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# Nitrogen-rich porous organic cages with high acetylene storage and separation performance†

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Searching for porous materials that can safely store and efficiently separate acetylene (C<sub>2</sub>H<sub>2</sub>), a commonly used petrochemical feedstock with highly explosive properties, is a pressing and significant task. Nitrogen-rich porous materials have garnered substantial attention for their ability to interact strongly with acidic C<sub>2</sub>H<sub>2</sub>. Herein, we report two novel nitrogen-rich porous organic cages (POCs), namely CPOC-107 and CPOC-203, constructed from the same bowl-shaped tetraformylcalix[4]resorcinarene but different nitrogen-rich imidazolium-based diamine synthons. X-ray crystallographic analysis reveals that CPOC-107 adopts a [2 + 4] lantern-shaped structure, whereas CPOC-203 takes on a [3 + 6] triangular prism shape. Moreover, the cages exhibit large cavity volumes of up to 787 Å<sup>3</sup> and high specific surface areas of up to 1202 m<sup>2</sup> g<sup>-1</sup>. Owing to their high surface areas and high nitrogen content, both cages exhibit impressive C<sub>2</sub>H<sub>2</sub> adsorption capabilities. Specifically, CPOC-107 achieves a remarkable C<sub>2</sub>H<sub>2</sub> uptake value of up to 146 cm<sup>3</sup> g<sup>-1</sup> at 298 K and 1 atm, the highest among those reported for all porous organic materials to date. Moreover, experimental breakthrough tests have confirmed the effective separation of C<sub>2</sub>H<sub>2</sub>/CO<sub>2</sub> mixtures using the CPOC-107 adsorbent.

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## Introduction

Acetylene (C<sub>2</sub>H<sub>2</sub>) is a crucial petrochemical material used in the production of industrial products involving polyurethane, polyester plastics, synthetic rubber, and so on.<sup>1,2</sup> However, storing C<sub>2</sub>H<sub>2</sub> safely remains challenging due to its flammability and explosive nature when subjected to pressures above 2 atm at room temperature.<sup>3</sup> Moreover, C<sub>2</sub>H<sub>2</sub> is usually produced from fractionation and oil cracking, which always involve a small amount of carbon dioxide (CO<sub>2</sub>). Therefore, the discrimination of CO<sub>2</sub> to afford high-purity C<sub>2</sub>H<sub>2</sub> is critical to high-level safety for various industrial applications.<sup>4</sup> Traditional methods to separate C<sub>2</sub>H<sub>2</sub>/CO<sub>2</sub> mixtures, such as solvent extraction and cryogenic distillations, not only suffer from high energy-consuming and environment-unfriendly problems but also possess the risk of introducing secondary by-products. Consequently, it is of great importance and urgency to seek better materials for safer storage of C<sub>2</sub>H<sub>2</sub> and high-efficiency and low-energy technologies to realize C<sub>2</sub>H<sub>2</sub>/CO<sub>2</sub> separation.

In recent years, adsorption and separation technologies based on porous materials have shown promise in addressing C<sub>2</sub>H<sub>2</sub> storage and separation problems.<sup>5–7</sup> In this region, porous metal–organic frameworks (MOFs) have rapidly developed.<sup>8,9</sup> For instances, FJI-H8 and SNNU-98, reported by Hong and Zhai groups, respectively, have realized gravimetric C<sub>2</sub>H<sub>2</sub> uptake values more than 220 cm<sup>3</sup> g<sup>-1</sup> under ambient conditions.<sup>10,11</sup> Furthermore, SNNU-45, a MOF prepared by the Zhai group, has demonstrated the separation of C<sub>2</sub>H<sub>2</sub>/CO<sub>2</sub> with breakthrough time up to 80 min g<sup>-1</sup>.<sup>12</sup> In contrast, the development of porous organic materials (POMs) for C<sub>2</sub>H<sub>2</sub> storage and separation is markedly slower than that of MOFs. To the best of our knowledge, POMs' C<sub>2</sub>H<sub>2</sub> uptake values are generally less than 100 m<sup>2</sup> g<sup>-1</sup> under ambient conditions, and their ability to separate C<sub>2</sub>H<sub>2</sub>/CO<sub>2</sub> mixtures *via* actual breakthrough experiments is also underexplored.<sup>13</sup> Therefore, it is crucial to increase their C<sub>2</sub>H<sub>2</sub> adsorption capacity and explore their C<sub>2</sub>H<sub>2</sub> purification ability to promote the development of POMs in this field.

Porous organic cages (POCs) are an emerging class of low-density crystalline POMs, which are held together from discrete (zero-dimensional; 0D) covalent-bonded macromolecules with permanent intrinsic cavities (0D framework) *via* weak intermolecular interactions.<sup>14–16</sup> Since their inception in 2009 from Cooper's group,<sup>17</sup> research on the design and synthesis of different linkages, shapes, topologies, sizes, and functions of POCs has attracted much attention from chemists and materials scientists.<sup>18–33</sup> Our group focuses on using concave-shaped calix[4]resorcinarene (C4RA) as synthons in construction of

