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# An amino-coordination metal–organic framework for highly selective C<sub>2</sub>H<sub>2</sub>/CH<sub>4</sub> and C<sub>2</sub>H<sub>2</sub>/C<sub>2</sub>H<sub>4</sub> separations through the appropriate control of window sizes†

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The efficient separation of C<sub>2</sub>H<sub>2</sub> versus C<sub>2</sub>H<sub>4</sub> and CH<sub>4</sub> to obtain high-purity C<sub>2</sub>H<sub>2</sub> and C<sub>2</sub>H<sub>4</sub> is of significance for making full, economic use of these raw chemicals. Herein, an amino-coordination microporous metal–organic framework **ZJU-198**, ZnL·DMF (ZJU = Zhejiang University, L = (2*E*,2*E'*)-3,3'-(5-amino-1,3-phenylene)diacrylic acid, DMF = *N,N'*-dimethylformamide), has been demonstrated as a valuable adsorbent for C<sub>2</sub>H<sub>2</sub>/C<sub>2</sub>H<sub>4</sub> and C<sub>2</sub>H<sub>2</sub>/CH<sub>4</sub> separations. The activated **ZJU-198a** exhibits moderate C<sub>2</sub>H<sub>2</sub> uptakes (99.4 cm<sup>3</sup> cm<sup>-3</sup> for 273 K and 98.4 cm<sup>3</sup> cm<sup>-3</sup> for 298 K under 1.0 bar) and moderately high C<sub>2</sub>H<sub>2</sub>/C<sub>2</sub>H<sub>4</sub> selectivity (5.8 to 7.7 at 273 K and 4.8 to 7.2 at 298 K). Specifically, the C<sub>2</sub>H<sub>2</sub>/CH<sub>4</sub> selectivity of **ZJU-198a** reaches up to 497.9 and 391.1 at 273 K and 298 K, respectively. To the best of our knowledge, the C<sub>2</sub>H<sub>2</sub>/CH<sub>4</sub> selectivity coefficients of **ZJU-198a** at both 298 K and 273 K are the highest values among the reported metal–organic frameworks, meaning that there is bright potential for **ZJU-198a** in hydrocarbon storage and separation.

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## Introduction

C<sub>2</sub> hydrocarbons are generally recognized as important raw chemicals to the petrochemical industries.<sup>1</sup> The efficient separation of C<sub>2</sub>H<sub>2</sub>/C<sub>2</sub>H<sub>4</sub> can make full, economic use of these raw chemicals. Ethylene is mainly produced from steam cracking of an alkane. However, the presence of spin-off acetylene has an impeditive effect on further polymerization of ethylene. That is why the C<sub>2</sub>H<sub>2</sub> purity of the C<sub>2</sub>H<sub>2</sub>/C<sub>2</sub>H<sub>4</sub> mixture must be guaranteed below 40 ppm.<sup>2–4</sup> What's more, acetylene that is chiefly yielded by the cracking of petroleum generally contains the adverse by-product methane (CH<sub>4</sub>).<sup>5</sup> Therefore, the efficient separation of C<sub>2</sub>H<sub>2</sub> over C<sub>2</sub>H<sub>4</sub> and CH<sub>4</sub> to obtain high-purity C<sub>2</sub>H<sub>4</sub> and C<sub>2</sub>H<sub>2</sub> is of economic significance.

Porous materials might offer alternative approaches over energy-consumptive commercial materials. Extensive efforts have been engaged in hydrocarbon adsorption and separation.

During the past decades, microporous metal–organic frameworks (MOFs) have attracted substantial attention in gas storage and separation.<sup>6–15</sup> Compared with other porous adsorbents, such as activated carbons and molecular sieves, MOFs have greater potential both at a research and application level by virtue of their attractive advantages.<sup>16–35</sup> On the one hand, the high porosity of MOFs allows them to take up large amounts of gas molecules; on the other hand, the easily-adjustable pore/window sizes and functionalization within MOFs offer significant improvements in gas separation selectivity.<sup>36–40</sup>

