reaction was completed, the resulting mixture was cooled to room temperature and filtered. The solids were washed with ethanol (3 × 20 mL) to collect the filtrate. Then, the filtrate was dried under vacuum condition. Finally, the filtrate was acidified using 3 M HCl to pH = 3 and then filtered. The solid was dried to obtain a white powder. The ligand purity was verified by <sup>1</sup>H NMR. <sup>1</sup>H NMR (400 MHz, DMSO-d<sub>6</sub>):  $\delta$ , 13.44 (s, 1H), 8.68–8.70 (m, 2H), 7.74–7.88 (m, 3H), 7.61–7.63 (m, 2H).

### Synthesis of Ni-3-F

Ni(NO<sub>3</sub>)<sub>2</sub>·6H<sub>2</sub>O (29.08 mg, 0.1 mmol) and 3-fluoro-4-(pyridin-4-yl)benzoic acid (21.72 mg, 0.1 mmol) were dissolved in 7.5 mL

DMF and 0.15 mL triethylamine. Then, they were transferred to a 25 mL Teflon-lined stainless-steel container and heated at 150 °C for 3 days. After cooling, green block crystals could be obtained by filtering and washing multiple times with DMF.

### Gas sorption experiment

All gas adsorption experiments were performed on an ASAP 3020 surface analyzer. Fresh samples were soaked in acetone for 7 days; during this time, fresh acetone was replaced 3 times each day. Before the adsorption experiments, the exchanged sample was treated in vacuum at room temperature for at least 6 hours. Then, in the adsorption tube, the sample was heated at 80 °C for 10 hours with a high vacuum (less than 100  $\mu\text{m Hg}$ ) to obtain activated Ni-3-F for the next adsorption tests. All adsorption experiments were carried out at liquid nitrogen temperature of 77 K or water bath temperature of 273–313 K.

### Breakthrough measurements

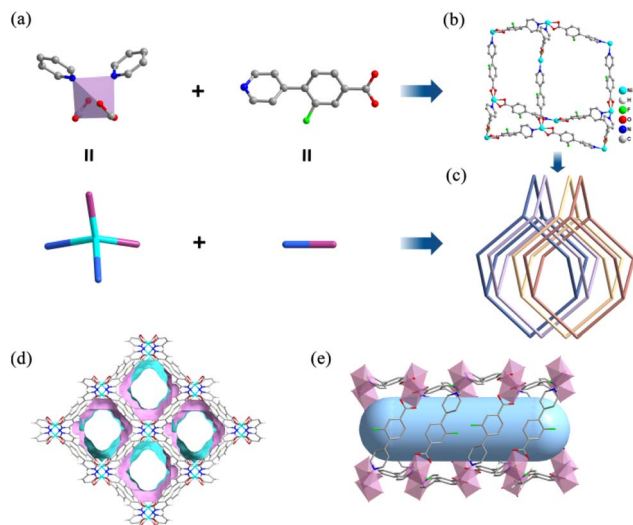
The breakthrough experiments were carried out by an HP-MC41 gas separation test system and a GC9860-5CNJ gas chromatograph. The breakthrough separation experiments for C<sub>2</sub>H<sub>6</sub>/C<sub>2</sub>H<sub>4</sub> (1/99, v/v) were conducted in a fixed bed under ambient conditions. The sample column is a transparent quartz column with a length of 200 mm and an inner diameter of 3 mm. All gas flow rates are controlled by a mass flow controller, and gas flow rates outside the column are measured by a gas chromatography (GC) detector. The initially activated Ni-3-F crystal (sample mass: 1.1395 g) was tightly packed into the column and then activated for 10 hours at 80 °C with Ar gas flow rate of 15 mL min<sup>-1</sup>. In continuous cycle experiments, the sample was purified and regenerated by Ar purging at 80 °C for 3 h.