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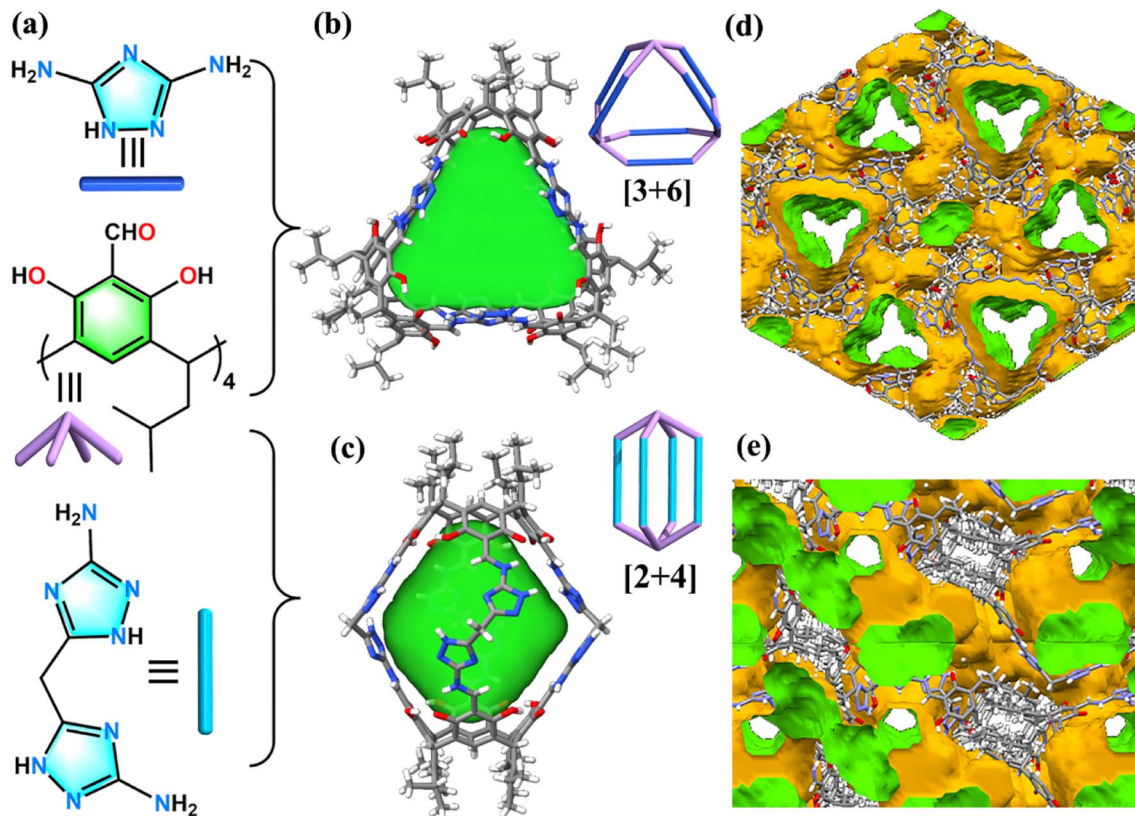


Fig. 1 (a) The chemical structures of organic synthons used for the construction of (b) [3 + 6] CPOC-203 and (c) [2 + 4] CPOC-107 obtained from single-crystal X-ray diffraction and the molecular packing for (d) CPOC-203 and (e) CPOC-107 in the solid state created with Mercury (voids and contact surface in the crystal shown in green and orange, respectively). Carbon is gold, oxygen red, nitrogen blue, and hydrogen white.

novel C4RA-based POCs and their applications.<sup>34–40</sup> In this work, we designed and synthesized two robust nitrogen-rich POCs aiming at efficient storage and separation of  $C_2H_2$ , as the basic nitrogen groups have been verified to have strong interaction with acidic  $C_2H_2$  gas. Both the [2 + 4] lantern-shaped cage (CPOC-107) and [3 + 6] triangular prism-shaped cage (CPOC-203) are constructed from the same bowl-shaped tetraformylcalix[4]resorcinarene (C4RACHO) but different nitrogen-rich imidazolium-based diamine synthons (Fig. 1a–c and S1–S7<sup>†</sup>). We found that both materials show high  $C_2H_2$  uptake capacity under ambient conditions ( $>110 \text{ cm}^3 \text{ g}^{-1}$ ), and the nitrogen content greatly influences their  $C_2H_2$  uptake capacity and  $C_2H_2/CO_2$  separation ability.

## Results and discussion

A mixture of C4RACHO and 3,5-diamino-1,2,4-triazole (DTA) organic synthons with a molar ratio of 1 : 2 in chlorobenzene and methanol mixture at 80 °C for 24 hours affords red block crystals of CPOC-203. Single crystallographic X-ray determination (SCXRD) suggests that CPOC-203 adopts a triangular prism-shaped cage structure (Fig. 1b), with a [3 + 6] assembly mode that is similar to the previously reported CPOC-201, constructed from C4RACHO and *m*-phenylenediamine synthons. CPOC-203 crystallizes in the triclinic system with the space group  $P\bar{1}$  with  $Z = 2$ , and its asymmetric unit contains one

full cage molecule as well as a large number of disordered solvate molecules ( $\sim 46.2\%$  of the unit cell volume), which have been removed by the routine SQUEEZE function of PLATON.<sup>41</sup> The central triangular prism core of CPOC-203 comprises three C4RACHO faces and six DTA edges. It has a volume of  $787 \text{ \AA}^3$  and a window diameter of  $7.04 \text{ \AA}$ , as calculated using Voidoo and Pywindow, respectively.<sup>42–44</sup> The cages pack window-to-window in the solid state with the closest distance of  $\sim 9 \text{ \AA}$  between neighboring prism faces, forming one-dimensional channels (Fig. 1d).