In terms of gas separation, the pores within MOFs can be judiciously modified through the immobilization of specific sites like Lewis basic sites (LBSs) and functional groups including amino groups to enhance the interaction between the framework and preferred gas molecules.<sup>41–43</sup> However, the aforementioned strategies bring a costly regeneration bill. This worrisome issue can be addressed through the accurate control of the pore/window sizes. Herein, our previously reported amino-coordination microporous metal–organic framework **ZJU-198**, which was validated as one of the best performing metal–organic frameworks for CO<sub>2</sub>/N<sub>2</sub> separation,<sup>44</sup> has been chosen with the appropriate window sizes and synthesized successfully. The activated **ZJU-198a** has been further demonstrated as a valuable adsorbent for C<sub>2</sub>H<sub>2</sub>/C<sub>2</sub>H<sub>4</sub> and C<sub>2</sub>H<sub>2</sub>/CH<sub>4</sub> separations and exhibited moderate C<sub>2</sub>H<sub>2</sub> storages (99.4 cm<sup>3</sup> cm<sup>-3</sup> at 273 K and 98.4 cm<sup>3</sup> cm<sup>-3</sup> at 298 K under 1.0 bar) and

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moderately high  $C_2H_2/C_2H_4$  selectivity (5.8 to 7.7 at 273 K and 4.8 to 7.2 at 298 K). It's worth noting that **ZJU-198a** has been further demonstrated for  $C_2H_2/CH_4$  separation with very high selectivity of 63.1 to 497.9 and 69.0 to 391.1 at 273 K and 298 K, respectively. To the best of our knowledge, **ZJU-198a** exhibits the highest performance for the separation of  $C_2H_2/CH_4$  both at 298 K and 273 K among the reported metal-organic frameworks, meaning that there is bright potential for **ZJU-198a** in hydrocarbon storage and separations.

## Experimental

### Materials and methods

All solvents and reagents except the organic ligand were commercially available and used without further purification. The syntheses of the organic linker (*2E,2E'*-3,3'-(5-amino-1,3-phenylene)diacrylic acid, simplified as 5-amino- $H_2L$ , and **ZJU-198** are referred to in our previously reported work.<sup>44</sup>  $^1H$  NMR spectra were obtained using a Bruker Advance DMX 500 MHz spectrometer with tetramethylsilane (TMS) as an internal standard. Elemental analyses (EA) for C, H, and N were performed using an EA1112 microelemental analyzer. Infrared spectra (IR) were obtained using a Thermo Fisher Nicolet iS10 spectrometer using KBr pellets. Thermogravimetric analyses (TGA) were performed using a Netzsch TG209F3 with a heating rate of  $10\text{ }^\circ\text{C min}^{-1}$  under the protection of a high-purity  $N_2$  atmosphere. All gas sorption isotherms were obtained using a Micromeritics ASAP 2020 surface area analyzer. The activation procedure of **ZJU-198** also corresponded to our previously reported work.<sup>44</sup> The sorption measurements were maintained at 196 K with a mixture of drikold and acetone. Ice-water and water baths were used for the adsorption isotherms of  $C_2H_2$ ,  $C_2H_4$  and  $CH_4$  at 273 K and 298 K, respectively.

### Ideal adsorbed solution theory (IAST)

The selectivity of the preferential adsorption of component 1 over component 2 in a mixture containing 1 and 2 can be formally defined as:

$$S_{\text{ads}} = \frac{q_1/q_2}{p_1/p_2}$$

In the above equation,  $q_1$  and  $q_2$  are the absolute component loadings of the adsorbed phase in the mixture. These component loadings are also termed the uptake capacity. We calculated the values of  $q_1$  and  $q_2$  using the Ideal Adsorbed Solution Theory (IAST) of Myers and Prausnitz.

### The isosteric heat, $Q_{\text{st}}$

The isosteric heat of  $C_2H_2$ ,  $C_2H_4$ , and  $CH_4$  adsorption,  $Q_{\text{st}}$ , defined as

$$Q_{\text{st}} = RT^2 \left( \frac{\partial \ln P}{\partial T} \right)$$

was determined using the Clausius-Clapeyron equation by fitting the adsorption isotherms taken at 273 K and 298 K to a Langmuir expression.

