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# Adsorption behaviour of molecular sieve and activated carbon for CO<sub>2</sub> adsorption at cold temperatures

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## Abstract

At present, insufficient works have provided insights into the application of adsorption to remove CO<sub>2</sub> in flue gas below room temperatures under ambient pressure. In this work, the effects of temperature, CO<sub>2</sub> partial pressure and moisture on dynamic adsorption characteristics for CO<sub>2</sub> are conducted for various adsorbents. Based on our findings, lower the adsorbing temperature can drastically enhance the adsorption of carbon dioxide over molecular sieves and activated carbon. Among various adsorbents, 13X molecular sieve shows highest adsorption capacity. With a concentration of 10% CO<sub>2</sub> in flue gas, the specific adsorption capacity of CO<sub>2</sub> over 13X molecular sieve is 0.11, 2.54 and 5.38 mmol/g at 80 °C, 0 °C and – 80 °C, respectively. In addition, the partial pressure of CO<sub>2</sub> also has a significant impact on the adsorption capacity. With the increment of the concentration of CO<sub>2</sub> from 1% to 10% under 0 °C, the specific capacity of 13X molecular sieve increases from 1.212 mmol/g to 2.538 mmol/g. Water vapor in flue gas can not only reduce the specific adsorption capacity of CO<sub>2</sub> due to competing adsorption, but also increase the heat penalty of molecular sieve regeneration due to the water adsorption. An overall analysis is conducted on the energy penalty of capture 1 ton CO<sub>2</sub> at various adsorption temperatures between – 80 °C and 80 °C, considering both the heat penalty of molecular sieve regeneration as well as the energy penalty for cooling the adsorber. It is found that the lowest energy penalty is about 2.01 GJ/ton CO<sub>2</sub> when the adsorption is conducted at 0 °C.

**Keywords:** Low temperature, CO<sub>2</sub> adsorption, Molecular sieve, Activated carbon, Energy consumption

## 1 Introduction

Global warming is harmful to human life and ecological environment. Excessive emission of carbon dioxide (CO<sub>2</sub>), a major anthropogenic greenhouse gas (GHG), into the atmosphere has the profound impact on the global warming. The global CO<sub>2</sub> emissions in 2019 was 36.71 billion tons from fossil fuels [1], which are the main emission sources of CO<sub>2</sub> in the atmosphere. To reduce GHG emission, it is essential to separate CO<sub>2</sub> from the exhaust gas emanated from combustion plants. Therefore, Post-combustion technology has attracted

extensive attention, and a lot of researches have focused on the following technologies: membrane purification, cryogenic distillation, absorption and adsorption [2].

Chemical absorption method has been widely used in the industry because of low cost, large absorption, and high selectivity [3, 4]. Whereas, due to the highly corrosive to equipment, high energy consumption and large efficiency loss, chemical absorption method still needs further improvement [5]. In contrast, solid adsorption exhibits favorable advantages including the absence of corrosivity, the low volatility and the low energy penalty [6, 7]. Adsorbent is one of the key factors affecting CO<sub>2</sub> capture by adsorption method. Molecular sieves are considered as CO<sub>2</sub> adsorbents with good application potential because

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of following advantages: stable chemical properties, high wear resistance, high heat resistance, low thermal effect and easy large-scale production. Among which, 13X and 5A molecular sieve adsorption of CO<sub>2</sub> has high selectivity and large adsorption capacity [8, 9].

In order to improve the adsorption performance of adsorbents for CO<sub>2</sub>, many researches have done on the modification of adsorbent and changing of adsorption conditions. It is found that the adsorption capacity of CO<sub>2</sub> on 13X molecular sieve can be improved by metal ion exchange, carbon black modification and amine functionalization [10–12]. However, the stability and industrial production of modified materials need further exploration. Reducing the adsorption temperature is also one of the effective ways to increase the adsorption capacity of CO<sub>2</sub> [13, 14]. Based on our previous findings [15], low temperature can reduce the energy consumption of pollutant removal condensing reducing water vapor content in flue gas, so we applied it on CO<sub>2</sub> capture.

In this paper, we test the adsorption capacity of following adsorbents, 3A, 4A, 5A, 13X Molecular sieve and activated carbon at different temperatures. The effect of CO<sub>2</sub> concentration and water vapor on the adsorption capacity of 13X molecular sieve have been explored. 6 times adsorption and desorption cycle tests are carried out to investigate the reusability of 13X molecular sieve. Finally, the energy consumption of adsorbent desorption is calculated.

## 2 Experimental section

### 2.1 Materials

All gases used in this study are supplied by Beijing Huayuan Chemical Co., Ltd. The specifications on the gases are as follows: He (high purity grade, 99.995% purity), N<sub>2</sub> (prepurified, 99.998% purity), CO<sub>2</sub> (prepurified, 99.998% purity), and CO<sub>2</sub>/He certified gas mixtures (9.86% CO<sub>2</sub> balance He). The adsorbent materials used in this study are 13X molecular sieve (powder and pellets with diameter of 0.6–0.9 mm), 3A molecular sieve (powder), 4A molecular sieve (powder), 5A molecular sieve (powder) and active carbon (powder), which are bought in Nankai University Catalyst Co., Ltd.