Then we further increase the nitrogen content in imidazolium-based diamine synthons by using bis(5-amino-1,2,4-triazol-3-yl)methane (BATM). Notably, suitable red block single crystals of CPOC-107 can be obtained by an eightfold Schiff base reaction of C4RACHO (1 equiv.) and BATM (2 equiv.) in dimethyl sulfoxide at 100 °C for 72 hours. SCXRD reveals that CPOC-107 crystallizes in a triclinic  $P\bar{1}$  space group with  $Z = 4$ , and contains a whole [2 + 4] organic cage in its asymmetric unit, and residual electron density as highly disordered solvent molecules ( $\sim 45.3\%$  of the unit cell volume), which were removed by SQUEEZE. The structure of CPOC-107 is a lantern-shaped structure with four near rhombic windows (Fig. 1c), featuring two C4RACHO as faces and four BATMs as pillars. The height of the cavity is  $15.4 \text{ \AA}$  which was measured from the center of the C4RACHO face, and its windows can be passed by a sphere with a diameter of about  $4.47 \text{ \AA}$ . Remarkably, CPOC-



107 has a cavity volume of about  $744 \text{ \AA}^3$ , the largest among those of all previously reported lantern-shaped CPOCs, with cavity volumes ranging from 358 to  $581 \text{ \AA}^3$ .<sup>36</sup> The side length of the rhombic windows is about  $4.47 \text{ \AA}$ , which can be passed by a sphere with a diameter of about  $4.47 \text{ \AA}$ . An examination of the CPOC-107's solid-state packing suggested that cage molecules pack *via* weak van der Waals interactions, and there is also a one-dimensional channel in window-to-window mode (Fig. 1e).

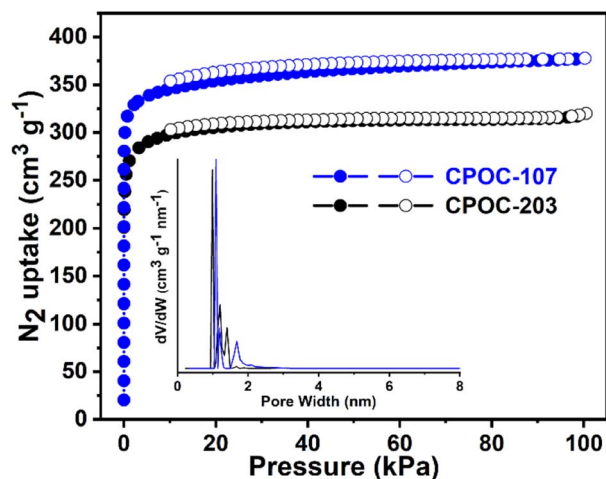


Fig. 2  $\text{N}_2$  gas sorption isotherms at 77 K for CPOC-107 and CPOC-203, inset: the calculated PSD of CPOC-107 and CPOC-203.

The presence of 1D channels in CPOC-107 and CPOC-203 prompts us to study their porosity. Thermal gravimetric analysis measurements showed their stabilities up to about  $280 \text{ }^\circ\text{C}$  (Fig. S7†). Before the gas sorption test, both cages are immersed and exchanged 6 times every 24 hours in MeOH before activating at  $100 \text{ }^\circ\text{C}$  under a high vacuum for 12 hours. Powder X-ray diffraction reveals that after desolvation, no phase change occurs in both materials (Fig. S8 and S9†).  $\text{N}_2$  gas sorption experiments confirmed their permanent porosity at 77 K (Fig. 2), and both the isotherms of CPOC-107 and CPOC-203 exhibited typical type I adsorption behavior with sharp increases at a pressure below  $0.1 P/P_0$ , which reveals their microporous nature. The Brunauer-Emmett-Teller (BET) specific surface areas were  $1202 \text{ m}^2 \text{ g}^{-1}$  for CPOC-107 and  $1132 \text{ m}^2 \text{ g}^{-1}$  for CPOC-203, respectively (Fig. S10 and S11†). The non-local density functional theory (NLDFT) was used to calculate the pore-size distribution (PSD), and both cages showed microporous cavities with  $\sim 1.08 \text{ nm}$  for CPOC-107 and  $\sim 0.98 \text{ nm}$  for CPOC-203 (inset in Fig. 2), which are respectively related to the calculated largest pore diameter of  $0.94$  and  $1.02 \text{ nm}$  using Zeo++ software.<sup>45</sup>

The high surface, together with the presence of a high content of basic nitrogen sites ( $14.8\%$  for CPOC-203 and  $20.1\%$  for CPOC-107) for both cages, further prompts us to use them as solid adsorbents for capturing acidic  $\text{C}_2\text{H}_2$  gas and separating  $\text{C}_2\text{H}_2/\text{CO}_2$  mixtures. Single-component gas equilibrium sorption isotherms of CPOC-107 and CPOC-203 were recorded at  $298 \text{ K}$  and pressure up to 1 bar. As shown in Fig. 3a, the saturated

