

## RESEARCH ARTICLE

View Article Online  
View Journal | View Issue

# The effect of pore sizes on D<sub>2</sub>/H<sub>2</sub> separation conducted by MOF-74 analogues†

Cite this: *Inorg. Chem. Front.*, 2022, **9**, 1674Liqiong Li,<sup>a,b</sup> Chunqing Ji,<sup>b,c</sup> Wenjing Wang,<sup>b</sup> Fan Wu,<sup>b</sup> Yan-Xi Tan<sup>\*a,b</sup> and Daqiang Yuan<sup>†a,b</sup>

Four stable MOF-74 analogues, namely Ni<sub>2</sub>(dobdc), Ni<sub>2</sub>(dobpdc), Ni<sub>2</sub>(olz) and Ni<sub>2</sub>(dotpdc), possessing abundant open metal sites (OMSs) and honeycomb channels with pore sizes ranging from 1.0 to 2.6 nm, were used to research the effects of the pore size on D<sub>2</sub>/H<sub>2</sub> separation from the hydrogen isotope mixture through dynamic column breakthrough experiments. With respect to consideration of the chemical affinity quantum sieving (CAQS) effect and the competitive adsorption between Ne and hydrogen isotope in (H<sub>2</sub>/D<sub>2</sub>/Ne: 1/1/98) and (H<sub>2</sub>/D<sub>2</sub>/Ne: 10/10/80) mixtures, the microporous Ni<sub>2</sub>(dobdc) exhibits the longest breakthrough time periods of 240 and 36.4 min g<sup>-1</sup>, respectively. In the (H<sub>2</sub>/D<sub>2</sub>: 50/50) mixture, mesoporous Ni<sub>2</sub>(olz) exhibits the longest breakthrough time of 15.0 min g<sup>-1</sup> owing to its more accessible OMSs and diffusion rate of hydrogen isotope being inclined to adsorb heavier D<sub>2</sub> rather than H<sub>2</sub>. Hence, mesoporous MOFs with abundant OMSs may be ideal candidates for D<sub>2</sub>/H<sub>2</sub> separation.

Received 19th January 2022,  
Accepted 20th February 2022

DOI: 10.1039/d2qi00156j

rsc.li/frontiers-inorganic

## Introduction

With concerns over the development of sustainable energy sources, controlled fusion is seen as the ideal energy solution, and the International Thermonuclear Experimental Reactor (ITER) programme is researching and developing this technology. However, hydrogen isotope separation is one of the most critical technical issues in the ITER fuel cycle. To date, this technology has not been effectively overcome.<sup>1–4</sup> The extraction, separation, and purification of H<sub>2</sub> and D<sub>2</sub> are very difficult due to their almost identical sizes, shapes, and physicochemical properties. Traditional techniques, such as low-temperature distillation, thermal diffusion, centrifugation, laser separation, and chromatography, are energy-intensive, inefficient, and costly.<sup>5–8</sup> Based on the chemical affinity quantum sieving (CAQS) effect proposed by Prof. Oh, heavier D<sub>2</sub> preferentially adsorbed onto the strong active sites to achieve high D<sub>2</sub>/H<sub>2</sub> separation.<sup>9</sup> Inspired by this, the assembling of strong active sites into porous frameworks will exhibit a highly efficient D<sub>2</sub>/H<sub>2</sub> separation, and such physisorption has the advantages of low energy consumption, process simplification, and low cost.<sup>10,11</sup>

Metal-organic frameworks (MOFs), as emerging materials with designable structures, large porosities, and abundant open metal sites (OMSs), are widely used in gas sorption and separation.<sup>12–27</sup> The use of MOFs as separation mixed-bed filters in flow separation systems for hydrogen isotope mixtures requires a very high selectivity for one of the components in the mixtures.<sup>28</sup> Therefore, MOFs with abundant OMSs as recognized strong active sites are ideal separating media for D<sub>2</sub>/H<sub>2</sub> separation. For example, Cu(I)-MFU-4L with strong active Cu(I) sites demonstrated high D<sub>2</sub>/H<sub>2</sub> selectivity at a very low temperature of 20 K, as measured by low-temperature thermal desorption spectroscopy.<sup>29,30</sup> In our previous studies, we investigated the D<sub>2</sub>/H<sub>2</sub> separation properties of FYJ-Y11,<sup>31</sup> M-MOF-74,<sup>32</sup> and M<sub>2</sub>(m-dobdc)<sup>33</sup> measured by the dynamic column breakthrough experiment, which is closer to simulating industrial separation processes. The famous MOF-74 series frameworks with high density of OMSs, particularly Co-MOF-74, exhibited satisfying D<sub>2</sub>/H<sub>2</sub> separation performances. Although numerous mesoporous MOFs have been synthesized, chemists are more inclined to use microporous MOFs for D<sub>2</sub>/H<sub>2</sub> separation because of their spatial confinement effects within the small pores. However, compared to microporous MOFs, mesoporous MOFs also have some advantages toward D<sub>2</sub>/H<sub>2</sub> separation, including more accessible OMSs for preferential combination of heavier D<sub>2</sub> based on CAQS and large pores for increasing diffusion rate of the hydrogen isotope. No effort was focused on determining how the above two factors affected the sorption and separation of the hydrogen isotope, which inspired us to explore the D<sub>2</sub>/H<sub>2</sub> separation using the mesoporous MOFs.

<sup>a</sup>College of Chemistry, Fuzhou University, Fuzhou, 350108, China<sup>b</sup>State Key Laboratory of Structural Chemistry, Fujian Institute of Research on the Structure of Matter, Chinese Academy of Sciences, Fuzhou, 350002 Fujian, China<sup>c</sup>University of the Chinese Academy of Sciences, Beijing, 100049, China.