### 2.2 Evaluation of CO<sub>2</sub> adsorption/desorption over adsorbents

Pure CO<sub>2</sub> adsorption tests are performed with MicrotracBEL catalyst analyzer BELCAT-II. First, 100 mg of adsorbents are set to the middle tube of a triple sample tube and pretreated with He at 150 °C for 1 h to remove adsorbed adsorbate. After cooling to specific temperature, the flowing gas is switched to 30 sccm of 9.86 vol% CO<sub>2</sub>/He for 1800 s to get breakthrough curve. The sample placement method is shown in Fig. 1. The adsorption capacity  $Q_m$  is calculated by integrating CO<sub>2</sub> concentration in

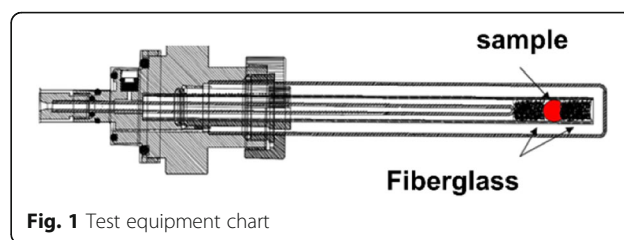


Fig. 1 Test equipment chart

the output steam. The effect of concentration CO<sub>2</sub> is performed, and CO<sub>2</sub> is diluted by He.

CO<sub>2</sub> reusability experiments are performed on MicrotracBEL catalyst analyzer BELCAT-II. 13X Molecular sieve adsorbed 9.86% CO<sub>2</sub> to equilibrium at 0 °C, then the purge is carried out at 20 °C with 30 mL/min of He for 2 h. Adsorbate is added to launch the second adsorption-desorption cycle, subsequently. 6 cycles are performed in total.

In this study, He is the balance gas rather than N<sub>2</sub> for the following reasons. Firstly, the thermal conductivities of CO<sub>2</sub> and N<sub>2</sub> are similar, while helium has a much higher thermal conductivity than CO<sub>2</sub> and is easily deprived of heat. Then, 13X has much higher selectivity for CO<sub>2</sub> than N<sub>2</sub>, that is, N<sub>2</sub> has little influence on the adsorption of CO<sub>2</sub> by 13X [16–19].

### 2.3 Effects of water vapor

The water vapor effect on the CO<sub>2</sub> uptakes using 13X at 53 °C has been investigated by breakthrough tests. Firstly, 20 g of 13X pellets (diameter: 0.6–0.9 mm) pretreated with N<sub>2</sub> at 150 °C for 2 h are loaded into a copper tube (inner diameter: 8 mm). Secondly, a mixture with a flow rate of 1 L/min is introduced into the copper tube in the water bath at 53 °C, the concentration of carbon dioxide and water vapor in the mixture are 10% and 15%, respectively. Finally, the concentration of CO<sub>2</sub> passing through the molecular sieve bed is detected by the flue gas analyzer (Testo 350) and the data is processed to obtain the adsorption capacity and breakthrough curve of 13X molecular sieve to CO<sub>2</sub> under the test conditions. In the control group, dry CO<sub>2</sub> gas is used as adsorbent and tested by the same method. In order to further explore the effect of water vapor on 13X molecular sieve adsorption of CO<sub>2</sub>, the molecular sieve is adsorbed with water vapor for 10 min and 60 min, respectively, and then the CO<sub>2</sub> dry gas adsorption test is carried out. The pretreatment temperature is set at 150 °C for the following two reasons,

The purpose of this paper is to explore the influence of temperature on adsorption capacity and estimate the energy consumption of CO<sub>2</sub> capture using 13X molecular sieve at different temperatures. This study will guide the following pilot test, which will be established based on the existing low-temperature adsorption platform,

and the pretreatment temperature of the adsorbent in the existing facilities is 150 °C. Although complete degassing of 13X could not be achieved at this temperature, and there may be some organic compounds that are difficult to desorbed, the pretreatment temperature of the penetration test was set at 150 °C to be closer to the actual application conditions.