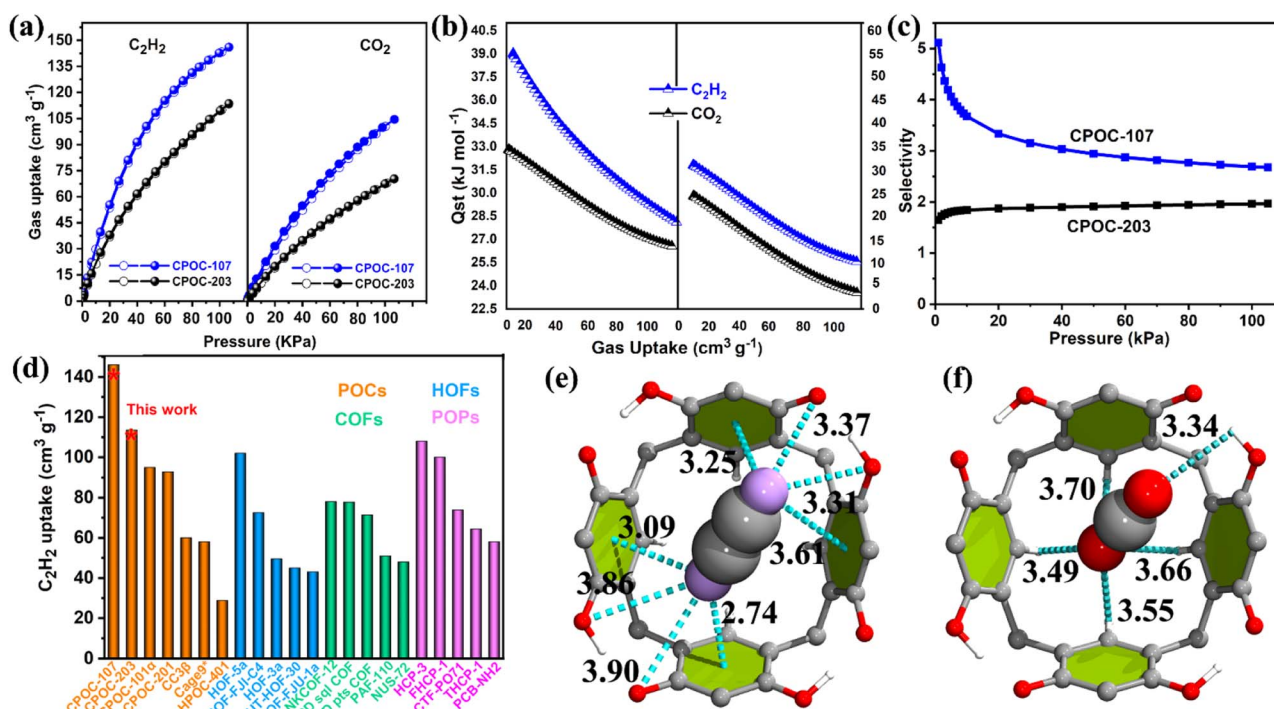


Fig. 3 (a)  $\text{C}_2\text{H}_2$  and  $\text{CO}_2$  sorption isotherms at 298 K; (b)  $Q_{\text{st}}$  values of  $\text{C}_2\text{H}_2$  and  $\text{CO}_2$ ; (c) the  $\text{C}_2\text{H}_2/\text{CO}_2$  IAST selectivity; (d) comparison of  $\text{C}_2\text{H}_2$  uptakes with different top-performed POM adsorbents under ambient conditions; (e)  $\text{C}_2\text{H}_2$  and (f)  $\text{CO}_2$  adsorption sites in CPOC-107 performed in order to understand its  $\text{C}_2\text{H}_2/\text{CO}_2$  separation mechanism. Carbon is gray, oxygen red, and hydrogen lavender. Dashed bonds highlight  $\text{H}\cdots\pi$  and  $\text{H}\cdots\text{O}$  interactions.





$C_2H_2$  adsorption value under the conditions above is  $146 \text{ cm}^3 \text{ g}^{-1}$  for **CPOC-107**, which is higher than that of **CPOC-203**, with a value of  $114 \text{ cm}^3 \text{ g}^{-1}$ . Both values are higher than those of our previously reported cages with similar structural assemblies. Specifically, the  $C_2H_2$  uptakes for the previously reported lantern-shaped  $[2 + 4]$  **CPOC-101** to **CPOC-104** (nitrogen content  $< 6.2\%$ ) are all less than  $95 \text{ cm}^3 \text{ g}^{-1}$ ,<sup>38,46</sup> while for the reported similar triangular prism-shaped  $[3 + 6]$  **CPOC-201** with a nitrogen content of  $5.8\%$  the  $C_2H_2$  uptake is only  $91 \text{ cm}^3 \text{ g}^{-1}$ .<sup>38</sup> The discussions above reveal that increasing the nitrogen content in CPOCs can improve their  $C_2H_2$  uptake ability. Notably, the  $C_2H_2$  uptake value ( $146 \text{ cm}^3 \text{ g}^{-1}$ ) of **CPOC-107** is the highest among those reported for all POMs (Fig. 3d), including POCs,<sup>47,48</sup> hydrogen-bonded organic frameworks (HOFs),<sup>49–52</sup> covalent organic frameworks (COFs)<sup>53–56</sup> and porous organic polymers (POPs).<sup>57–59</sup>