## Results and discussion

### Crystal structure

Single crystal X-ray diffraction analysis shows that Ni-3-F crystallizes in the orthorhombic system and *Pnna* space group. In the structure of Ni-3-F, the Ni(II) center adopts a tetra-coordination model, in which two pairs of pyridine and carboxyl groups from four neighboring 3-fluoro-4-(pyridin-4-yl)benzoic acid ligands are coordinated with the Ni(II) cation to form a 4-connected tetrahedral node (Fig. 1a). If simplifying the 3-fluoro-4-(pyridin-4-yl)benzoic acid ligand as a 2-connected linker, Ni-3-F possesses a 3D framework with specific *dia* topology (Fig. 1b). Additionally, in order to stabilize its structure, four independent frameworks interpenetrate with each other to form a 3D structure with 1D channel (Fig. 1c). The pore size is approximately 6.7 Å (calculated by *zeo++* package) along the crystallographic *b*-axis (Fig. 1d and e). Furthermore, the porosity and the solvent-accessible pore volume void of Ni-3-F calculated by PLATON<sup>33,34</sup> are 38.1% and 1214.76 Å<sup>3</sup>, respectively. More importantly, despite the fourfold interpenetration, all the N/O/F atoms are distributed on the surface pore of Ni-3-F, which may provide more accessible binding sites for the C<sub>2</sub>H<sub>6</sub> molecules.





**Fig. 1** (a) The coordination environment of Ni(II) ions in Ni-3-F. (b) The perspective view of a single set of a diamond network in Ni-3-F. (c) Four-fold interpenetrated *dia* nets in Ni-3-F. (d) The 1D channel viewed along the *b*-axis in Ni-3-F. (e) The rectangular 1D channel viewed along the *a*-axis.

### Stability of Ni-3-F

The phase purity of Ni-3-F can be verified by powder X-ray diffraction (PXRD) experiments. As can be seen in Fig. S1,<sup>†</sup> the PXRD pattern of the as-synthesized sample matches well with the simulated ones. After Ni-3-F is soaked in common organic solvents, such as methanol, ethanol, acetone, acetonitrile and dichloromethane for 5 days, the PXRD patterns show that it can maintain its original structure (Fig. S2<sup>†</sup>). Furthermore, in order to determine its thermostability, thermogravimetric analysis (TGA) and variable temperature X-ray diffraction (VT-PXRD) experiments were conducted. As shown in Fig. S3,<sup>†</sup> there is no obvious weight loss until 350 °C. From the variable temperature X-ray diffraction (VT-PXRD) experiments (Fig. S4<sup>†</sup>), we find that the framework can be maintained at least up to 200 °C. The above results indicate that Ni-3-F has excellent structural stability, which can serve as a potential adsorbent in the actual industrial environment.

### Gas sorption

On the basis of the structural stability and specially endowed channel, we conducted the gas adsorption tests for Ni-3-F. Firstly, the permanent porosity of Ni-3-F was established by N<sub>2</sub> adsorption experiments at 77 K. As seen in Fig. S5,<sup>†</sup> the 77 K N<sub>2</sub> isotherm exhibits reversible type-I adsorption behavior and the saturation adsorption capacity reaches 150.8 cm<sup>3</sup> g<sup>-1</sup>. The corresponding Brunauer–Emmett–Teller (BET) surface area is 583.4 m<sup>2</sup> g<sup>-1</sup>. According to the abundance of F atoms and densely distributed N/O atoms on the pore wall, we speculate that Ni-3-F may generate stronger interaction for C<sub>2</sub>H<sub>6</sub> molecule.<sup>35–39</sup> In order to verify our hypothesis, we carried out single-component adsorption experiments for C<sub>2</sub>H<sub>6</sub> and C<sub>2</sub>H<sub>4</sub>. As shown in Fig. 2a and b, the adsorption curves for C<sub>2</sub>H<sub>6</sub> increase more sharply than those for C<sub>2</sub>H<sub>4</sub> from 273 K to 313 K. At the same temperature, the