## Results and discussion

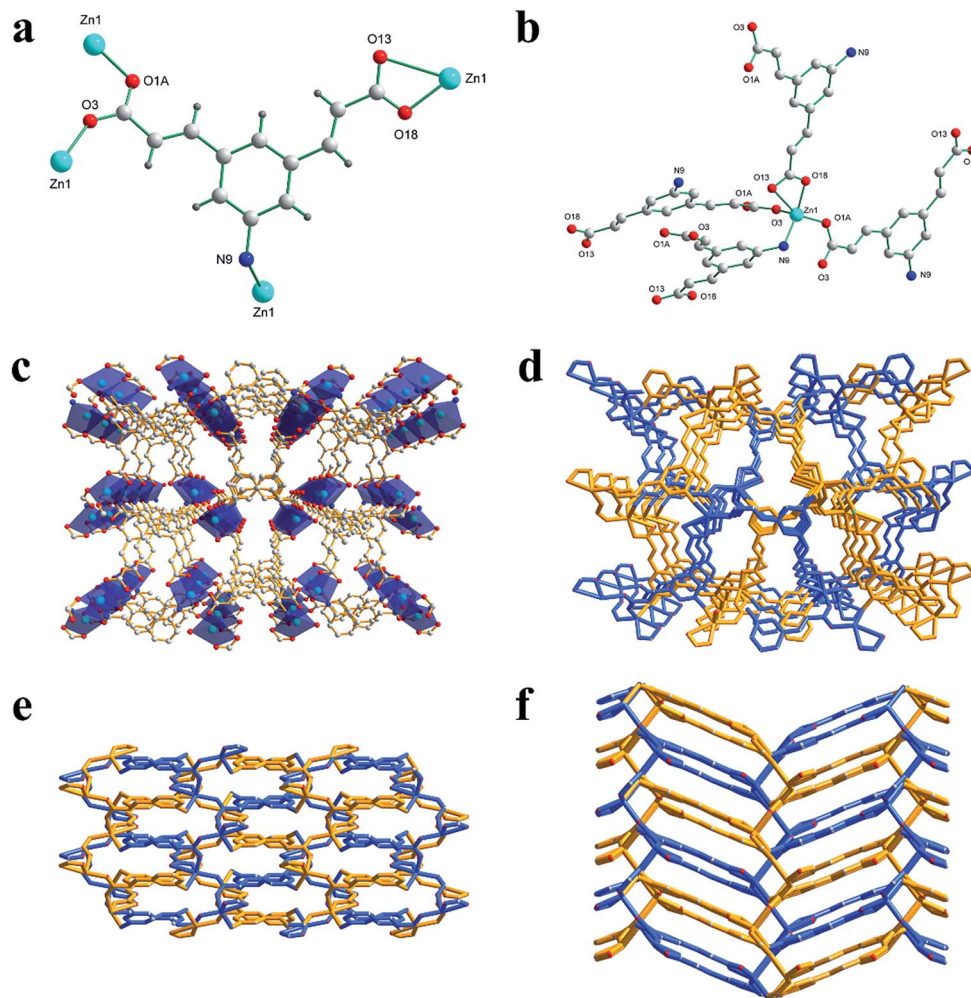
The solvothermal reaction of the organic ligand 5-amino- $H_2L$  with  $Zn(NO_3)_2 \cdot 6H_2O$  in a mixture of solvents DMF/ $H_2O$ /acetonitrile afforded **ZJU-198** as colorless layer-shaped crystals, which has a formula of  $ZnL \cdot DMF$  (DMF = *N,N*-dimethylformamide) determined by single-crystal X-ray diffraction and elemental analysis (EA). The purity of the phase was further indicated by powder X-ray diffraction (PXRD).

Single-crystal X-ray diffraction analysis demonstrates that **ZJU-198** crystallizes in the space group of *Pbca* with a (4, 5)-coordination network. It's clear to see that each Zn1 atom exhibits 5-coordination connecting with O1A, O3, O13, O18, and N9 from four different organic linkers to construct an asymmetric pentahedron as the secondary building unit (SBU) (Fig. 1b). Furthermore, the four oxygen atoms and the nitrogen atom of the same organic linker coordinate to four different Zn1 atoms (Fig. 1a). The O1A atom and O3 atom from the same bidentate carboxylate group connect two different Zn1 atoms while O13 and O18 exhibit the same coordination condition. The SBUs link the organic ligands further to form a three-dimensional (3D) framework. It's worth noting that the zigzag coordination tendency makes the unique orderly overlapping channels, but with no interpenetration of the framework (Fig. 1d-f). Only two types of channel exist, which are approximately  $3.6\text{ \AA} \times 4.1\text{ \AA}$  and  $2.1\text{ \AA} \times 5.0\text{ \AA}$  as viewed from the *a* axis (Fig. 1c), and the van der Waals radii of the atoms have been already been taken into account when labelling the size of these channels.