In contrast, under the same conditions, the  $CO_2$  adsorbed capacities of **CPOC-107** and **CPOC-203** are only  $100$  and  $70 \text{ cm}^3 \text{ g}^{-1}$  (Fig. 3a), much lower than their  $C_2H_2$  uptake capacities under the same conditions. Such a result reveals that the affinity for  $C_2H_2$  is stronger than that for  $CO_2$  in both cages. In order to quantify the affinity (low-coverage heat of adsorption;  $Q_{st}$ ) between the cage hosts and the guest gas molecules, their  $C_2H_2$  and  $CO_2$  sorption isotherms at  $273 \text{ K}$  have also been measured (Fig. S12†). The  $Q_{st}$  values are calculated using adsorption isotherms at  $273$  and  $298 \text{ K}$  and fitted by a virial equation (Fig. S13–S16†). The calculated  $Q_{st}$  values for  $C_2H_2$  were  $39.1$  and  $34.9 \text{ kJ mol}^{-1}$  for **CPOC-107** and **CPOC-203**, respectively, which are higher than those for  $CO_2$  with values of  $32.8$  and  $23.2 \text{ kJ mol}^{-1}$ , respectively (Fig. 3b). Such calculated results highly indicate the preferential sorption of  $C_2H_2$  over  $CO_2$  in both cages. Moreover, their gas selectivity values have been calculated using the widely studied ideal adsorbed solution theory (IAST), and the equimolar binary  $C_2H_2/CO_2$  for **CPOC-107** is  $2.7$  at  $298 \text{ K}$  and  $100 \text{ kPa}$ , which is much higher than  $1.9$  for **CPOC-203**. Moreover, the higher  $C_2H_2$  capacity and  $C_2H_2/CO_2$  selectivity of **CPOC-107** suggest that its separation ability for  $C_2H_2/CO_2$  may be better than that of **CPOC-203**. Therefore, their separation potentials ( $\Delta q$ ) are a comprehensive index to evaluate the separation effectiveness of adsorbents based on combining adsorption capacity and selectivity. The calculated  $\Delta q$  value for **CPOC-107** is  $2.67 \text{ mmol g}^{-1}$ , and for **CPOC-203** it is  $1.30 \text{ mmol g}^{-1}$  (Fig. S17†), consistent with our guess.<sup>60</sup>

Moreover, the detailed dispersion-corrected density functional theory (DFT-D) calculations for **CPOC-107** were also carried out by loading  $CO_2$  and  $C_2H_2$  molecules into its crystal structure for further optimization. The lowest-energy binding configurations of the final gas-loaded structures of **CPOC-107** were calculated using DFT-D. In the gas-loaded **CPOC-107**, both  $C_2H_2$  and  $CO_2$  molecules were observed to preferentially reside around C4RA's cavities *via* weak Waals interactions (Fig. 3e and f). Specifically, for the  $C_2H_2$  molecule, both hydrogen atoms were oriented toward the four C4RA's phenyl rings through  $H \cdots \pi$  interactions at distances ranging from  $2.74$  to  $3.61 \text{ \AA}$ . In contrast, their two hydrogen tails were observed to interact with the four C4RA's hydroxy groups through  $H \cdots O$  interactions at distances ranging from  $3.31$  to  $3.90 \text{ \AA}$ . For the  $CO_2$  molecule,

one oxygen atom remained closer to the cage's window through  $O \cdots H$  interactions at a distance of  $3.34 \text{ \AA}$ . At the same time, the other one was oriented towards the bottom of C4RA through  $O \cdots H$  interactions at distances ranging from  $3.49$  to  $3.70 \text{ \AA}$ . The calculated static binding energies of  $C_2H_2$  and  $CO_2$  were  $-38.9$  and  $-31.1 \text{ kJ mol}^{-1}$ , respectively, for **CPOC-107**. These binding energies and the hydrogen-bond number confirmed the stronger host-guest interactions between  $C_2H_2$  and the cage compared to that of  $CO_2$ , which is entirely consistent with our experimental observations.

Lab-scale fixed-bed breakthrough experiments have been performed under ambient conditions to make clear the separation performance of  $C_2H_2/CO_2$  by using **CPOC-107** and **CPOC-203** as adsorbents. An equimolar  $CO_2/C_2H_2$  gas mixture typically flowed over a packed column of the activated samples with a total flow of  $2 \text{ mL min}^{-1}$  at  $298 \text{ K}$  and  $1 \text{ bar}$ . As shown in Fig. 4a,  $CO_2$  passed through the packed column first to produce