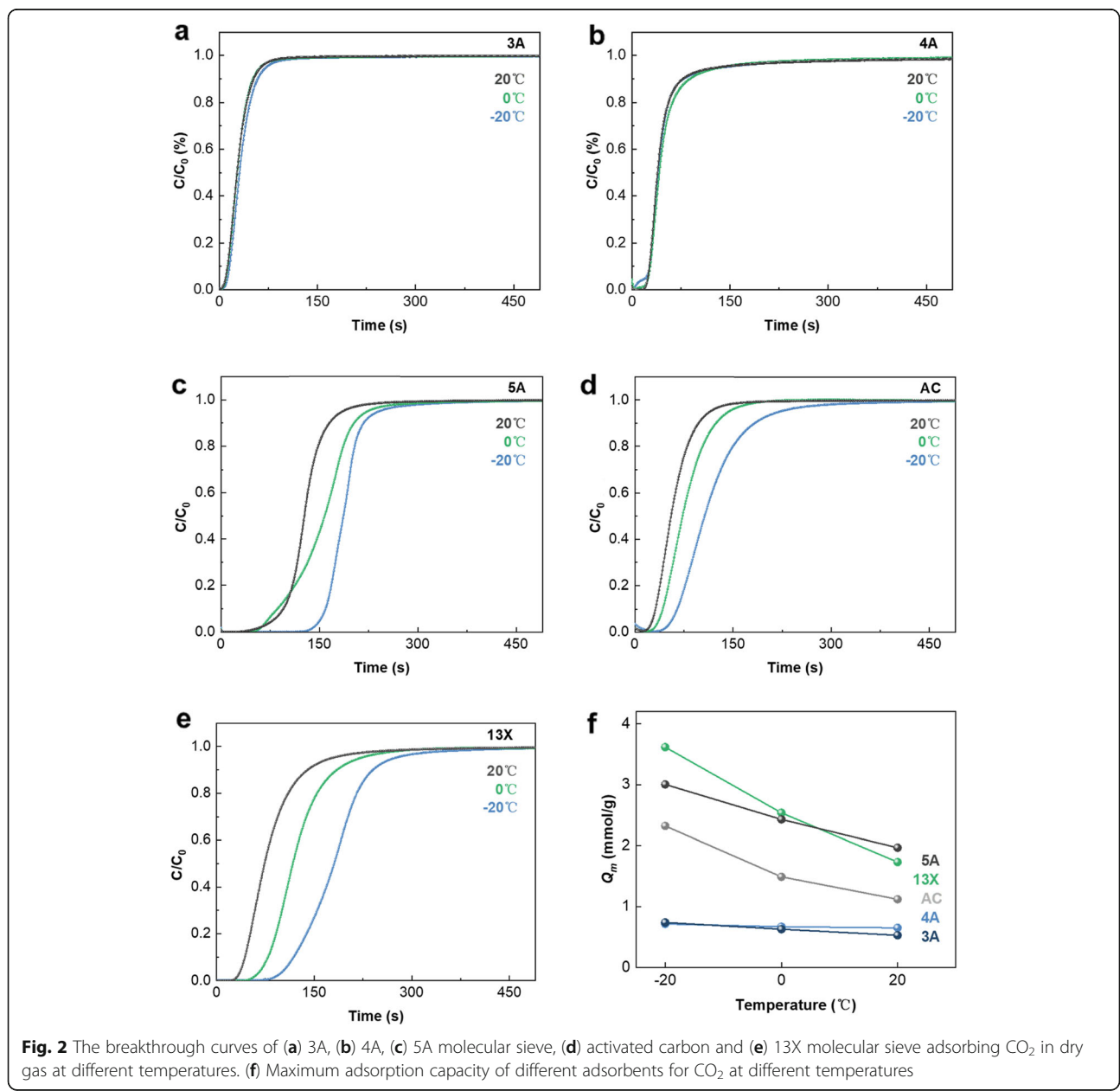
### 3 Results and discussion

#### 3.1 CO<sub>2</sub> breakthrough experiments

In this study, 3A, 4A, 5A, 13X molecular sieve and activated carbon, which are commonly used in industry, are selected to verify the adsorption capacity by CO<sub>2</sub> through breakthrough tests. Figure 2a-e show the

breakthrough curve obtained with an inlet CO<sub>2</sub> concentration of 9.86 vol% for all the tested adsorption temperatures.

The adsorption capacity of the above adsorbents for CO<sub>2</sub> at the test temperature is shown in Fig. 2f. As shown in Fig. 2, 5A and 13X molecular sieves have much higher CO<sub>2</sub> adsorption capacity than 3A and 4A molecular sieves. For all adsorbents, the adsorption capacity increases with decreasing temperature. At ambient temperature, 5A molecular sieve shows the best performance of CO<sub>2</sub> adsorption. However, the adsorption capacity of 13X exceeds 5A molecular sieve at temperatures below 0 °C since the temperature has a much more significant impact on the adsorption performance of 13X



**Fig. 2** The breakthrough curves of (a) 3A, (b) 4A, (c) 5A molecular sieve, (d) activated carbon and (e) 13X molecular sieve adsorbing CO<sub>2</sub> in dry gas at different temperatures. (f) Maximum adsorption capacity of different adsorbents for CO<sub>2</sub> at different temperatures

molecular sieve. This makes 13X molecular sieve a favorable choice for CO<sub>2</sub> removal through temperature swing adsorption (TSA) at low temperatures. Compared to other adsorbents, 13X molecular sieve has larger pore size, lower Si/Al ratio and stronger polarity. The pore size of 13X is around 8–10 Å, that is larger than 5A (around 5 Å), 4A (around 4 Å), 3A (around 4 Å). Although the dipole moment of CO<sub>2</sub> molecule is zero, it has strong interaction with cations of molecular sieve because it contains strong polar quadrupole moment [20]. Therefore, 13X with strong polarity has better adsorption performance for CO<sub>2</sub>.

