Removal of Toluene by Adsorption/Desorption Using Ultra-stable Y Zeolite

Lei Xu^{1,2,3} · Yonghong Li^{1,2,3} · Jiang Zhu^{1,2,3} · Zhiyuan Liu^{1,2,3}

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Abstract

The adsorption performance of toluene on ultra-stable Y zeolite (USY) was studied via dynamic adsorption. The effects of bed temperature, initial concentration, and feed flow rate on adsorption were investigated. The Yoon–Nelson model was used to fit the toluene breakthrough curves. The length of mass transfer zone was calculated based on breakthrough curves. The Langmuir–Freundlich model fit the adsorption isotherms of toluene on USY, which indicated that the surface of USY was heterogeneous. The adsorption isosteric heat calculated from adsorption isotherms ranged from 54.3 to 69.8 kJ/mol, indicating physical adsorption. The combined technique of temperature swing adsorption with vacuum swing adsorption (TVSA) exhibited excellent desorption performance, which was attributed to the low desorption activation energy. Under optimized TVSA conditions, the desorption rate of toluene reached 90.6% within 10 min. The long-term cyclic utilization results indicated that the adsorption capacity of USY was stable.

Keywords Adsorption · Desorption · USY · Toluene · Heavy VOC

List of Symbols

q	Adsorbed amount of toluene at time t (g/g)	t	Adsorption time (min)
q_e	Adsorbed amount of toluene at saturation (g/g)	$t_{0.5}$	Time corresponding to $C/C_0=0.5$ (min)
q_m	Maximum theoretical adsorption capacity (g/g)	$t_{0.05}$	Time corresponding to $C/C_0=0.05$ (min)
Q	Adsorbed amount of toluene (mmol/g)	$t_{0.95}$	Time corresponding to $C/C_0=0.95$ (min)
F	Feed flow rate of toluene vapor (mL/min)	H_{MTZ}	Length of the mass transfer zone (cm)
W	Weight of adsorbent (g)	H	Length of the tubular adsorbent bed (cm)
C_0	Initial concentration of toluene (mg/m ³)	p	Toluene partial pressure (Pa)
C	Outlet concentration of toluene (mg/m ³)	b	Affinity term at experimental condition
d_r	Desorption rate of toluene (%)	$1/n$	Exponent of Langmuir–Freundlich model
m	Mass of fresh adsorption tube (g)	A	Affinity coefficient
m_a	Mass of adsorption tube before desorption (g)	ΔH	Isosteric heat of adsorption (kJ/mol)
m_d	Mass of adsorption tube after desorption (g)	T	Adsorption temperature (K)
k	Rate constant of Yoon–Nelson model	R	Gas constant (8.314 J K ⁻¹ mol ⁻¹)
k_0	Pseudo-zero-order rate constant (g/min)	E_d	Activation energy of desorption (kJ/mol)
k_1	Pseudo-first-order rate constant (min ⁻¹)	β_H	TPD heating rate (K/min)
		T_p	Temperature corresponding to desorption peak (K)

✉ Yonghong Li
yhli@tju.edu.cn

¹ Key Lab for Green Chemical Technology of Ministry of Education, School of Chemical Engineering and Technology, Tianjin University, Tianjin 300350, China

² National Engineering Research Center for Distillation Technology, Tianjin 300350, China

³ Collaborative Innovation Center of Chemical Science and Engineering, Tianjin 300350, China

Introduction

Volatile organic compounds (VOCs) usually refer to organic compounds with boiling points within the range of 50–260 °C at atmospheric pressure [1]. These compounds include aromatics, aliphatics, aldehydes, ketones, and esters. Discharged VOCs can react with NO_x in the atmosphere to generate photochemical smog, which poses a serious threat

to human health and the environment [2]. About 29.4 million tons of industrial VOC emissions were estimated to be discharged into the atmosphere in China in 2013 [3]. This large amount of VOC emissions has resulted in serious environmental issues. Hence, efforts must be made to reduce the emission of VOCs. Toluene is one of the main components of VOCs, and it widely exists in the printing, painting, semiconductor, and leather industries. In recent years, toluene has attracted increasing research attention [4–6].