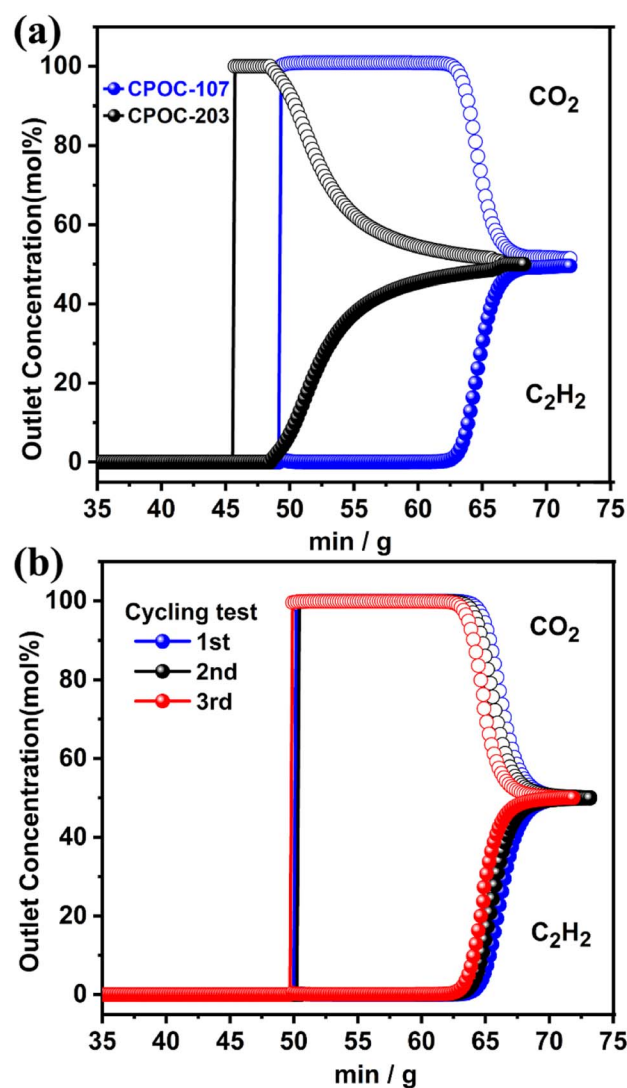


Fig. 4 (a) Experimental breakthrough curves for an equimolar mixture of  $C_2H_2/CO_2$  at  $298 \text{ K}$  and  $1 \text{ bar}$ ; (b) the recyclability of **CPOC-107** under multiple mixed gas column breakthrough tests.



an outflow of pure gas containing no detectable C<sub>2</sub>H<sub>2</sub>, and then C<sub>2</sub>H<sub>2</sub> eluted following a substantial time-lapse for both CPOC materials. The breakthrough time values of CPOC-107 and CPOC-203 are ~13 and 5 min g<sup>-1</sup>, respectively. The longer effective separation time of CPOC-107 than CPOC-203 suggested that the C<sub>2</sub>H<sub>2</sub>/CO<sub>2</sub> separation ability of CPOC-107 is better than that of CPOC-203, consistent with the above-mentioned IAST and Δ*q* results. An ideal separation material should possess recyclability performance to meet practical applications. To evaluate the durability, multiple cycling breakthrough tests for CPOC-107 have been carried out under the same conditions. As displayed in Fig. 4b, the breakthrough time remains unchanged after three recycling experiments, indicating that CPOC-107 is an auspicious C<sub>2</sub>H<sub>2</sub>/CO<sub>2</sub> separation system.

## Conclusions

In summary, we presented two novel C4RA-based POCs with high nitrogen content (>14%), including [2 + 4] lantern-shaped CPOC-107 and [3 + 6] triangular prism-shaped CPOC-203. Both cages exhibit high surface areas (>1100 m<sup>2</sup> g<sup>-1</sup>), and high C<sub>2</sub>H<sub>2</sub> uptake capacity (>110 cm<sup>3</sup> g<sup>-1</sup>) at 298 K and 1 atm. Notably, the nitrogen content of CPOC-107 is up to 20.1%, and thus its C<sub>2</sub>H<sub>2</sub> uptake capacity under ambient conditions is up to 146 cm<sup>3</sup> g<sup>-1</sup>, which is the highest among those reported for POMs. Moreover, CPOC-107 can also efficiently separate C<sub>2</sub>H<sub>2</sub>/CO<sub>2</sub> with a breakthrough time of 13 min g<sup>-1</sup>. This work suggests that nitrogen-rich POCs can be promising materials for safer C<sub>2</sub>H<sub>2</sub> storage, as well as C<sub>2</sub>H<sub>2</sub> purification application. Further studies are focusing on design and synthesis of functionalized POCs by introducing specific group sites for improving their gas storage and separation performances.

## Conflicts of interest

There are no conflicts to declare.