### 3.2 The effect of temperature

The breakthrough curve of 13X molecular sieve adsorbing CO<sub>2</sub> in dry gas at different temperatures is shown in Fig. 3a. The results demonstrate that the adsorption capacity of 13X molecular sieve is clearly negatively affected by the operating temperature increase (from –80 °C to 80 °C). The adsorption capacities of 13X molecular sieve as shown in Fig. 3b enhances to 11.8 times, which is from 0.42 mmol/g at 80 °C to 5.38 mmol/g at –80 °C. This may be because the adsorption of carbon dioxide by 13X is thought to be primarily a physical process that emits heat, raising the temperature will inhibit the reaction going forward. Therefore, reducing the adsorption temperature can effectively improve the adsorption capacity of molecular sieve to CO<sub>2</sub> and prolong the breakthrough time, which has a good application prospect in engineering. It is worth noting that at 20 °C, the CO<sub>2</sub> adsorption capacity of 13X molecular sieve is only 1.79 mmol/g, lower than previous studies [21] that the CO<sub>2</sub> adsorption capacity of 13X under the same conditions is about 3.8 mmol/g. This may be because the

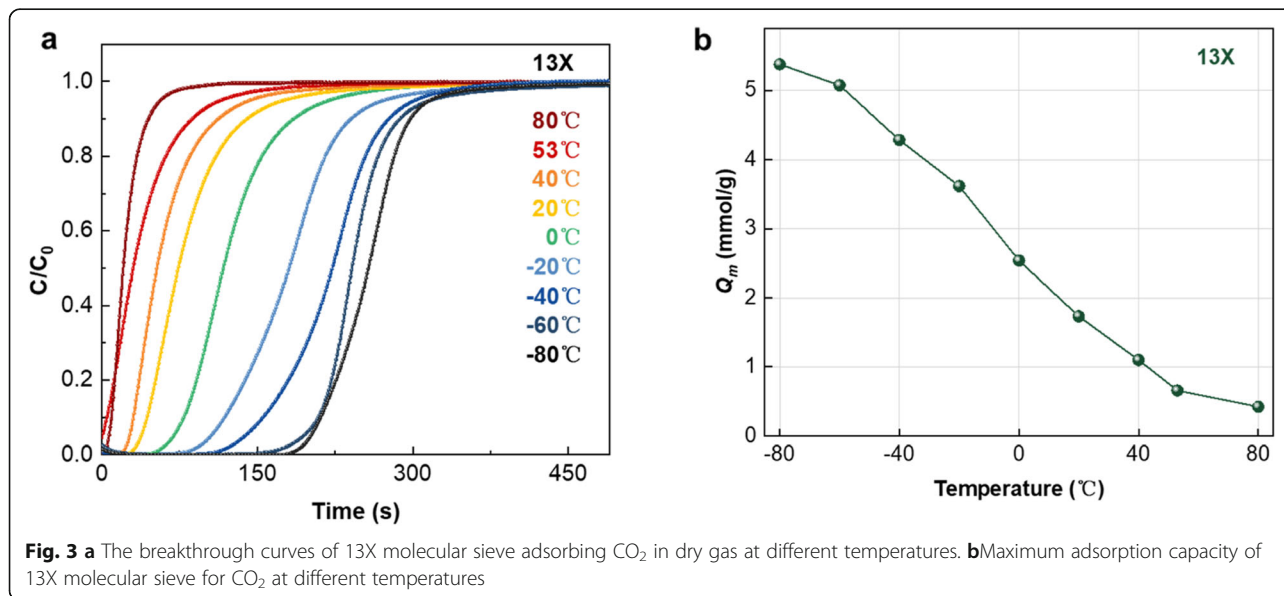
pretreatment at 150 °C in this study could not achieve complete degassing of the material, so the adsorption capacity is low.