E-mail: tyx@fjirsm.ac.cn, ydq@fjirsm.ac.cn

† Electronic supplementary information (ESI) available: Additional diagrams and materials characterization. See DOI: 10.1039/d2qi00156j

As the structural analogue of the famous  $\text{Ni}_2(\text{dobdc})$  ( $\text{Ni-MOF-74}$ ),<sup>34</sup> stable  $\text{Ni}_2(\text{dobpdc})$ ,<sup>35</sup>  $\text{Ni}_2(\text{olz})$ <sup>36</sup> and  $\text{Ni}_2(\text{dotpdc})$ <sup>37</sup> possessed abundant OMSs after activation and honeycomb 1D channels with pore sizes 1.9, 2.2 and 2.6 nm, respectively, ranging from microporous to mesoporous pores (Fig. 1). These four MOFs provided an ideal platform for researching the effect of the pore size on  $\text{D}_2/\text{H}_2$  separation. Based on the above considerations, we evaluated the  $\text{D}_2/\text{H}_2$  separation of  $\text{Ni}_2(\text{dobdc})$ ,  $\text{Ni}_2(\text{dobpdc})$ ,  $\text{Ni}_2(\text{olz})$  and  $\text{Ni}_2(\text{dotpdc})$  frameworks by considering the effect of the pore size during the breakthrough process, which would propose optimal operating parameters for hydrogen isotope separation under simulated industrial conditions.

## Results and discussion

The materials  $\text{Ni}_2(\text{dobdc})$ ,  $\text{Ni}_2(\text{dobpdc})$ ,  $\text{Ni}_2(\text{olz})$ , and  $\text{Ni}_2(\text{dotpdc})$  were synthesized by the solvothermal method as previously reported.<sup>32–35</sup> Their purities were confirmed by PXRD patterns (Fig. S3–S6†). The involvement of  $\text{Ni}^{2+}$  and O atoms from the hydroxyl and carboxyl groups allowed these MOFs to retain their original skeletons under 180 °C and high vacuum, providing activated samples for gas sorption.  $\text{N}_2$  sorption experiments further established the permanent porosities of these activated samples at 77 K, which showed the Brunner–Emmett–Teller surface areas (Fig. S2†) of 1280, 2574, 2659 and 2842  $\text{m}^2 \text{g}^{-1}$  for the microporous  $\text{Ni}_2(\text{dobdc})$  and  $\text{Ni}_2(\text{dobpdc})$ , and mesoporous  $\text{Ni}_2(\text{olz})$  and  $\text{Ni}_2(\text{dotpdc})$ , respectively (Fig. 2). The pore size distributions of  $\text{Ni}_2(\text{dobdc})$  (1.0 nm),  $\text{Ni}_2(\text{dobpdc})$  (1.9 nm),  $\text{Ni}_2(\text{olz})$  (2.2 nm) and  $\text{Ni}_2(\text{dotpdc})$  (2.6 nm) frameworks were analyzed by the NLDFT method (Fig. S1†).

Upon activation and dehydration, a high concentration of OMS was exposed in the hexagonal channels of the material, which contributed to increased absorption at low pressures.<sup>38–40</sup> Due to its low zero-point energy and high enthalpy of adsorption,  $\text{D}_2$  would be preferentially adsorbed onto OMSs,<sup>41,42</sup> while the large pore size allowed the diffusion process to proceed rapidly, thereby resulting in fast adsorption kinetics.<sup>43,44</sup>

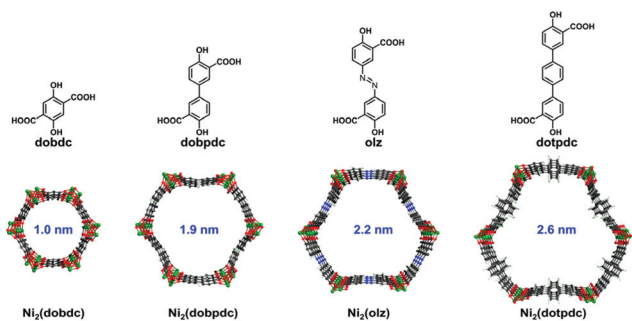


Fig. 1 Ligands and structures of  $\text{Ni}_2(\text{dobdc})$ ,  $\text{Ni}_2(\text{dobpdc})$ ,  $\text{Ni}_2(\text{olz})$  and  $\text{Ni}_2(\text{dotpdc})$  with different pore sizes.