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## Notes and references

- V. V. Voronin, M. S. Ledovskaya, A. S. Bogachenkov, K. S. Rodygin and V. P. Ananikov, *Molecules*, 2018, **23**, 2442.
- P. J. Stang and F. Diederich, *Modern acetylene chemistry*, VCH Weinheim, 1995.
- R. Matsuda, R. Kitaura, S. Kitagawa, Y. Kubota, R. V. Belosludov, T. C. Kobayashi, H. Sakamoto, T. Chiba, M. Takata, Y. Kawazoe and Y. Mita, *Nature*, 2005, **436**, 238–241.
- A. Corma, E. Corresa, Y. Mathieu, L. Sauvanaud, S. Al-Bogami, M. S. Al-Ghrami and A. Bourane, *Catal. Sci. Technol.*, 2017, **7**, 12–46.
- H. Li, C. Liu, C. Chen, Z. Di, D. Yuan, J. Pang, W. Wei, M. Wu and M. Hong, *Angew. Chem., Int. Ed.*, 2021, **60**, 7547–7552.
- W. Gong, H. Cui, Y. Xie, Y. Li, X. Tang, Y. Liu, Y. Cui and B. Chen, *J. Am. Chem. Soc.*, 2021, **143**, 14869–14876.
- B. Zhang, Y. Rao, L. Hou, B. Liu and Q. Li, *ACS Mater. Lett.*, 2022, **4**, 1774–1779.
- Y. Li and G. Wen, *Eur. J. Inorg. Chem.*, 2020, **2020**, 2303–2311.
- G. Verma, J. Ren, S. Kumar and S. Ma, *Eur. J. Inorg. Chem.*, 2021, **2021**, 4498–4507.
- J.-W. Wang, S.-C. Fan, H.-P. Li, X. Bu, Y.-Y. Xue and Q.-G. Zhai, *Angew. Chem., Int. Ed.*, 2023, e202217839.
- J. Pang, F. Jiang, M. Wu, C. Liu, K. Su, W. Lu, D. Yuan and M. Hong, *Nat. Commun.*, 2015, **6**, 7575.
- Y.-P. Li, Y. Wang, Y.-Y. Xue, H.-P. Li, Q.-G. Zhai, S.-N. Li, Y.-C. Jiang, M.-C. Hu and X. Bu, *Angew. Chem., Int. Ed.*, 2019, **58**, 13590–13595.
- W. Wang, L. Wang, F. Du, G.-D. Wang, L. Hou, Z. Zhu, B. Liu and Y.-Y. Wang, *Chem. Sci.*, 2023, **14**, 533–539.
- X. Yang, Z. Ullah, J. F. Stoddart and C. T. Yavuz, *Chem. Rev.*, 2023, 4602–4634.
- T. Hasell and A. I. Cooper, *Nat. Rev. Mater.*, 2016, **1**, 16053.
- M. Mastalerz, *Acc. Chem. Res.*, 2018, **51**, 2411–2422.
- T. Tozawa, J. T. A. Jones, S. I. Swamy, S. Jiang, D. J. Adams, S. Shakespeare, R. Clowes, D. Bradshaw, T. Hasell, S. Y. Chong, C. Tang, S. Thompson, J. Parker, A. Trewin, J. Bacsá, A. M. Z. Slawin, A. Steiner and A. I. Cooper, *Nat. Mater.*, 2009, **8**, 973–978.
- T. Jiao, H. Qu, L. Tong, X. Cao and H. Li, *Angew. Chem., Int. Ed.*, 2021, **60**, 9852–9858.
- X. Liu, G. Zhu, D. He, L. Gu, P. Shen, G. Cui, S. Wang, Z. Shi, D. Miyajima, S. Wang and S. Zhang, *CCS Chem.*, 2022, **4**, 2420–2428.
- S. Huang, Z. Lei, Y. Jin and W. Zhang, *Chem. Sci.*, 2021, **12**, 9591–9606.
- H. Duan, F. Cao, H. Hao, H. Bian and L. Cao, *ACS Appl. Mater. Interfaces*, 2021, **13**, 16837–16845.
- S. Bera, K. Dey, T. K. Pal, A. Halder, S. Tothadi, S. Karak, M. Addicoat and R. Banerjee, *Angew. Chem., Int. Ed.*, 2019, **58**, 4243–4247.
- M. Hua, S. Wang, Y. Gong, J. Wei, Z. Yang and J.-K. Sun, *Angew. Chem., Int. Ed.*, 2021, **60**, 12490–12497.
- Q.-P. Hu, H. Zhou, T.-Y. Huang, Y.-F. Ao, D.-X. Wang and Q.-Q. Wang, *J. Am. Chem. Soc.*, 2022, **144**, 6180–6184.
- S. Wu, Y. Ni, Y. Han, S. Xin, X. Hou, J. Zhu, Z. Li and J. Wu, *J. Am. Chem. Soc.*, 2022, **144**, 23158–23167.
- G. Montà-González, F. Sancenón, R. Martínez-Mañez and V. J. C. R. Martí-Centelles, *Chem. Rev.*, 2022, **122**, 13636–13708.
- H. Wang, Y. Jin, N. Sun, W. Zhang and J. Jiang, *Chem. Soc. Rev.*, 2021, **50**, 8874–8886.
- F. Qiu, X. Chen, W. Wang, K. Su and D. Yuan, *CCS Chem.*, 2023, DOI: [10.31635/ccschem.023.202302903](https://doi.org/10.31635/ccschem.023.202302903).
- R. D. Mukhopadhyay, Y. Kim, J. Koo and K. Kim, *Acc. Chem. Res.*, 2018, **51**, 2730–2738.