maximum adsorption capacity of C<sub>2</sub>H<sub>6</sub> for Ni-3-F is always higher than that of C<sub>2</sub>H<sub>4</sub>. For example, at 298 K and 100 kPa, the uptake for C<sub>2</sub>H<sub>6</sub> is 77.44 cm<sup>3</sup> g<sup>-1</sup>, which is higher than that of some reported C<sub>2</sub>H<sub>6</sub>-selective adsorbents, such as UiO-67 (67.42 cm<sup>3</sup> g<sup>-1</sup>),<sup>27</sup> Cu(Qc)<sub>2</sub> (41.5 cm<sup>3</sup> g<sup>-1</sup>),<sup>40</sup> ZIF-8 (56 cm<sup>3</sup> g<sup>-1</sup>)<sup>41</sup> and FJI-H11-Me (58.0 cm<sup>3</sup> g<sup>-1</sup>)<sup>30</sup> but lower than that of some top-ranking materials, like Ni-MOF 2 (133 cm<sup>3</sup> g<sup>-1</sup>),<sup>42</sup> MFM-300(In) (114.24 cm<sup>3</sup> g<sup>-1</sup>)<sup>43</sup> and Co-9-ina (84.1 cm<sup>3</sup> g<sup>-1</sup>)<sup>37</sup> under the same conditions. In comparison, the uptake for C<sub>2</sub>H<sub>4</sub> is only 65.13 cm<sup>3</sup> g<sup>-1</sup>. More importantly, in the low-pressure region, the adsorption isotherm for C<sub>2</sub>H<sub>6</sub> also rises more sharply than that for C<sub>2</sub>H<sub>4</sub>, which indicates that Ni-3-F shows the stronger affinity for C<sub>2</sub>H<sub>6</sub> (Fig. 2c). In order to investigate the cycle performance of Ni-3-F on C<sub>2</sub>H<sub>6</sub> and C<sub>2</sub>H<sub>4</sub>, five continuous cycles of C<sub>2</sub>H<sub>6</sub> and C<sub>2</sub>H<sub>4</sub> adsorption experiments at 298 K were recorded. As seen in Fig. 2d and S6,<sup>†</sup> after five cycles, the C<sub>2</sub>H<sub>6</sub> and C<sub>2</sub>H<sub>4</sub> adsorption capacity show no obvious decrease.

In order to further assess the different interactions of C<sub>2</sub>H<sub>6</sub> and C<sub>2</sub>H<sub>4</sub>, the heat of adsorption (*Q*<sub>st</sub>) was calculated with adsorption isotherms at 273 K and 298 K. As shown in Fig. S7–S9,<sup>†</sup> the *Q*<sub>st</sub> for C<sub>2</sub>H<sub>6</sub> (25.47 kJ mol<sup>-1</sup>) is much higher than that for C<sub>2</sub>H<sub>4</sub> (21.09 kJ mol<sup>-1</sup>) at zero coverage, implying that Ni-3-F indeed shows stronger interactions towards C<sub>2</sub>H<sub>6</sub>, which is beneficial for the preferential capture of C<sub>2</sub>H<sub>6</sub> in the separation experiments. It is worth noting that compared with some known C<sub>2</sub>H<sub>6</sub>-selective adsorbents, such as JNU-2 (29.4 kJ mol<sup>-1</sup>),<sup>43</sup> MUF-15 (29.2 kJ mol<sup>-1</sup>),<sup>44</sup> Co-9-ina (30.6 kJ mol<sup>-1</sup>),<sup>37</sup> Fe<sub>2</sub>(O<sub>2</sub>)(dobdc) (66.8 kJ mol<sup>-1</sup>),<sup>4</sup> PCN-250 (33.47 kJ mol<sup>-1</sup>)<sup>29</sup> and Cu(Qc)<sub>2</sub> (28.8 kJ mol<sup>-1</sup>),<sup>40</sup> the *Q*<sub>st</sub> for C<sub>2</sub>H<sub>6</sub> adsorption (25.47 kJ mol<sup>-1</sup>) on Ni-3-F is lower. Such low *Q*<sub>st</sub> highlights Ni-3-F as a promising C<sub>2</sub>H<sub>6</sub>-selective adsorbent with a low regenerative energy requirement.