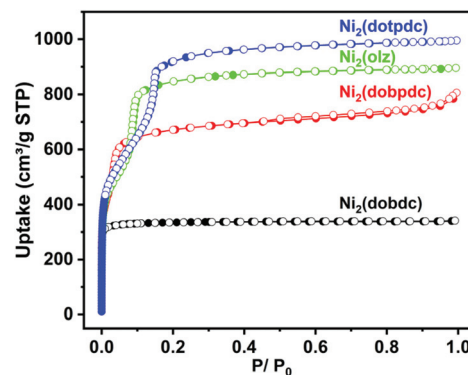
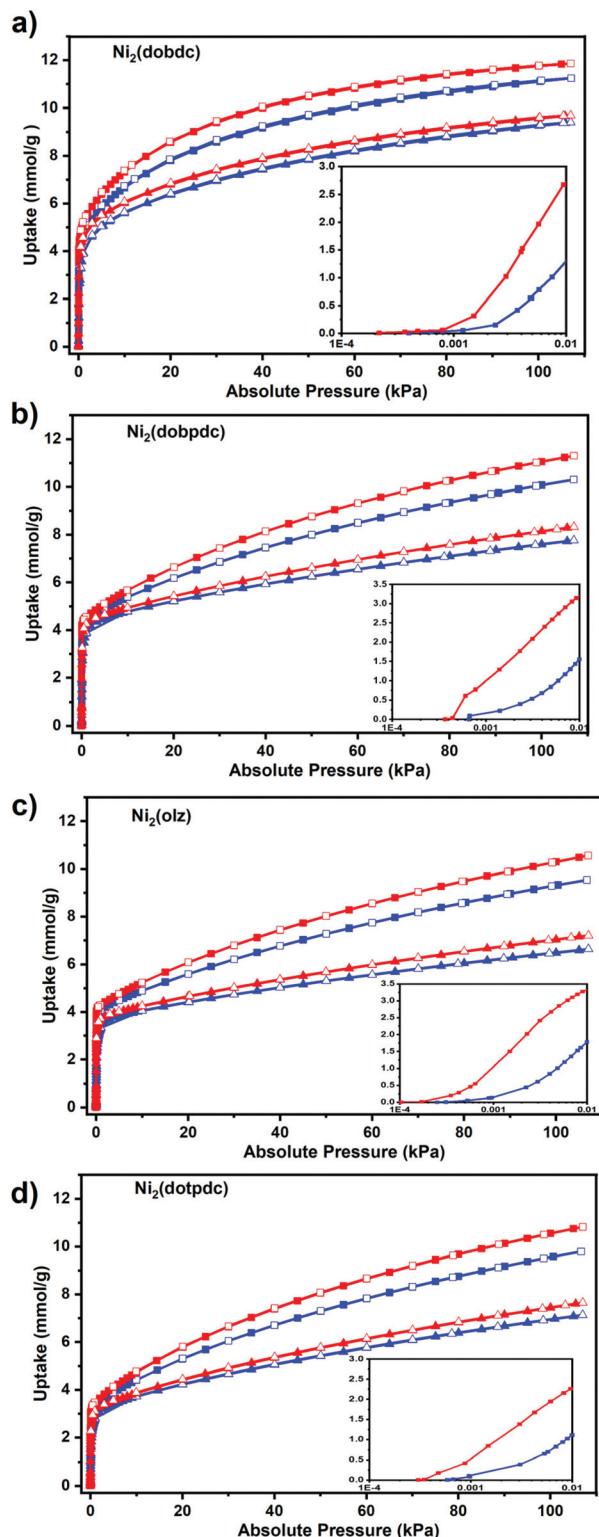


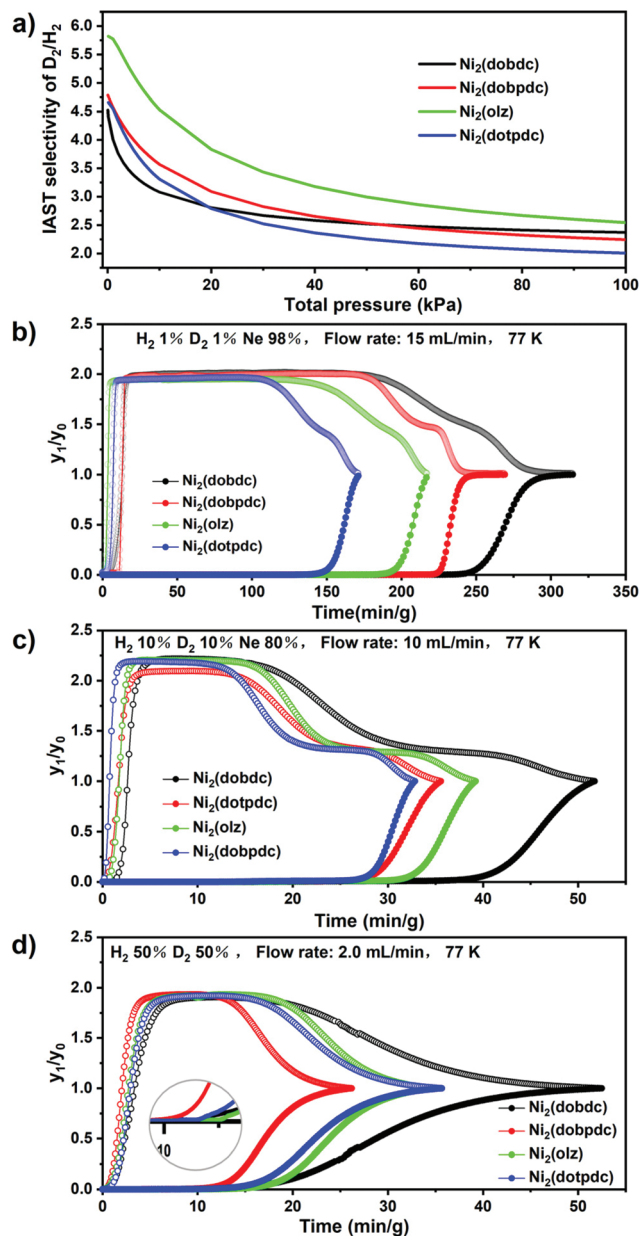
Fig. 2  $\text{N}_2$  sorption isotherms of  $\text{Ni}_2(\text{dobdc})$ ,  $\text{Ni}_2(\text{dobpdc})$ ,  $\text{Ni}_2(\text{olz})$  and  $\text{Ni}_2(\text{dotpdc})$  at 77 K (filled, adsorption; empty, desorption).