- 30 L. Chen, C. Li, E. Fu, M. Li, Y. Kuboi, Z.-Y. Li, Z. Chen, J. Chen, X. Liu, X. Tang, L. Frederic, F. Maurel, C. Adachi, F. Mathevet and S. Zhang, *ACS Mater. Lett.*, 2023, **5**, 1450–1455.
- 31 W.-T. Dou, C.-Y. Yang, L.-R. Hu, B. Song, T. Jin, P.-P. Jia, X. Ji, F. Zheng, H.-B. Yang and L. Xu, *ACS Mater. Lett.*, 2023, **5**, 1061–1082.
- 32 M. C. Brand, F. Greenwell, R. Clowes, B. D. Egleston, A. Kai, A. I. Cooper, T. D. Bennett and R. L. Greenaway, *J. Mater. Chem. A*, 2021, **9**, 19807–19816.
- 33 S. Lee, I. Kevlishvili, H. J. Kulik, H.-T. Kim, Y. G. Chung and D.-Y. Koh, *J. Mater. Chem. A*, 2022, **10**, 24802–24812.
- 34 F. Gao, C. Luo, X. Wang, C. Zhan, Y. Li, Y. Li, Q. Meng, M. Yang, K. Su, D. Yuan, R. Zhu and Q. Zhao, *Adv. Funct. Mater.*, 2023, **33**, 2211900.
- 35 N. Xu, K. Su, E.-S. M. El-Sayed, Z. Ju and D. Yuan, *Chem. Sci.*, 2022, **13**, 3582–3588.
- 36 M. Yang, F. Qiu, E.-S. M. El-Sayed, W. Wang, S. Du, K. Su and D. Yuan, *Chem. Sci.*, 2021, **12**, 13307–13315.
- 37 X. Zhang, K. Su, A. G. A. Mohamed, C. Liu, Q. Sun, D. Yuan, Y. Wang, W. Xue and Y. Wang, *Energy Environ. Sci.*, 2022, **15**, 780–785.
- 38 K. Su, W. Wang, S. Du, C. Ji, M. Zhou and D. Yuan, *J. Am. Chem. Soc.*, 2020, **142**, 18060–18072.
- 39 M. Yang, X. Chen, Y. Xie, E.-S. M. El-Sayed, N. Xu, W. Wang, K. Su and D. Yuan, *Sci. China: Chem.*, 2023, **66**, 1763–1770.
- 40 K. Su, W. Wang, S. Du, C. Ji and D. Yuan, *Nat. Commun.*, 2021, **12**, 3703.
- 41 A. L. Spek, *Acta Crystallogr., Sect. C: Struct. Chem.*, 2015, **71**, 9–18.
- 42 <https://xray.bmc.uu.se/usf/>.
- 43 G. J. Kleywegt and T. A. Jones, *Acta Crystallogr., Sect. D: Biol. Crystallogr.*, 1994, **50**, 178–185.
- 44 S. Sanz, K. Ferreira, R. D. McIntosh, S. J. Dalgarno and E. K. Brechin, *Chem. Commun.*, 2011, **47**, 9042–9044.
- 45 S. M. Taylor, R. D. McIntosh, C. M. Beavers, S. J. Teat, S. Piligkos, S. J. Dalgarno and E. K. Brechin, *Chem. Commun.*, 2011, **47**, 1440–1442.
- 46 W. Wang, K. Su, E.-S. M. El-Sayed, M. Yang and D. Yuan, *ACS Appl. Mater. Interfaces*, 2021, **13**, 24042–24050.
- 47 S. M. Elbert, N. I. Regenauer, D. Schindler, W.-S. Zhang, F. Rominger, R. R. Schroeder and M. Mastalerz, *Chem.–Eur. J.*, 2018, **24**, 11438–11443.
- 48 C. D. Charles and E. D. Bloch, *Supramol. Chem.*, 2019, **31**, 508–513.
- 49 P. Li, Y. He, Y. Zhao, L. Weng, H. Wang, R. Krishna, H. Wu, W. Zhou, M. O’Keeffe, Y. Han and B. Chen, *Angew. Chem., Int. Ed.*, 2015, **54**, 574–577.
- 50 H. Wang, B. Li, H. Wu, T.-L. Hu, Z. Yao, W. Zhou, S. Xiang and B. Chen, *J. Am. Chem. Soc.*, 2015, **137**, 9963–9970.
- 51 Y. Yang, H. Zhang, Z. Yuan, J.-Q. Wang, F. Xiang, L. Chen, F. Wei, S. Xiang, B. Chen and Z. Zhang, *Angew. Chem., Int. Ed.*, 2022, **61**, e202207579.
- 52 L. Wang, L. Yang, L. Gong, R. Krishna, Z. Gao, Y. Tao, W. Yin, Z. Xu and F. Luo, *Chem. Eng. J.*, 2020, **383**, 123117.
- 53 L. Chen, C. Gong, X. Wang, F. Dai, M. Huang, X. Wu, C.-Z. Lu and Y. Peng, *J. Am. Chem. Soc.*, 2021, **143**, 10243–10249.
- 54 L. Jiang, Y. Tian, T. Sun, Y. Zhu, H. Ren, X. Zou, Y. Ma, K. R. Meihaus, J. R. Long and G. Zhu, *J. Am. Chem. Soc.*, 2018, **140**, 15724–15730.
- 55 Z. Zhang, C. Kang, S. B. Peh, D. Shi, F. Yang, Q. Liu and D. Zhao, *J. Am. Chem. Soc.*, 2022, **144**, 14992–14996.
- 56 P. Zhang, Z. Wang, Y. Yang, S. Wang, T. Wang, J. Liu, P. Cheng, Y. Chen and Z. Zhang, *Sci. China: Chem.*, 2022, **65**, 1173–1184.
- 57 S. Zhang, M. K. Taylor, L. Jiang, H. Ren and G. Zhu, *Chem.–Eur. J.*, 2020, **26**, 3205–3221.
- 58 Z. Jia, J. Pan and D. Yuan, *ChemistryOpen*, 2017, **6**, 554–561.
- 59 X. Liu, C. Xu, X. Yang, Y. He, Z. Guo and D. Yan, *Microporous Mesoporous Mater.*, 2019, **275**, 95–101.
- 60 Y. Jiang, J. Hu, L. Wang, W. Sun, N. Xu, R. Krishna, S. Duttwyler, X. Cui, H. Xing and Y. Zhang, *Angew. Chem., Int. Ed.*, 2022, **61**, e202200947.