In order to evaluate the adsorption selectivity for C<sub>2</sub>H<sub>6</sub> and C<sub>2</sub>H<sub>4</sub>, an ideal adsorbed solution theory (IAST) calculation was employed on the basis of the single-component C<sub>2</sub>H<sub>6</sub> and C<sub>2</sub>H<sub>4</sub> adsorption isotherms at different temperatures (Fig. S10–S19<sup>†</sup>). As we can see from Fig. 2e, the adsorption selectivity for C<sub>2</sub>H<sub>6</sub>/C<sub>2</sub>H<sub>4</sub> (1/99, v/v) at 298 K can reach 1.80, which is higher than that of some reported MOFs, such as In-soc-MOF-1 (1.4),<sup>45</sup> MIL-142A (1.5)<sup>46</sup> and Cu(ina)<sub>2</sub> (1.3).<sup>40</sup> More importantly, as the temperature increases, the IAST selectivities show no obvious decrease. Even at 313 K, the C<sub>2</sub>H<sub>6</sub>/C<sub>2</sub>H<sub>4</sub> (1/99) selectivity can also climb to 1.69 at 1 bar, which indicates that Ni-3-F may achieve the separation of C<sub>2</sub>H<sub>6</sub> and C<sub>2</sub>H<sub>4</sub> at high temperature conditions. In order to further assess the separation ability of Ni-3-F for C<sub>2</sub>H<sub>6</sub>/C<sub>2</sub>H<sub>4</sub>, we calculated the separation potential ( $\Delta q$ ) at different temperatures. As demonstrated in Fig. 2f, at 298 K and 1 bar, the  $\Delta q$  for C<sub>2</sub>H<sub>6</sub>/C<sub>2</sub>H<sub>4</sub> (1/99) can reach 2.21 mmol g<sup>-1</sup>. When the temperature rises to 313 K, the  $\Delta q$  can also be 1.45 mmol g<sup>-1</sup>. All the above results collectively illustrate that Ni-3-F can not only realize the separation of C<sub>2</sub>H<sub>6</sub> and C<sub>2</sub>H<sub>4</sub> but give a high productivity of C<sub>2</sub>H<sub>4</sub> in the separation process.

### Theoretical mechanism calculations

In order to further explore the mechanism of Ni-3-F preferentially adsorbing C<sub>2</sub>H<sub>6</sub> rather than C<sub>2</sub>H<sub>4</sub>, theoretical calculations