In order to better investigate the adsorption behaviour of this series of materials for hydrogen isotopes, adsorption isotherms were obtained for  $\text{H}_2$  and  $\text{D}_2$  at 77 K and 87 K, respectively.  $\text{Ni}_2(\text{dobdc})$  exhibited uptakes of 11.2  $\text{mmol g}^{-1}$  for  $\text{H}_2$  and 11.6  $\text{mmol g}^{-1}$  for  $\text{D}_2$  at 110 kPa and 77 K, which were slightly higher than those of  $\text{Ni}_2(\text{dobpdc})$  ( $\text{H}_2$ : 10.3  $\text{mmol g}^{-1}$ ,  $\text{D}_2$ : 11.3  $\text{mmol g}^{-1}$ ),  $\text{Ni}_2(\text{olz})$  ( $\text{H}_2$ : 9.6  $\text{mmol g}^{-1}$ ,  $\text{D}_2$ : 10.6  $\text{mmol g}^{-1}$ ) and  $\text{Ni}_2(\text{dotpdc})$  ( $\text{H}_2$ : 9.8  $\text{mmol g}^{-1}$ ,  $\text{D}_2$ : 10.83  $\text{mmol g}^{-1}$ ) (Fig. 3). It can be found that for the total adsorption, the microporous material had the highest adsorption of  $\text{D}_2$  and  $\text{H}_2$ . However, at a very low pressure of 0.01 kPa,  $\text{Ni}_2(\text{olz})$  exhibited the highest uptakes of  $\text{D}_2$  (3.27  $\text{mmol g}^{-1}$ ) and  $\text{H}_2$  (1.8  $\text{mmol g}^{-1}$ ), followed by  $\text{Ni}_2(\text{dobpdc})$  ( $\text{D}_2$ : 3.15  $\text{mmol g}^{-1}$ ,  $\text{H}_2$ : 1.55  $\text{mmol g}^{-1}$ ),  $\text{Ni}_2(\text{dobdc})$  ( $\text{D}_2$ : 2.7  $\text{mmol g}^{-1}$ ,  $\text{H}_2$ : 1.4  $\text{mmol g}^{-1}$ ) and  $\text{Ni}_2(\text{dotpdc})$  ( $\text{D}_2$ : 2.25  $\text{mmol g}^{-1}$ ,  $\text{H}_2$ : 1.10  $\text{mmol g}^{-1}$ ) (Fig. 3 Insert). The higher adsorption can be attributed to the strong bonding between the OMSs and the hydrogen isotope molecules in the backbone, which was further confirmed by the enthalpy of adsorption calculated using the Clausius–Clapeyron equation (Table S1†). The  $\text{D}_2/\text{H}_2(50/50)$  selectivity of four MOFs was evaluated by the ideal adsorption solution theory (IAST) to predict their  $\text{D}_2/\text{H}_2$  separation capacities (Fig. 4a and S7–S10†). It is found that the  $\text{D}_2/\text{H}_2(50/50)$  selectivity of  $\text{Ni}_2(\text{olz})$  reached 5.6 under 77 K and 0.01 kPa, followed by  $\text{Ni}_2(\text{dobpdc})$  (4.8),  $\text{Ni}_2(\text{dobdc})$  (4.5) and  $\text{Ni}_2(\text{dotpdc})$  (4.6). According to previous studies,  $\text{Ni}_2(\text{olz})$  was by far the MOF with the highest IAST selectivity at 77 K.

Breakthrough experiments were carried out at 77 K to check the actual separation performances of  $\text{Ni}_2(\text{dobdc})$ ,  $\text{Ni}_2(\text{dobpdc})$ ,  $\text{Ni}_2(\text{olz})$  and  $\text{Ni}_2(\text{dotpdc})$ . Therefore, the hydrogen isotope mixtures with different compositions, ( $\text{H}_2/\text{D}_2/\text{Ne}$ : 1/1/98), ( $\text{H}_2/\text{D}_2/\text{Ne}$ : 10/10/80) and ( $\text{H}_2/\text{D}_2$ : 50/50), were used to assess the practical  $\text{D}_2/\text{H}_2$  separation capabilities of these isostructural materials. For these four adsorbents, when the ( $\text{H}_2/\text{D}_2/\text{Ne}$ : 1/1/98) mixture flowed through the packed column at a flow rate of 15  $\text{mL min}^{-1}$ ,  $\text{H}_2$  always flowed out first because of its lower adsorption capacity and weaker bonding to the adsorbent, while  $\text{D}_2$  remained in the packed column after the hydrogen separation. In packed columns filled with  $\text{Ni}_2(\text{dobdc})$ , the  $\text{D}_2$  retention time reached a maximum of 240  $\text{min g}^{-1}$ , longer



**Fig. 3** The hydrogen isotope sorption of Ni<sub>2</sub>(dobdc) (a), Ni<sub>2</sub>(dobpdc) (b), Ni<sub>2</sub>(olz) (c) and Ni<sub>2</sub>(dotpdc) (d) at 77 and 78 K (filled, adsorption; empty, desorption). Insert: Sorption below a very low pressure of 0.01 kPa. Note: D<sub>2</sub> under 77 K (red □); H<sub>2</sub> under 77 K (blue □); D<sub>2</sub> under 87 K (red Δ); H<sub>2</sub> under 87 K (blue Δ).



**Fig. 4** (a) H<sub>2</sub>/D<sub>2</sub>(50/50) IAST selectivities of Ni<sub>2</sub>(dobdc), Ni<sub>2</sub>(dobpdc), Ni<sub>2</sub>(olz) and Ni<sub>2</sub>(dotpdc) at 77 K. (b–d) Breakthrough curves for D<sub>2</sub>/H<sub>2</sub> separation on Ni<sub>2</sub>(dobdc) (black), Ni<sub>2</sub>(dobpdc) (red), Ni<sub>2</sub>(olz) (green), Ni<sub>2</sub>(dotpdc) (blue). The hollow circle represents H<sub>2</sub>, and the solid circle represents D<sub>2</sub>.

than those of Ni<sub>2</sub>(dobpdc) (215 min g<sup>-1</sup>), Ni<sub>2</sub>(olz) (180 min g<sup>-1</sup>) and Ni<sub>2</sub>(dotpdc) (142 min g<sup>-1</sup>) (Fig. 4b). D<sub>2</sub> retention times decreased with an increase in pore sizes of these four materials. When the gas mixture (H<sub>2</sub>/D<sub>2</sub>/Ne: 10/10/80) flowed through the packed column at a flow rate of 10 mL min<sup>-1</sup>, the D<sub>2</sub> retention time of the microporous Ni<sub>2</sub>(dobdc) reached a maximum of 36.4 min g<sup>-1</sup>, but mesoporous Ni<sub>2</sub>(olz) and Ni<sub>2</sub>(dotpdc) exhibited D<sub>2</sub> retention times of 30.0 and 26.5 min g<sup>-1</sup>, both of which exceeded that of microporous Ni<sub>2</sub>(dobpdc) (25 min g<sup>-1</sup>) (Fig. 4c). When a high concentration

of the hydrogen isotope mixture ( $H_2/D_2$ : 50/50) was passed through the packed column at a flow rate of  $2 \text{ mL min}^{-1}$ , mesoporous  $Ni_2(olz)$  showed the longest  $D_2$  retention time of  $15.0 \text{ min g}^{-1}$ , which exceeded those of  $Ni_2(dobdc)$  ( $13.5 \text{ min g}^{-1}$ ) and  $Ni_2(dotpdc)$  ( $13.0 \text{ min g}^{-1}$ ) with the largest pore size. Microporous  $Ni_2(dobpdc)$  exhibited the shortest  $D_2$  retention time of  $10.0 \text{ min g}^{-1}$  (Fig. 4d).