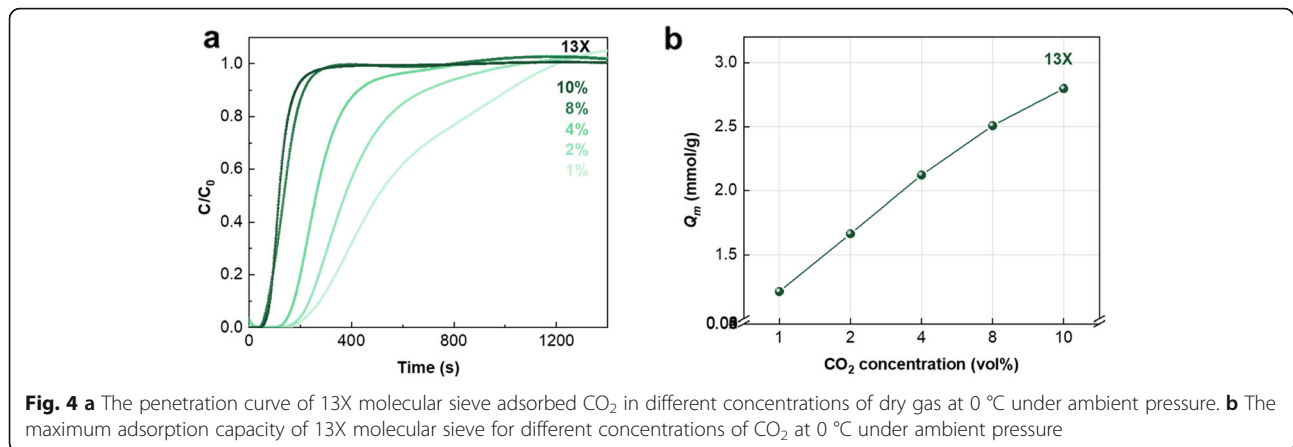
### 3.3 The effect of CO<sub>2</sub> concentration

In practical application, CO<sub>2</sub> content are different according to the types of flue gas. Hence, materials with good adsorption performance over a wide temperature range are expected to be used for separating CO<sub>2</sub> from flue gas. The effect of CO<sub>2</sub> concentration on the adsorption capacity of 13X is studied and breakthrough curves are shown in Fig. 4a. As shown in Fig. 4b, in the experimental range, the concentration of CO<sub>2</sub> has a positive effect on the adsorption capacity of 13X. With the CO<sub>2</sub> concentration increases from 1% to 10%, the adsorption capacity increases by 109.4% which is from 1.212 mmol/g to 2.538 mmol/g. It should be noted that the adsorption capacity of 13X can be more than 2.1 mmol/g when the CO<sub>2</sub> concentration exceeds 4%. Thus, 13X molecular sieves is considered as a promising carbon capture materials with good adsorption potential in a wide concentration range. As shown in Fig. 3b, under ambient pressure, the specific adsorption capacity increases almost linearly with CO<sub>2</sub> concentration below 4%.

### 3.4 The effect of water vapor

Flue gases from coal-fired power plants that have been wet-desulphurized usually contain nearly 15% water vapor (saturated at 53 °C). H<sub>2</sub>O may compete with CO<sub>2</sub> during the adsorption process and even destroy the pore structure of adsorbents, resulting in a decrease in adsorption performance of adsorbents [22]. Hence, to get closer to the actual flue gas emission, this paper





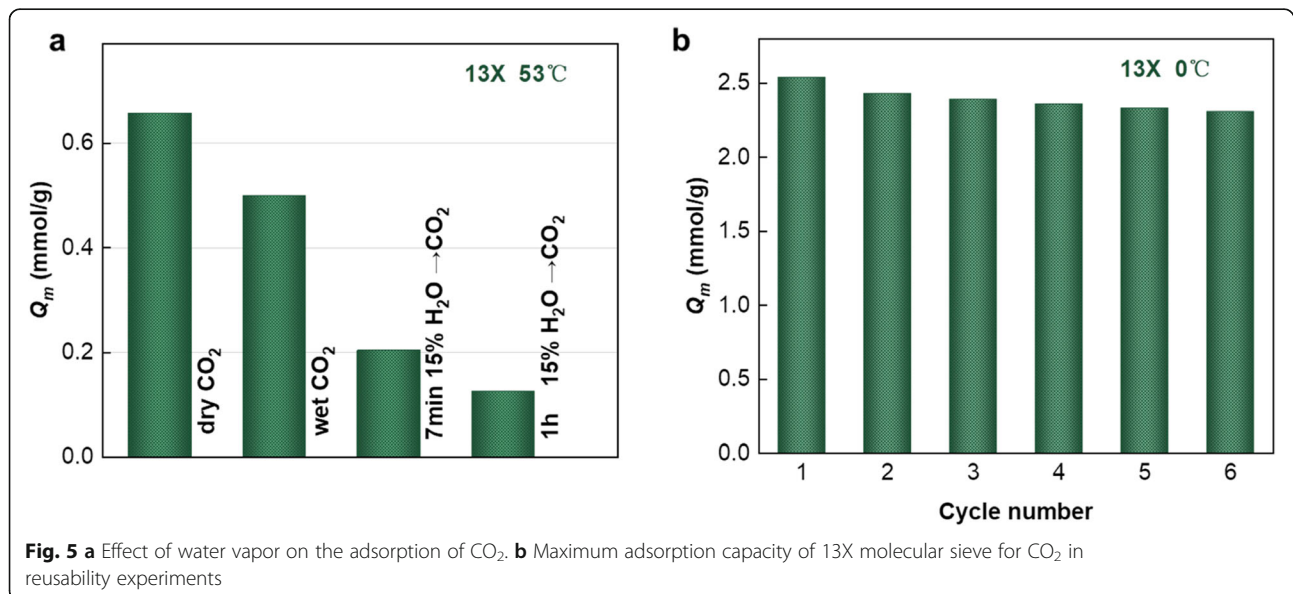
explored the influence of 15% H<sub>2</sub>O on CO<sub>2</sub> adsorption of 13X at 53 °C, results are shown in the Fig. 5a.