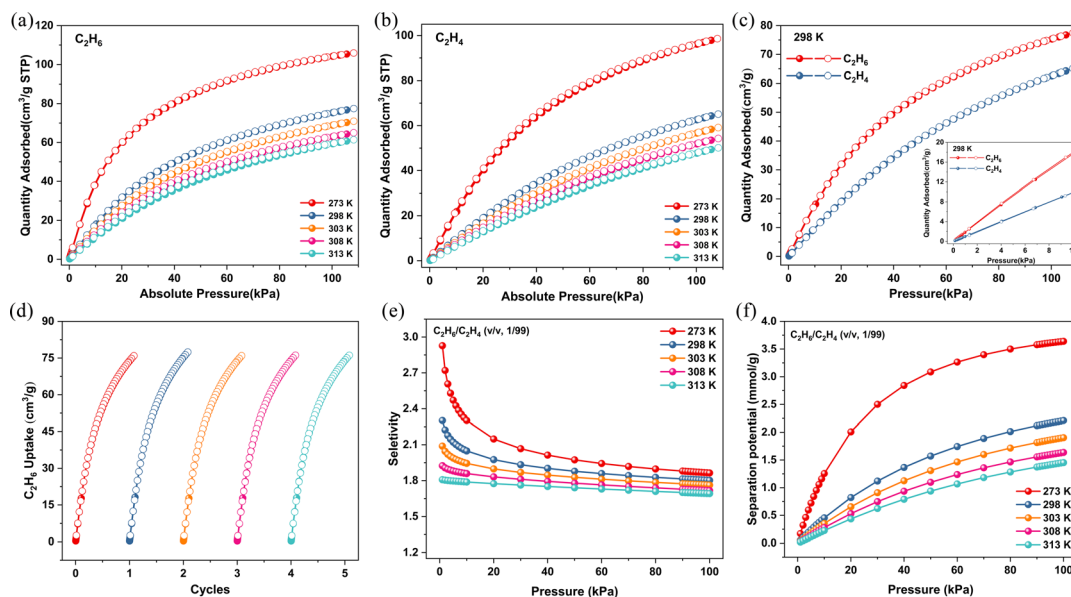


Fig. 2 Single-component adsorption isotherms of  $C_2H_6$  (a) and  $C_2H_4$  (b) in the range of 273–313 K. (c) The comparison of  $C_2H_6$  and  $C_2H_4$  isotherms for Ni-3-F at 298 K. (d) Five cycles of  $C_2H_6$  adsorption isotherms at 298 K. (e) IAST selectivity and (f) separation potential for  $C_2H_6/C_2H_4$  (1/99) at 273 K, 298 K, 303 K, 308 K and 313 K.

were carried out. As shown in Fig. 3, both  $C_2H_6$  and  $C_2H_4$  could form C–H $\cdots$ F and C–H $\cdots$  $\pi$  interactions with the framework. However, it is found that the  $C_2H_4$  molecule interacts with the framework only through C–H $\cdots$  $\pi$  interactions (the separations between C and C atoms, 3.50–4.07 Å) and C–H $\cdots$ F interactions (the separations between H and F atoms, 2.66 Å) (Fig. 3a). By contrast,  $C_2H_6$  has more interactions with the framework, including C–H $\cdots$  $\pi$  interactions with benzene rings (C $\cdots$ C separations, 3.66–4.16 Å), C–H $\cdots$ F interactions with F atoms (H $\cdots$ F separations, 3.43 Å and 2.82 Å), C–H $\cdots$ O interactions between the carboxyl group (H $\cdots$ O separation, 3.39 Å), as well as C–H $\cdots$ N interactions with pyridine (H $\cdots$ N, 2.91 Å and 3.15 Å) (Fig. 3b). The static binding energies of  $C_2H_6$  and  $C_2H_4$  are 48.48 and 42.40 kJ mol $^{-1}$ , respectively, which is consistent with the experimentally observed abnormal affinity between the framework and the gas molecules. The above results show that the presence of multiple interaction sites can produce more

interaction between Ni-3-F and  $C_2H_6$ , which is conducive to the one-step separation of  $C_2H_6/C_2H_4$  to obtain high-purity  $C_2H_4$ .

### Column breakthrough tests

In order to verify the actual separation ability of Ni-3-F for  $C_2H_6/C_2H_4$ , we carried out breakthrough experiments in a packed bed with activated Ni-3-F sample. We used  $C_2H_6/C_2H_4$  with a volume ratio of 1/99 to perform column breakthrough experiments. As shown in Fig. 4a, under the condition of 298 K and 1 bar,  $C_2H_4$  always flows out of the fixed bed first, and after a certain time,  $C_2H_6$  could be detected at the end of the fixed bed. The separation time of pure  $C_2H_4$  is 28.8 min g $^{-1}$ . According to the gas flow rate of 1.05 mL min $^{-1}$ , after one separation cycle, about 27.14 L kg $^{-1}$  polymer-grade  $C_2H_4$  could be directly collected.