After sufficient acetone-exchange and suitable activation, the  $CO_2$  sorption at 196 K is further operated to explore the porosity of desolvated **ZJU-198a**. As depicted in Fig. S5,<sup>†</sup> the sorption data of  $CO_2$ -196 K is consistent with the typical type-I sorption characteristic with a Langmuir surface area and BET of  $488.5\text{ m}^2\text{ g}^{-1}$  and  $343.1\text{ m}^2\text{ g}^{-1}$ , respectively. As for the applicable window size and moderate porosity of **ZJU-198a**, we were encouraged to explore the adsorption performance of  $C_2H_2$ ,  $C_2H_4$ , and  $CH_4$  at low pressures. Herein, the low-pressure adsorption isotherms of  $C_2H_2$ ,  $C_2H_4$ , and  $CH_4$  at 273 K and 298 K are illustrated in Fig. 2. Compared with  $C_2H_4$  and  $CH_4$ , it's exciting that the  $C_2H_2$  adsorption capacity of **ZJU-198a** zooms up rapidly to reach saturation even at extremely low pressure. Under 0.01 bar, **ZJU-198a** takes up a great amount of  $72.5\text{ cm}^3\text{ cm}^{-3}$ ,  $37.3\text{ cm}^3\text{ cm}^{-3}$ , and  $0.13\text{ cm}^3\text{ cm}^{-3}$  for  $C_2H_2$ ,  $C_2H_4$ , and  $CH_4$  at 273 K, respectively and  $41.4\text{ cm}^3\text{ cm}^{-3}$ ,  $3.1\text{ cm}^3\text{ cm}^{-3}$ , and  $0.03\text{ cm}^3\text{ cm}^{-3}$  for  $C_2H_2$ ,  $C_2H_4$ , and  $CH_4$  at 298 K, respectively. The saturation capacities of  $C_2H_2$ ,  $C_2H_4$ , and  $CH_4$  are  $99.4\text{ cm}^3\text{ cm}^{-3}$ ,  $92.4\text{ cm}^3\text{ cm}^{-3}$ , and  $21.1\text{ cm}^3\text{ cm}^{-3}$  at 273 K, respectively, and  $98.4\text{ cm}^3\text{ cm}^{-3}$ ,  $89.2\text{ cm}^3\text{ cm}^{-3}$ , and  $8.8\text{ cm}^3\text{ cm}^{-3}$  at 298 K, respectively. It's worth noting that there is almost no decline in  $C_2H_2$  adsorption with the temperature rise, and the  $CH_4$  molecule has no competitive advantages against the  $C_2H_2$  molecule especially at extremely low pressure.

The adsorption selectivity for  $C_2H_2$  over  $C_2H_4$  and  $CH_4$  is another prerequisite for assessing an adsorbent material, except for when assessing the mono-component adsorption. As





**Fig. 1** The X-ray single crystal structure of **ZJU-198**, indicating that (a) the organic ligand 5-amino-H<sub>2</sub>L coordinates four Zn<sup>2+</sup>; (b) each Zn<sup>2+</sup> exhibits 5-coordination that connects four different organic linkers to construct an asymmetric pentahedron at the secondary building site (SBU); (c) the zigzag channels of about 3.6 Å × 4.1 Å and 2.1 Å × 5.0 Å are viewed from the *a* axis; (d–f) the coordination tendency of the orderly overlapping framework (C, gray; O, red; Zn, cyan; N, blue; H atoms are omitted for clarity).