In control group, when dry CO<sub>2</sub> (10 vol%, 53 °C) passes through the 13X molecular sieve bed, the adsorption capacity of 13X molecular sieve is 0.656 mmol/g and the breakthrough time is 7 min. When the mixture gas contains 15% H<sub>2</sub>O (wet CO<sub>2</sub>), the adsorption capacity for CO<sub>2</sub> decreased to 0.499 mmol/g due to competing adsorption. Because H<sub>2</sub>O has strong polarity, the adsorption of H<sub>2</sub>O on 13X molecular sieve, a polar adsorbent, is much stronger than CO<sub>2</sub>. The adsorption capacity of 13X molecular sieve to H<sub>2</sub>O at 53 °C is 9.289 mmol/g, which is much higher than CO<sub>2</sub> [23].

When the CO<sub>2</sub> breakthrough experiment is conducted after purging water vapor (15 vol%) through the 13X molecular sieve bed for 7 min, the adsorption capacity for CO<sub>2</sub> is 0.230 mmol/g, which decreases 54%

compared with purging H<sub>2</sub>O and CO<sub>2</sub> into the bed simultaneously. When the CO<sub>2</sub> breakthrough experiment is conducted on 13X molecular sieve which is saturated with water, the adsorption capacity for CO<sub>2</sub> is only 19% that of control group. This behavior indicates that although the water vapor hinders the CO<sub>2</sub> adsorption process significantly, it does not inactivate the 13X molecular sieve completely.

The water vapor in flue gas can not only weaken the adsorption capacity of CO<sub>2</sub>, but also has a significant impact on the energy penalty on the regeneration of molecular sieve considering that the desorption heat of H<sub>2</sub>O is much higher than that of CO<sub>2</sub>. Therefore, the energy penalty for molecular sieve regeneration can be significantly reduced when the adsorption occurs at sub-zero temperatures where moisture content in flue gas can be reduced to pretty low levels.



### 3.5 Reusability of the 13X molecular sieve

The desorption performance and reusability of 13X molecular sieve are two key properties of a good adsorbent material in practical applications. The results of reusing experiments are shown in Fig. 5b. The adsorption capacities in the 2nd ~ 6th runs with reused 13X molecular sieve decreases slightly compared with the fresh 13X molecular sieve, and the extent of the decrease is less than 1.5%. After 6 cycles, the adsorption capacity remains 92% of the first run.

It is worth mentioning that purging the 13X molecular sieve at 20 °C with noble gas can recycle most of the adsorbed CO<sub>2</sub>. That means in practical applications, this method not only has long lifetime, but also has low economic cost by avoiding heating the adsorbent in desorption process. Therefore, our results suggests that 13X molecular sieve exhibits high chemical stability and reusability for collecting CO<sub>2</sub>. However, considering that the reusability of 13X molecular sieve for CO<sub>2</sub> removal is illustrated by only 6 cycles, increasing cycle number will be more convincing in future studies to examine the reusability.

### 3.6 Energy penalty analysis

To evaluate the energy penalty for removal of CO<sub>2</sub> from flue gas by adsorption at various temperatures, the following assumptions are claimed in this study.

- i) Moving bed adsorption-desorption process is adopted. The adsorption occurs in the adsorber and regeneration occurs in the desorber.
- ii) Energy penalty includes two parts: (1) heat penalty for molecular sieve regeneration and (2) electricity penalty caused by refrigeration system for cooling the adsorber which only required when adsorption occurs at below ambient temperature (20 °C).
- iii) Heat penalty for molecular sieve regeneration can be simply divided into three parts: water desorption heat, CO<sub>2</sub> desorption heat and energy for heating the adsorbents.
- iv) The molecular sieve is heated to 120 °C to completely remove the adsorbed H<sub>2</sub>O and CO<sub>2</sub> [24, 25], Therefore, in order to reduce energy consumption, the molecular sieve regeneration temperature is set at 120 °C.
- v) Heat recovery of heated molecular sieve can reduce the total energy penalty significantly, but has not been considered in this study.
- vi) Flue gas is cooled to the adsorption temperatures and is saturated with H<sub>2</sub>O at corresponding temperatures. Both CO<sub>2</sub> and H<sub>2</sub>O in flue gas are completely adsorbed.
- vii) For adsorption at below ambient temperatures, two-stage cooling process is adopted for the

adsorber. In the upper stage of adsorber, the heat is removed by cooling water; in the lower stage of adsorber, the heat is removed by refrigeration system.

- viii) Coefficient of Performance (COP) of commercial refrigerator is considered at each cooling temperature.
- ix) Electricity penalty is converted to heat penalty by a coefficient of 40%.