To the best of our knowledge, the adsorbent that may be applied in practical industry should have good durability. As depicted in Fig. 4b, after 5 cycles of breakthrough tests, the separation performance shows no significant decline, which proves that Ni-3-F has desirable repeatability and can serve as an ideal physical adsorbent in the industrial environment. As we know, the gas flow rates usually have an influence on gas separation. Therefore, the breakthrough experiments with different gas flow rates have also been investigated. As shown in Fig. 4c, when the gas flow rate gradually increases, Ni-3-F could still maintain excellent  $C_2H_6/C_2H_4$  separation performance. Furthermore, in consideration of the high-temperature separation atmosphere in the industry and the inevitability of water vapor in the air, the adsorbent should also hold good separation ability in high temperature and high-humidity conditions. As shown in Fig. 4d, when the temperature is progressively enhanced, Ni-3-F could always realize one-step acquisition of high-purity  $C_2H_4$  from the  $C_2H_6/C_2H_4$  mixture. Even when the

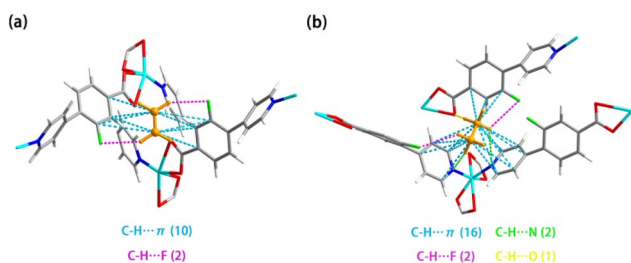


Fig. 3 Calculated preferential adsorption locations of  $C_2H_4$  (a) and  $C_2H_6$  (b) in Ni-3-F (the purple dotted line represents C–H $\cdots$ F interactions; the blue dotted line represents C–H $\cdots$  $\pi$  interactions; the yellow dotted line represents C–H $\cdots$ O interactions; the green dotted line represents C–H $\cdots$ N interactions).