In the actual application of separation, excellent regeneration ability and structural stability were both important for suitable adsorbents; therefore, breakthrough experiments of the ( $H_2/D_2$ : 50/50) mixture on  $Ni_2(dobdc)$ ,  $Ni_2(dobpdc)$ ,  $Ni_2(olz)$  and  $Ni_2(dotpdc)$  were tested two times to evaluate their cycle performances. There is no noticeable degradation of the breakthrough time on these MOFs during their second cycling tests. Furthermore, the PXRD patterns confirm that the structural integrities of MOFs can be well preserved after the breakthrough tests (Fig. S3–S6†).

Compared to microporous  $Ni_2(dobdc)$  and  $Ni_2(dobpdc)$ , the mesoporous  $Ni_2(olz)$  and  $Ni_2(dotpdc)$  always displayed lower  $D_2/H_2$  separation capacities in a three-component mixture with low concentrations of  $D_2$  and  $H_2$ . Simultaneously, they promoted their  $D_2/H_2$  separation capacities to close or even surpass that of the famous  $Ni_2(dobdc)$  in the ( $H_2/D_2$ : 50/50) mixture. Such an interesting phenomenon was first observed in MOFs. In our opinion, in the absence of Ne gas during the breakthrough experiment,  $D_2$  would be preferentially adsorbed onto the OMSs of the MOFs with large pores based on the CAQS effect because of their more accessible OMSs and migration rates of the hydrogen isotope. However, breakthrough experiments with Ne as the carrier gas might suffer competitive adsorption between Ne and hydrogen isotope. Heavier and larger Ne preferred to occupy accessible OMSs in MOFs with large pores rather than the unapproachable OMSs in MOFs with narrow pores, in which the reserved OMSs can preferentially adsorb  $D_2$  to reach the  $D_2/H_2$  separation. Further, a breakthrough experiment with Ne as the carrier gas would cause a new problem, the separation between Ne and  $D_2$ , leading to complicated separation procedures and high cost. Hence, the mesoporous isomers of MOF-74(Ni), particularly  $Ni_2(olz)$ , might be ideal candidates for  $D_2/H_2$  separation.

## Conclusions

In summary, four analogues, including  $Ni_2(dobdc)$ ,  $Ni_2(dobpdc)$ ,  $Ni_2(olz)$  and  $Ni_2(dotpdc)$ , possessed honeycomb 1D channels with abundant OMSs, enabling their  $D_2/H_2$  separation capacities based on the CAQS effect. Two key factors, pore size and competitive adsorption between the hydrogen isotope and Ne as carrier gas, can significantly influence the MOF  $D_2/H_2$  separation capacities during the ground-breaking experiments. In ( $H_2/D_2/Ne$ : 1/1/98) and ( $H_2/D_2/Ne$ : 10/10/80) mixtures, microporous  $Ni_2(dobdc)$  exhibited the best  $D_2/H_2$  separation capacities with  $D_2$  retention times of 240 and  $36.4 \text{ min g}^{-1}$ , respectively, as its narrow OMSs were inclined to adsorb small  $D_2$  rather than bigger Ne during its competitive

adsorption process. Nevertheless, it will cause a new problem of Ne/ $D_2$  separation. In the ( $H_2/D_2$ : 50/50) mixture, mesoporous  $Ni_2(olz)$  exhibited the best  $D_2/H_2$  separation capacity with a  $D_2$  retention time of  $15.0 \text{ min g}^{-1}$  as its more accessible OMSs and migration rate of hydrogen isotope were inclined to adsorb heavier  $D_2$  rather than  $H_2$ . These results supported the important guidance on choosing the MOFs for  $D_2/H_2$  separation.

## Experimental

### Materials and general methods

All chemicals were obtained commercially and used as received without any further purification. Powder X-ray diffraction data were collected on a Rigaku Miniflex 600 diffractometer ( $Cu \text{ K}\alpha \lambda = 1.540598 \text{ \AA}$ ). Adsorption and desorption isotherms of all the gases under low pressure (0–1.1 bar) were measured using a Micromeritics ASAP 2020 PLUS instrument. The breakthrough experiments were performed using a home-built dynamic gas breakthrough setup.

### Synthesis of $Ni_2(dobdc)$

The  $Ni_2(dobdc)$  sample was synthesized according to the reported method with minor modifications.<sup>34</sup> 2,5-Dihydroxyterephthalic acid ( $H_4dobdc$ ) (40.42 mg, 0.204 mmol) was completely dissolved in a mixture of *N,N*-dimethylformamide, anhydrous ethanol and deionized water in a volume ratio of 15:1:1 after sonication, and then 198 mg (0.68 mmol) of  $Ni(NO_3)_2 \cdot 6H_2O$  was added to the above mixture and stirred at room temperature to completely disperse in solution and to obtain a green synthetic solution. The solution was completely added to a stainless steel reactor with a PTFE liner, and the reaction was carried out at a temperature of  $120 \text{ }^\circ\text{C}$  for 24 h. When the reaction was complete, the reactor was left to cool down naturally at room temperature. The product was collected once by centrifugation and further rinsed with DMF.