is well-known, the Ideal Adsorbed Solution Theory (IAST) is recognized to estimate the gas adsorption separation. Thus, the results of the IAST calculation for C<sub>2</sub>H<sub>2</sub>/C<sub>2</sub>H<sub>4</sub> (1 : 99, v/v) and C<sub>2</sub>H<sub>2</sub>/CH<sub>4</sub> (50 : 50, v/v) are expressed in Fig. 3. The selectivity coefficients of C<sub>2</sub>H<sub>2</sub>/C<sub>2</sub>H<sub>4</sub> are 5.8 to 7.7 at 273 K and 4.8 to 7.2 at 298 K, respectively. It's quite surprising to read that the selectivity of C<sub>2</sub>H<sub>2</sub>/CH<sub>4</sub> reaches up to 497.9 and 391.1 for 273 K and 298 K, respectively. Table 1 lists the comparison of **ZJU-198a** with some other promising MOFs for C<sub>2</sub>H<sub>2</sub>/CH<sub>4</sub> separation.<sup>45–50</sup> We are compelled to admit that the C<sub>2</sub>H<sub>2</sub> adsorption capacity of **ZJU-198a** is moderately limited by the relatively low porosity. However, the C<sub>2</sub>H<sub>2</sub>/CH<sub>4</sub> selectivity of **ZJU-198a** drastically outperforms those of other MOFs. To the best of our knowledge, the C<sub>2</sub>H<sub>2</sub>/CH<sub>4</sub> selectivity coefficients of **ZJU-198a** at both 273 K and 298 K are the highest values among the as yet reported metal-organic frameworks (MOFs).

The moderate gas capacity and excellent gas separation make **ZJU-198a** a valuable candidate for hydrocarbon adsorption and separation. Furthermore, the regeneration energy cost

attributed to the binding energy is another essential consideration. The binding energy between the adsorbed gas molecule and framework is reflected in the isosteric heat of adsorption ( $Q_{st}$ ). Fig. 4 illustrates the isosteric heat of C<sub>2</sub>H<sub>2</sub>, C<sub>2</sub>H<sub>4</sub>, and CH<sub>4</sub> with **ZJU-198a**. Unexpectedly, the isosteric heat of C<sub>2</sub>H<sub>4</sub> (37.4 kJ mol<sup>-1</sup>) is higher than that of C<sub>2</sub>H<sub>2</sub> (26.1 kJ mol<sup>-1</sup>), C<sub>2</sub>H<sub>4</sub>, and CH<sub>4</sub> (16.2 kJ mol<sup>-1</sup>).

The discrepancy between the C<sub>2</sub>H<sub>2</sub> molecule and C<sub>2</sub>H<sub>4</sub> molecule is distinctly far less than that between the C<sub>2</sub>H<sub>2</sub> molecule and CH<sub>4</sub> molecule. This is a reasonable excuse for the performance of the C<sub>2</sub>H<sub>2</sub>/C<sub>2</sub>H<sub>4</sub> separation of **ZJU-198a** not looking as outstanding as that of C<sub>2</sub>H<sub>2</sub>/CH<sub>4</sub>. However, there is still a hysteric circumstance about the adsorption of C<sub>2</sub>H<sub>4</sub> versus C<sub>2</sub>H<sub>2</sub> especially at the extremely-low pressure referred to in the insets of Fig. 2. Herein, transient breakthrough simulations were carried out to separate the feed gases C<sub>2</sub>H<sub>2</sub>/C<sub>2</sub>H<sub>4</sub> (1 : 99, v/v), the typical industrial ingredient. As is shown in Fig. 5, the C<sub>2</sub>H<sub>2</sub>/C<sub>2</sub>H<sub>4</sub> mixture is clearly separated by **ZJU-198a**. After a certain time ( $\tau_{break}$ , 64.5 minutes), the impurity level of



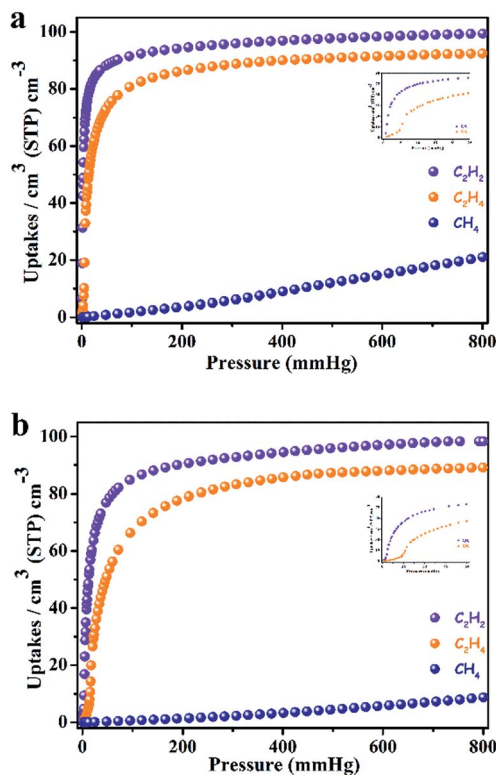


Fig. 2 The single-component adsorption isotherms for  $\text{C}_2\text{H}_2$  (violet),  $\text{C}_2\text{H}_4$  (orange), and  $\text{CH}_4$  (blue) of ZJU-198a at 273 K (a) and 298 K (b). The insets exhibit the adsorption data of  $\text{C}_2\text{H}_2$  and  $\text{C}_2\text{H}_4$  at extremely low pressure.