The parameters in the following equations were calculated use the data in Table 1. The desorption energy consumption calculation formula is shown in Eq. 1.

$$\begin{aligned} \Delta E_1 &= \Delta E_{CO_2} + \Delta E_{H_2O} + \Delta E_{13X} \\ &= (n(CO_2) \times \Delta H_{CO_2}) + (n(H_2O) \times \Delta H_{H_2O}) + (m(13X) \times C_{p13X} \times \Delta T) \\ &\quad \Delta T = 120^\circ C - T \end{aligned} \quad (1)$$

The refrigeration energy consumption calculation formula is shown in Eq. 2.

$$\begin{aligned} \Delta Q &= \Delta Q_{CO_2} + \Delta Q_{gas} + \Delta Q_{13X} \\ &= \left( n(CO_2) \times \Delta H_{CO_2} \times \left( 1 - \frac{Q_{m1}}{Q_{m0}} \right) \right) + (m(gas) \times C_{p13X} \times \Delta T) \\ &\quad + (m(13X) \times C_{p13X} \times \Delta T) \Delta T = T - 20^\circ C \end{aligned} \quad (2)$$

Refrigeration will consume electric energy, and electricity is converted from heat energy (conversion efficiency is 40%). The calculation method of heat energy consumption corresponding to low-temperature adsorption refrigeration is shown in Eq. 3. The thermal energy required for carbon dioxide separation by adsorption is calculated as shown in Eq. 4.

$$\Delta E_2 = \frac{\Delta Q}{COP \times 0.4} \quad (3)$$

$$\Delta E = \Delta E_1 + \Delta E_2 \quad (4)$$

The calculation results of thermal energy consumption for carbon dioxide separation by adsorption method at different adsorption temperatures are shown in Table 2. The results show that the energy consumption at 0 °C is the lowest and most economical. When the adsorption temperature increases above 0 °C, thermal energy consumption of CO<sub>2</sub> separation by adsorption increases

**Table 1** Adsorption and desorption parameters

Parameters	Symbol	unit	Value
n (CO <sub>2</sub> )/tCO <sub>2</sub>	/	kmol/ton	22.72
Desorption temperature [26]	T <sub>re</sub>	°C	120
Solid specific heat of 13X	C <sub>p13X</sub>	kJ/(kg·°C)	0.95
Specific heat of flu gas	C <sub>p flu gas</sub>	kJ/(kg·°C)	1.37
Density of flu gas	ρ <sub>flu gas</sub>	kg/m <sup>3</sup>	1.34
Heat of adsorption of CO <sub>2</sub> [22]	ΔH <sub>CO2</sub>	kJ/mol	30.73
Heat of adsorption of H <sub>2</sub> O [22]	ΔH <sub>H2O</sub>	kJ/mol	53.29

**Table 2** Overall energy penalty analysis of removing 1 ton CO<sub>2</sub> from flue gas

Temperature	°C	-80	-60	-40	-20	0	20	40	60	80
H <sub>2</sub> O Content	v%	$5 \times 10^{-5}$	0.001	0.01	0.1	0.6	2.3	7.3	19.7	46.8
CO <sub>2</sub> Content	v%	10	10	10	10	10	10	10	10	10
Adsorption data										
Adsorption capacity for CO <sub>2</sub>	Q <sub>m</sub> mmol/g	5.38	5.07	4.29	3.62	2.51	1.67	0.97	0.50	0.11
Adsorbed CO <sub>2</sub>	m <sub>CO2</sub> kg	1000	1000	1000	1000	1000	1000	1000	1000	1000
Adsorbed H <sub>2</sub> O	m <sub>H2O</sub> kg	0.00	0.04	0.4	4	25	94	299	806	1915
Adsorbent mass	m <sub>13X</sub> ton	4.23	4.48	5.30	6.28	9.04	13.6	23.4	45.5	212
Desorption heat per mass of CO <sub>2</sub>										
CO <sub>2</sub> adsorption heat	$\Delta E_{CO2}$ GJ/ton	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70
Heating molecular sieve	$\Delta E_{13X}$ GJ/ton	0.80	0.77	0.81	0.84	1.03	1.29	1.78	2.89	8.07
H <sub>2</sub> O adsorption heat	$\Delta E_{H2O}$ GJ/ton	0.00	0.00	0.00	0.00	0.07	0.28	0.90	2.39	5.67
Heat penalty	$\Delta E_1$ GJ/ton	1.50	1.46	1.51	1.54	1.80	2.27	3.38	5.98	14.4
Refrigeration energy per mass of CO <sub>2</sub>										
CO <sub>2</sub> adsorption heat in the lower stage	$\Delta Q_{CO2}$ GJ/ton	0.48	0.47	0.43	0.38	0.23	/	/	/	/
Molecular sieve cooling	$\Delta Q_{13X}$ GJ/ton	0.40	0.34	0.30	0.24	0.17	/	/	/	/
Flue gas cooling	$\Delta Q_{gas}$ GJ/ton	0.73	0.59	0.44	0.29	0.15	/	/	/	/
Total cooling load	$\Delta Q$ GJ/ton	1.61	1.39	1.17	0.91	0.55	/	/	/	/
Equivalent heat penalty	$\Delta E_2$ GJ/ton	11.94	4.89	1.96	0.71	0.21	/	/	/	/
Total energy penalty of CO <sub>2</sub> capture										
In total	$\Delta E$ GJ/ton	13.4	6.35	3.47	2.25	2.01	2.27	3.38	5.98	14.4