### Synthesis of $Ni_2(dobpdc)$

$Ni_2(dobpdc)$  sample was synthesized according to the reported method with minor modifications.<sup>35</sup> 2,5-Dihydroxybiphenyldicarboxylic acid ( $H_4dobpdc$ ) (41.1 mg, 0.15 mmol) and  $Ni(NO_3)_2 \cdot 6H_2O$  (109 mg, 0.375 mmol) were placed in the PTFE liner of a 20 ml reaction vessel. To this, 15 mL of mixed solvent (deionised water/DMF/anhydrous ethanol = 1:1:1) was added. The liner was covered and sonicated for 10 min and then placed in a stainless steel reactor. The reaction was carried out in an oven at  $120 \text{ }^\circ\text{C}$  for 36 h. The samples were collected by filtration and rinsed with DMF.

### Synthesis of $Ni_2(olz)$

$Ni_2(olz)$  sample was synthesized according to the reported method with minor modifications.<sup>36</sup> The metal salt  $Ni(NO_3)_2 \cdot 6H_2O$  (218 mg, 0.750 mmol) was dissolved in 10 mL of ethanol and 10 mL of  $H_2O$ , and olsalazine acid ( $H_4olz$ )

90.7 mg (0.300 mmol) was dissolved separately in 10 mL of *N,N*-diethylformamide (DEF). These solutions were combined and then distributed into three 20 mL glass scintillation vials, sealed with a PTFE-lined cap and heated in an oven at 120 °C for 24 h. The reaction mixtures were then combined, and the solvent was decanted. The orange solid was collected by filtration and washed with a continuous aliquot of DMF (3 × 20 mL).

### Synthesis of Ni<sub>2</sub>(dotpdc)

Ni<sub>2</sub>(dotpdc) sample was synthesized according to the reported method with minor modifications.<sup>37</sup> 4,4''-Dihydroxy-[1,1':4',1''-terphenyl]-3,3''-dicarboxylic acid (H<sub>4</sub>dotpdc) (147 mg, 0.75 mmol) and Ni(NO<sub>3</sub>)<sub>2</sub>·6H<sub>2</sub>O (328 mg, 1.5 mmol) were placed in a 20 mL glass scintillation vial with 15 mL of mixed solvent (deionised water/DMF/anhydrous ethanol = 1:1:1). The vials were capped and sonicated until completely dissolved, and then heated in an oven at 100 °C for 24 h. The green crystal samples were collected by filtration and rinsed with DMF.

All of the above samples were, respectively, soaked in DMF for 3 days and then in methanol for 3 days, during which the solvent was changed every 12 h. The methanol-exchanged samples were heated at 180 °C for 24 h under dynamic vacuum (<10 μmHg) to remove the excess solvent, resulting in activated powder for gas sorption.

### Breakthrough measurements

The breakthrough experiment was conducted with a custom-built dynamic gas breakthrough setup (Fig. S10†). The activated sample was first transferred to a glove box and loaded into a stainless-steel column (11 cm, inner diameter of 0.2 cm) with silica wool (30 mg) filling the void space. Then, the sorbent was heated at 120 °C for 10 h at a Ne flow rate of 10 mL min<sup>-1</sup> to make the sample tight and fully activated. In order to ensure that the whole test process was carried out at 77 K, both the packed column and the pre-cooling line were cooled with liquid nitrogen for at least 30 min before the breakthrough measurements and continued to be cooled during the entire test. After cooling down of the temperature, the flow of Ne was then turned off, and the hydrogen isotope mixture was allowed to flow into the column. The composition and content of the outlet effluent were continuously monitored using a mass spectrometer (Pfeiffer Vacuum). For the different components of the gas used in the test, we used different flow rates to ensure that the test was performed under the best conditions. For (H<sub>2</sub>/D<sub>2</sub>/Ne: 1/1/98) a flow rate of 15 mL min<sup>-1</sup> was used, for (H<sub>2</sub>/D<sub>2</sub>/Ne: 10/10/80) a flow rate of 10 mL min<sup>-1</sup> was used and for (H<sub>2</sub>/D<sub>2</sub>: 50/50) a flow rate of 2 mL min<sup>-1</sup> was used. After each breakthrough experiment, the sample was regenerated under Ne flow (10 mL min<sup>-1</sup>) at 120 °C for 10 h.

### Conflicts of interest

There are no conflicts to declare.

## Acknowledgements

This work was financially supported by the Key Research Program of Frontier Sciences, by the CAS (QYZDB-SSW-SLH019), and by the National Natural Science Foundation of China (21771177).