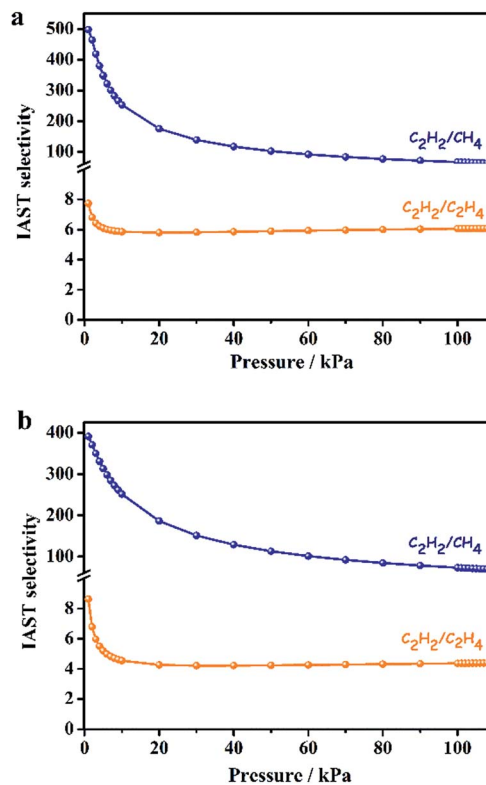


Fig. 3 (a) The IAST calculations of  $\text{C}_2\text{H}_2/\text{C}_2\text{H}_4$  and  $\text{C}_2\text{H}_2/\text{CH}_4$  adsorption selectivity for ZJU-198a at 273 K; (b) the IAST calculations of  $\text{C}_2\text{H}_2/\text{C}_2\text{H}_4$  and  $\text{C}_2\text{H}_2/\text{CH}_4$  adsorption selectivity for ZJU-198a at 298 K.

$\text{C}_2\text{H}_2$  exceeded the purity level at 40 ppm. During the time  $0 \sim \tau_{\text{break}}$ , the amount of  $\text{C}_2\text{H}_2$  captured in ZJU-198a is  $126.8 \text{ mmol L}^{-1}$ , which is still a satisfactory value.

The crystal structure analysis was carried out to demonstrate the excellent  $\text{C}_2\text{H}_2/\text{CH}_4$  and  $\text{C}_2\text{H}_2/\text{C}_2\text{H}_4$  separations of ZJU-198a. Note that the empirical kinetic sizes of  $\text{C}_2\text{H}_2$ ,  $\text{C}_2\text{H}_4$ , and  $\text{CH}_4$  are  $3.32 \text{ \AA} \times 3.34 \text{ \AA}$ ,  $3.28 \text{ \AA} \times 4.18 \text{ \AA}$ , and  $3.82 \text{ \AA} \times 3.94 \text{ \AA}$ , respectively.<sup>51</sup> It's clear to see that there only exists one available window of ZJU-198a of approximately  $3.6 \text{ \AA} \times 4.1 \text{ \AA}$ , which is slightly larger than the size of the  $\text{C}_2\text{H}_2$  molecule, close to that of the  $\text{C}_2\text{H}_4$  molecule while smaller than that of the  $\text{CH}_4$  molecule. Herein, it's easy to understand that the good-enough window of the framework plays an important role in selecting the preferential  $\text{C}_2\text{H}_2$  molecule and closing the door on the  $\text{CH}_4$  molecule. How does the relatively low porosity of ZJU-198a feature in the moderately high  $\text{C}_2\text{H}_2$  adsorption? The  $\text{C}_2\text{H}_2$  molecules were captured in the framework and the diffusion between the adjacent channels was limited by the narrow channels. Therefore, ZJU-198a with orderly overlapping channels exhibits moderately high  $\text{C}_2\text{H}_2$  storage and excellent  $\text{C}_2\text{H}_2/\text{CH}_4$  and  $\text{C}_2\text{H}_2/\text{C}_2\text{H}_4$  separations.