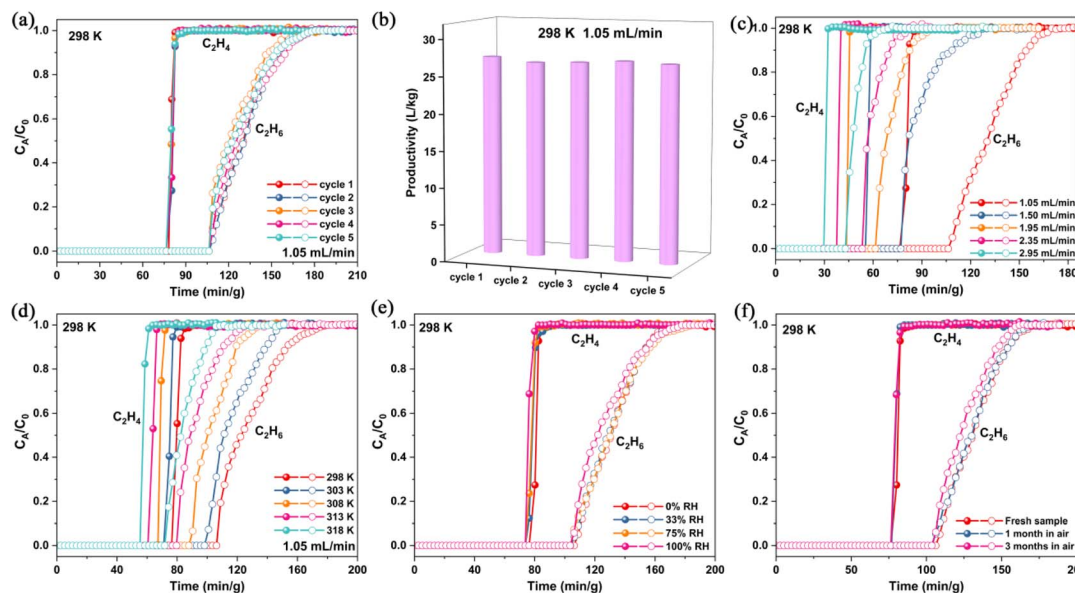


Fig. 4 Ni-3-F breakthrough experiments for  $C_2H_6/C_2H_4$  (1/99, v/v). (a) Cyclic breakthrough tests of Ni-3-F for  $C_2H_6/C_2H_4$  (1/99, v/v) with the flow rate of  $1.05 \text{ mL min}^{-1}$ . (b) Five-cycle  $C_2H_4$  yields for  $C_2H_6/C_2H_4$  (1/99, v/v) at  $1.05 \text{ mL min}^{-1}$  and 298 K. (c) Breakthrough experiments of Ni-3-F at 298 K with different flow rates. (d) Breakthrough experiments of Ni-3-F at different temperatures with a gas flow rate of  $1.05 \text{ mL min}^{-1}$ . (e) Breakthrough experiments of Ni-3-F under different relative humidity conditions and 298 K with a flow rate of  $1.05 \text{ mL min}^{-1}$ . (f) Breakthrough experiments of Ni-3-F after exposing to air for different time duration with a gas flow rate of  $1.05 \text{ mL min}^{-1}$ .

temperature increases to 318 K,  $14.74 \text{ L kg}^{-1}$  of  $C_2H_4$  can be obtained. More importantly, when we introduce the moist  $C_2H_6/C_2H_4$  mixture into the fixed bed, polymer-grade  $C_2H_4$  can also be eluted out. As shown in Fig. 4e, the breakthrough curves in different humidity conditions could be coincident with that of the fresh sample, implying that the moisture has no effect on the separation of  $C_2H_6/C_2H_4$ . Moreover, Ni-3-F also exhibits excellent air stability, which can be demonstrated by the almost overlapping separation curves of the samples placed in air for 1 or 3 months with fresh samples (Fig. 4f). On the whole, the above results all show that Ni-3-F can realize the excellent separation of  $C_2H_6/C_2H_4$  and can work well under various harsh conditions.

## Conclusions

In summary, we have successfully prepared a four-fold interpenetrating MOF material (Ni-3-F), which has high-density of N/O/F atoms and realizes the preferential adsorption of  $C_2H_6$  from  $C_2H_6/C_2H_4$ . At 298 K, the adsorption capacity of  $C_2H_6$  ( $77.44 \text{ cm}^3 \text{ g}^{-1}$ ) is significantly higher than that of  $C_2H_4$  ( $65.13 \text{ cm}^3 \text{ g}^{-1}$ ), and the selectivity of  $C_2H_6/C_2H_4$  (1/99, v/v) can reach 1.80. The breakthrough experiments proved that high-purity  $C_2H_4$  (>99.95%) can be directly obtained from the mixture of  $C_2H_6/C_2H_4$  (1/99, v/v) in one step, and the yield reaches  $27.14 \text{ L kg}^{-1}$ . More importantly, Ni-3-F can maintain good separation performance at different temperatures, flow rates and relative humidity conditions. The theoretical calculation results show that  $C_2H_6$  can have a variety of interactions with the framework, and the interactions between Ni-3-F and  $C_2H_6$  are obviously stronger than those of  $C_2H_4$ . All the above results indicate that

the aromatic pore surface with multiple adsorption sites can successfully obtain high-purity  $C_2H_4$  from the  $C_2H_6/C_2H_4$  mixture in one step.

## Data availability

All data included in this study are available upon request by contacting the corresponding author.

## Author contributions

M. Y. W. determined the project. Y. Q. Z. and M. Y. W. designed the MOF synthesis methods. Y. Q. Z. and Z. Y. J. synthesized Ni-3-F. Y. Q. Z. and Y. Z. Z. carried out the power X-ray diffraction. Y. Q. Z. and Y. Z. Z. performed the single-crystal X-ray diffraction experiments. Y. Q. Z. and Z. Y. J. collected data of single-component gas sorption measurements and dynamic breakthrough experiments. Y. Q. Z. wrote the manuscript with support from M. Y. W. All authors contributed to revise the manuscript.

## Conflicts of interest

There are no conflicts to declare.

## Acknowledgements

This work is supported by NSFC (22271282) and the Self-deployment Project Research Program of Haixi Institutes, Chinese Academy of Sciences with the grant number of CXZX-2022-JQ04. Additionally, this work is also supported by Fujian



Science & Technology Innovation Laboratory for Optoelectronic Information of China (No. 2021ZR120) and NSF of Fujian Province (No. 2021J01517 and 2020J06034).

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