## Notes and references

- 1 C. Day and T. Giegerich, The Direct Internal Recycling concept to simplify the fuel cycle of a fusion power plant, *Fusion Eng. Des.*, 2013, **88**, 616–620.
- 2 R. Smith, D. A. J. Whittaker, B. Butler, A. Hollingsworth, R. E. Lawless, X. Lefebvre, S. A. Medley, A. I. Parracho, B. Wakeling and J.-E. Contributors, Hydrogen isotope separation for fusion power applications, *J. Alloys Compd.*, 2015, **645**, S51–S55.
- 3 M. Glugla, R. Lasser, L. Dorr, D. K. Murdoch, R. Haange and H. Yoshida, The inner deuterium/tritium fuel cycle of ITER, *Fusion Eng. Des.*, 2003, **69**, 39–43.
- 4 M. Glugla, D. K. Murdoch, A. Antipenkov, S. Beloglazov, I. Cristescu, I. R. Cristescu, C. Day, R. Laesser and A. Mack, ITER fuel cycle R&D: Consequences for the design, *Fusion Eng. Des.*, 2006, **81**, 733–744.
- 5 J. Y. Kim, H. Oh and H. R. Moon, Hydrogen Isotope Separation in Confined Nanospaces: Carbons, Zeolites, Metal-Organic Frameworks, and Covalent Organic Frameworks, *Adv. Mater.*, 2019, **31**, 23.
- 6 H. Oh and M. Hirscher, Quantum Sieving for Separation of Hydrogen Isotopes Using MOFs, *Eur. J. Inorg. Chem.*, 2016, **2016**, 4278–4289.
- 7 J. J. Cai, Y. L. Xing and X. B. Zhao, Quantum sieving: feasibility and challenges for the separation of hydrogen isotopes in nanoporous materials, *RSC Adv.*, 2012, **2**, 8579–8586.
- 8 D. W. Cao, H. L. Huang, Y. S. Lan, X. J. Chen, Q. Y. Yang, D. H. Liu, Y. Gong, C. J. Xiao, C. L. Zhong and S. M. Peng, Ultrahigh effective H<sub>2</sub>/D<sub>2</sub> separation in an ultramicroporous metal-organic framework material through quantum sieving, *J. Mater. Chem. A*, 2018, **6**, 19954–19959.
- 9 S. A. FitzGerald, C. J. Pierce, J. L. C. Rowsell, E. D. Bloch and J. A. Mason, Highly Selective Quantum Sieving of D<sub>2</sub> from H<sub>2</sub> by a Metal-Organic Framework As Determined by Gas Manometry and Infrared Spectroscopy, *J. Am. Chem. Soc.*, 2013, **135**, 9458–9464.
- 10 J. E. Bachman, D. A. Reed, M. T. Kapelewski, G. Chachra, D. Jonnavittula, G. Radaelli and J. R. Long, Enabling alternative ethylene production through its selective adsorption in the metal-organic framework Mn<sub>2</sub>(m-dobdc), *Energy Environ. Sci.*, 2018, **11**, 2423–2431.
- 11 R. Yaris and J. R. Sams, Quantum Treatment of the Physical Adsorption of Isotopic Species, *J. Chem. Phys.*, 1962, **37**, 571–576.
- 12 K. Sumida, D. L. Rogow, J. A. Mason, T. M. McDonald, E. D. Bloch, Z. R. Herm, T.-H. Bae and J. R. Long, Carbon

- Dioxide Capture in Metal–Organic Frameworks, *Chem. Rev.*, 2012, **112**, 724–781.
- 13 H. Furukawa, K. E. Cordova, M. O’Keeffe and O. M. Yaghi, ChemInform Abstract: The Chemistry and Applications of Metal–Organic Frameworks, *Science*, 2013, **341**, 1230444.
- 14 X.-M. Liu, L.-H. Xie and Y. Wu, Recent advances in the shaping of metal–organic frameworks, *Inorg. Chem. Front.*, 2020, **7**, 2840–2866.
- 15 X.-Y. Dao and W.-Y. Sun, Single- and mixed-metal–organic framework photocatalysts for carbon dioxide reduction, *Inorg. Chem. Front.*, 2021, **8**, 3178–3204.
- 16 Y. Cui, B. Li, H. He, W. Zhou, B. Chen and G. Qian, Metal–Organic Frameworks as Platforms for Functional Materials, *Acc. Chem. Res.*, 2016, **49**, 483–493.
- 17 Y. B. He, W. Zhou, G. D. Qian and B. L. Chen, Methane storage in metal–organic frameworks, *Chem. Soc. Rev.*, 2014, **43**, 5657–5678.
- 18 M. Tu, S. Wannapaiboon and R. A. Fischer, Liquid phase stepwise growth of surface mounted metal–organic frameworks for exploratory research and development of applications, *Inorg. Chem. Front.*, 2014, **1**, 442–463.
- 19 B. Liu, Y.-H. Jiang, Z.-S. Li, L. Hou and Y.-Y. Wang, Selective CO<sub>2</sub> adsorption in a microporous metal–organic framework with suitable pore sizes and open metal sites, *Inorg. Chem. Front.*, 2015, **2**, 550–557.
- 20 H. H. Wu, Q. H. Gong, D. H. Olson and J. Li, Commensurate Adsorption of Hydrocarbons and Alcohols in Microporous Metal Organic Frameworks, *Chem. Rev.*, 2012, **112**, 836–868.
- 21 Y. Peng, V. Krungleviciute, I. Eryazici, J. T. Hupp, O. K. Farha and T. Yildirim, Methane Storage in Metal–Organic Frameworks: Current Records, Surprise Findings, and Challenges, *J. Am. Chem. Soc.*, 2013, **135**, 11887–11894.
- 22 B. Li, H. L. Wang and B. L. Chen, Microporous Metal–Organic Frameworks for Gas Separation, *Chem. – Asian J.*, 2014, **9**, 1474–1498.
- 23 Z. J. Zhang, Z. Z. Yao, S. C. Xiang and B. L. Chen, Perspective of microporous metal–organic frameworks for CO<sub>2</sub> capture and separation, *Energy Environ. Sci.*, 2014, **7**, 2868–2899.
- 24 Z. R. Herm, E. D. Bloch and J. R. Long, Hydrocarbon Separations in Metal–Organic Frameworks, *Chem. Mater.*, 2014, **26**, 323–338.
- 25 Y. Wang, M. He, X. Gao, X. Wang, G. Xu, Z. Zhang and Y. He, A ligand conformation preorganization approach to construct a copper–hexacarboxylate framework with a novel topology for selective gas adsorption, *Inorg. Chem. Front.*, 2019, **6**, 263–270.
- 26 J. Ha, J. H. Lee and H. R. Moon, Alterations to secondary building units of metal–organic frameworks for the development of new functions, *Inorg. Chem. Front.*, 2020, **7**, 12–27.
- 27 P. Nugent, Y. Belmabkhout, S. D. Burd, A. J. Cairns, R. Luebke, K. Forrest, T. Pham, S. Q. Ma, B. Space, L. Wojtas, M. Eddaoudi and M. J. Zaworotko, Porous materials with optimal adsorption thermodynamics and kinetics for CO<sub>2</sub> separation, *Nature*, 2013, **495**, 80–84.
- 28 P. Kowalczyk, P. A. Gauden, A. P. Terzyk and S. Furmaniak, Impact of the carbon pore size and topology on the equilibrium quantum sieving of hydrogen isotopes at zero coverage and finite pressures, *J. Phys.: Condens. Matter*, 2009, **21**, 12.
- 29 I. Weinrauch, I. Savchenko, D. Denysenko, S. M. Souliou, H. H. Kim, M. Le Tacon, L. L. Daemen, Y. Cheng, A. Mavrandonakis, A. J. Ramirez-Cuesta, D. Volkmer, G. Schütz, M. Hirscher and T. Heine, Capture of heavy hydrogen isotopes in a metal–organic framework with active Cu(I) sites, *Nat. Commun.*, 2017, **8**, 14496.
- 30 S. A. FitzGerald, D. Mukasa, K. H. Rigdon, N. Zhang and B. R. Barnett, Hydrogen Isotope Separation within the Metal–Organic Framework Cu(I)-MFU-4 L, *J. Phys. Chem. C*, 2019, **123**, 30427–30433.
- 31 Y. Si, X. He, J. Jiang, Z. Duan, W. Wang and D. Yuan, Highly effective H<sub>2</sub>/D<sub>2</sub> separation in a stable Cu-based metal–organic framework, *Nano Res.*, 2021, **14**, 518–525.
- 32 Y. Si, W. Wang, E.-S. M. El-Sayed and D. Yuan, Use of breakthrough experiment to evaluate the performance of hydrogen isotope separation for metal–organic frameworks M-MOF-74 (M=Co, Ni, Mg, Zn), *Sci. China: Chem.*, 2020, **63**, 881–889.
- 33 F. Wu, L. Li, Y. Tan, E.-S. M. El-Sayed and D. Yuan, The competitive and synergistic effect between adsorption enthalpy and capacity in D<sub>2</sub>/H<sub>2</sub> separation of M<sub>2</sub>(m-dobdc) frameworks, *Chin. Chem. Lett.*, 2021, **32**, 3562–3565.
- 34 W. L. Queen, M. R. Hudson, E. D. Bloch, J. A. Mason, M. I. Gonzalez, J. S. Lee, D. Gygi, J. D. Howe, K. Lee, T. A. Darwish, M. James, V. K. Peterson, S. J. Teat, B. Smit, J. B. Neaton, J. R. Long and C. M. Brown, Comprehensive study of carbon dioxide adsorption in the metal–organic frameworks M<sub>2</sub>(dobdc) (M = Mg, Mn, Fe, Co, Ni, Cu, Zn), *Chem. Sci.*, 2014, **5**, 4569–4581.
- 35 T. M. McDonald, J. A. Mason, X. Q. Kong, E. D. Bloch, D. Gygi, A. Dani, V. Crocella, F. Giordanino, S. O. Odoh, W. S. Drisdell, B. Vlasisavljevich, A. L. Dzubak, R. Poloni, S. K. Schnell, N. Planas, K. Lee, T. Pascal, L. W. F. Wan, D. Prendergast, J. B. Neaton, B. Smit, J. B. Kortright, L. Gagliardi, S. Bordiga, J. A. Reimer and J. R. Long, Cooperative insertion of CO<sub>2</sub> in diamine-appended metal–organic frameworks, *Nature*, 2015, **519**, 303–308.
- 36 D. J. Levine, T. Runcevski, M. T. Kapelewski, B. K. Keitz, J. Oktawiec, D. A. Reed, J. A. Mason, H. Z. H. Jiang, K. A. Colwell, C. M. Legendre, S. A. FitzGerald and J. R. Long, Olsalaiine-Based Metal–Organic Frameworks as Biocompatible Platforms for H<sub>2</sub> Adsorption and Drug Delivery, *J. Am. Chem. Soc.*, 2016, **138**, 10143–10150.
- 37 D. N. J. Xiao, J. Oktawiec, P. J. Milner and J. R. Long, Pore Environment Effects on Catalytic Cyclohexane Oxidation in Expanded Fe<sub>2</sub>(dobdc) Analogues, *J. Am. Chem. Soc.*, 2016, **138**, 14371–14379.
- 38 S. R. Caskey, A. G. Wong-Foy and A. J. Matzger, Dramatic Tuning of Carbon Dioxide Uptake via Metal Substitution in a Coordination Polymer with Cylindrical Pores, *J. Am. Chem. Soc.*, 2008, **130**, 10870–10871.