greatly. The possible explanation is that the higher water vapor content in flue gas, the lower adsorption capacity of molecular sieve at high temperature. Water vapor will not only reduce the adsorption capacity of 13X for CO<sub>2</sub>, but also increase the heat consumption during the desorption. The decrease of adsorption capacity of molecular sieve will lead to the increase of the amount of molecular sieve, and then increase the sensible heat of the molecular sieve during the desorption process. The adsorption amount increases significantly below 0 °C, but the refrigeration needs a lot of energy, as a result the total energy consumption is higher than 0 °C.

#### 4 Conclusion

In this study, the adsorption capacity of common adsorbents as conducted at test temperature (-20 °C, 0 °C, 20 °C) is 13X > 5A > active carbon > 4A > 3A, thus showing a beneficial effect of the large pore sizes and polarity on the adsorption capacity. 13X molecular sieve is used as adsorbent to study the effects of temperature, CO<sub>2</sub> concentration and water vapor. Decreasing temperature has positive effect on the adsorption of 13X molecular sieve. The adsorption capacity under -80 °C is the highest, which is 5.380 mmol/g, nearly 10 times higher than that under 80 °C. On the other hand, increase of CO<sub>2</sub> concentration has positive effect on the adsorption of CO<sub>2</sub> on the 13X molecular sieve, too. When the

concentration of CO<sub>2</sub> increases to 10 times (from 1% to 10%), the adsorption capacity increases from 1.212 mmol/g to 2.550 mmol/g, an increase of about 110.4%. Whereas water vapor has negative effect. When the mixture gas contains 15% H<sub>2</sub>O, the adsorption capacity of 13X molecular sieve for CO<sub>2</sub> decreases significantly compared with the control group, from 0.656 mmol/g to 0.499 mmol/g. The adsorption and desorption cycling tests indicate that 13X molecular sieve has high chemical stability and reusability for the removal of CO<sub>2</sub> from mixture gas.

#### 5 Nomenclature

T Temperature (°C).

T<sub>re</sub> Desorption temperature (°C).

C<sub>p13X</sub> Solid specific heat of 13X (kg·°C).

C<sub>p fl u gas</sub> Specific heat of flue gas kJ/(kg·°C).

ρ<sub>fl u gas</sub> Density of flue gas (kg/m<sup>3</sup>).

ΔH<sub>CO2</sub> Heat of adsorption of CO<sub>2</sub> (kJ/mol).

ΔH<sub>H2O</sub> Heat of adsorption of H<sub>2</sub>O (kJ/mol).

ΔE<sub>CO2</sub> CO<sub>2</sub> adsorption heat (GJ/ton).

ΔE<sub>13X</sub> Heating molecular sieve (GJ/ton).

ΔE<sub>H2O</sub> H<sub>2</sub>O adsorption heat (GJ/ton).

ΔE<sub>1</sub> Heat penalty (GJ/ton).

ΔE<sub>2</sub> Equivalent heat penalty (GJ/ton).

ΔE Total heat penalty (GJ/ton).

Q<sub>m</sub> Adsorption capacity for CO<sub>2</sub> (mmol/g).

$m_{CO_2}$  Adsorbed  $CO_2$  (kg).  
 $m_{H_2O}$  Adsorbed  $H_2O$  (kg).  
 $m_{13X}$  Adsorbent mass (ton).  
 $\Delta Q_{13X}$  Molecular sieve cooling (GJ/ton).  
 $\Delta Q_{gas}$  Flue gas cooling (GJ/ton).  
 $\Delta Q_{CO_2}$   $CO_2$  adsorption heat in the lower stage (GJ/ton).  
 $\Delta Q$  Total cooling load (GJ/ton).  
 C Concentration of carbon dioxide after adsorption (%).  
 $C_0$  Concentration of carbon dioxide before adsorption (%).

#### Abbreviations

GHG: Greenhouse gas;  $CO_2$ : Carbon dioxide; COP: Coefficient of Performance

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#### Authors' contributions

S.W. organized this study; Y.W., Y.K. contributed significantly on the experiment design and test. S.G. L.L., H.N., P.X. and B.H. guide the experiments. S.W. wrote the manuscript. All authors discussed and commented on the manuscript. The author(s) read and approved the final manuscript.

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#### Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

#### Declarations

#### Ethics approval and consent to participate

Not applicable.

#### Consent for publication

Not applicable.

#### Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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