## Conclusions

The amino-coordination microporous metal-organic framework ZJU-198 with a good-enough window has been synthesized

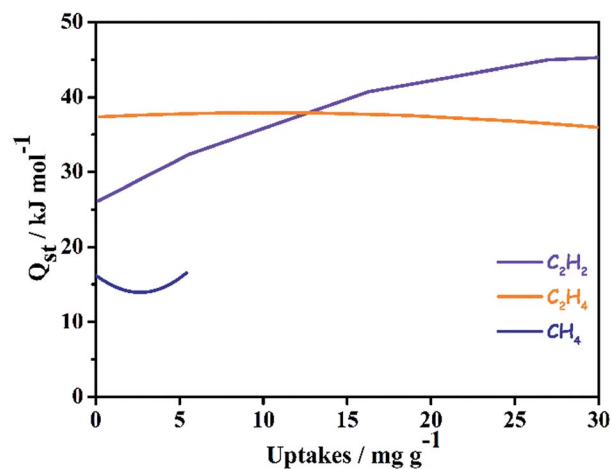


Fig. 4 The isothermic heat of  $\text{C}_2\text{H}_2$ ,  $\text{C}_2\text{H}_4$ , and  $\text{CH}_4$  adsorption,  $Q_{\text{st}}$ , in ZJU-198a.

successfully and further demonstrated as a valuable adsorbent. The activated ZJU-198a exhibits moderate  $\text{C}_2\text{H}_2$  storage and excellent  $\text{C}_2\text{H}_2/\text{CH}_4$  and  $\text{C}_2\text{H}_2/\text{C}_2\text{H}_4$  separations. Especially, the selectivity of  $\text{C}_2\text{H}_2/\text{CH}_4$  is the highest value among the as yet reported metal-organic frameworks (MOFs). Herein, we believe that making the best of the size-sieving effect of the framework



Table 1 The comparison of the adsorption data for selected MOFs

MOFs	Surface area (m <sup>2</sup> g <sup>-1</sup> , BET)	C <sub>2</sub> H <sub>2</sub> uptake (at 1.0 bar, RT, cm <sup>3</sup> g <sup>-1</sup> )	Selectivity for C <sub>2</sub> H <sub>2</sub> /CH <sub>4</sub>	Q <sub>st</sub> of C <sub>2</sub> H <sub>2</sub> (kJ mmol <sup>-1</sup> )	Ref.
ZJNU-55	450	56.3	64.9	42.4	46
BUT-70A	695	69.5	66.6	25.6	47
UTSA-5a	462	59.8	28.4	30.8	48
Cu-TDPAH	—	177.7	127.1	42.5	45
UTSA-50a	604	90.6	68	39.4	50
ZJU-199a	987	128.0	33.5	38.5	49
ZJU-198a	343	72.9	<b>391.1</b>	<b>26.1</b>	<b>This work</b>

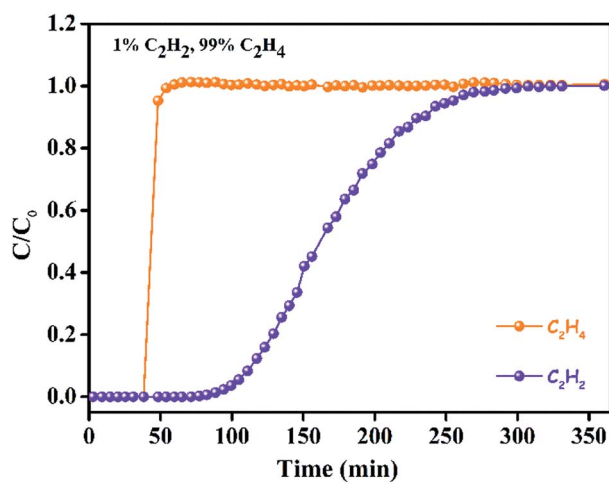


Fig. 5 The breakthrough curves of ZJU-198a for the C<sub>2</sub>H<sub>2</sub>/C<sub>2</sub>H<sub>4</sub> separation (1 : 99; v/v) operated at 1 bar and 298 K. C<sub>A</sub> and C<sub>0</sub> are the concentrations of each gas at the inlet and outlet, respectively.

to achieve efficient gas separation will be a significant approach for further applications.

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