- 39 W. Zhou, H. Wu and T. Yildirim, Enhanced H<sub>2</sub> Adsorption in Isostructural Metal–Organic Frameworks with Open Metal Sites: Strong Dependence of the Binding Strength on Metal Ions, *J. Am. Chem. Soc.*, 2008, **130**, 15268–15269.
- 40 E. D. Bloch, L. J. Murray, W. L. Queen, S. Chavan, S. N. Maximoff, J. P. Bigi, R. Krishna, V. K. Peterson, F. Grandjean, G. J. Long, B. Smit, S. Bordiga, C. M. Brown and J. R. Long, Selective Binding of O<sub>2</sub> over N<sub>2</sub> in a Redox-Active Metal–Organic Framework with Open Iron(II) Coordination Sites, *J. Am. Chem. Soc.*, 2011, **133**, 14814–14822.
- 41 J. Xu, R. Sinelnikov and Y. Huang, Capturing Guest Dynamics in Metal–Organic Framework CPO-27-M (M = Mg, Zn) by <sup>2</sup>H Solid-State NMR Spectroscopy, *Langmuir*, 2016, **32**, 5468–5479.
- 42 H. Oh, I. Savchenko, A. Mavrandonakis, T. Heine and M. Hirscher, Highly Effective Hydrogen Isotope Separation in Nanoporous Metal–Organic Frameworks with Open Metal Sites: Direct Measurement and Theoretical Analysis, *ACS Nano*, 2014, **8**, 761–770.
- 43 D. Cattaneo, S. J. Warrender, M. J. Duncan, R. Castledine, N. Parkinson, I. Haley and R. E. Morris, Water based scale-up of CPO-27 synthesis for nitric oxide delivery, *Dalton Trans.*, 2016, **45**, 618–629.
- 44 A. L. Myers and J. M. Prausnitz, Thermodynamics of Mixed-Gas Adsorption, *AIChE J.*, 1965, **11**, 121–127.