Several techniques have been applied in controlling VOC emissions, including adsorption [7], absorption [8], photocatalysis [9], thermocatalysis [10], plasma catalytic oxidation [11], and biofiltration [12]. Among these methods, adsorption is an effective way to remove VOCs with low concentration and high velocity, because of its high efficiency and low cost [13]. The most commonly used adsorbent is activated carbon because of its large adsorption capacity. However, the regeneration of activated carbon is difficult because of its thermal and chemical instability [14]. Therefore, zeolites as adsorbents are becoming increasingly popular for their large surface area, high thermal and hydrothermal stability, adjustable hydrophobicity, auxiliary mesopore regeneration, and non-flammable characteristics [15, 16].

On the basis of the desorption methods, the adsorption are divided into temperature swing adsorption (TSA) and pressure swing adsorption (PSA). Given its short desorption time and low energy consumption, PSA or vacuum swing adsorption (VSA) has experienced rapid development. However, this method is commonly used for the treatment of light VOCs, like ethanol, acetone, and ethane [17–19]. For heavy VOCs (e.g., aromatics), the desorption rate is low using single VSA. Sui et al. [20] investigated the removal of o-xylene using silica gel by VSA. They found that the maximum desorption rate of o-xylene is 58% via single VSA. Therefore, the combination of temperature swing adsorption and vacuum swing adsorption (TVSA) was proposed for the removal of heavy VOCs. TVSA was expected to lower the desorption temperature, enhance the desorption rate, and shorten the desorption time of heavy VOCs. Pak et al. [21] studied the adsorption and desorption of toluene using commercial activated carbons by TVSA. They reported a toluene desorption rate of 90% under the desorption conditions of 90 °C and 13 kPa. However, the desorption equilibrium time was as long as 150 min, and the adsorption breakthrough time sharply decreased from 200 min to 80 min after five cycles. The poor stability and long desorption time limit the application of TVSA with activated carbon as adsorbent. Ultra-stable Y zeolite (USY) is an excellent adsorbent for heavy VOC because of its large specific surface area, suitable pore width and excellent thermal stability. However, few studies have been reported on TVSA with USY as adsorbent. The mechanism of VOC adsorption and desorption on USY remains unclear. This paper may provide guidance for

the application of USY in treating emissions from the paint and printing industries, which involve large aromatic VOCs.

This work aimed to (1) test the effects of adsorption conditions, (2) analyze the dynamics and thermodynamics of adsorption and desorption, (3) reveal the superiority of TVSA and optimize the operational conditions of TVSA, and (4) determine the feasibility of the industrial application of TVSA in the removal of heavy VOCs.

Material and Method

Materials

USY (Si/Al=11, 25, 40) used in the experiments was purchased from Zibo Mengzhong Import and Export Trade Co., Ltd. (Shandong, China). The cation type of USY was hydrogen. Toluene ($C_7H_8 > 99.5\%$) was purchased from Tianjin Yuanli Chemical Co., Ltd. (Tianjin, China).

Characterization of USY

The nitrogen adsorption–desorption isotherms of USY were measured by Autosorb-iQ2-MP (Quantachrome, USA) at 77 K. Before sorption measurement, the samples were outgassed at 573 K for 5 h. The specific surface area and micropore volume were calculated by Brunauer–Emmett–Teller (BET) and t-plot models, respectively. The pore width distribution of USY was estimated by density functional theory.

Temperature programmed desorption (TPD) experiments were performed on self-built equipment, composed of a quartz reactor placed inside an electronic temperature programmed furnace and connected to a gas chromatograph with an FID detector. The toluene-laden USY (0.2 g) was quickly packed in a quartz tube between two silica wool plugs. The nitrogen flow rate was 30 mL/min, and the heating rate varied from 3 to 15 K/min.

Dynamic Adsorption and Desorption of Toluene

The dynamic adsorption and desorption of toluene were carried out in the self-made experimental device (Fig. 1). Air flowed out from the cylinder and was split into three streams. One of the streams was used to generate toluene vapor, the other stream was used to generate moisture, and the third was used as dilute gas. By adjusting the flow rates of the three streams, toluene stream with a certain concentration and moisture was obtained. The toluene mixture was introduced to the adsorption tube (adsorbent mass=0.5 g, particle size=40–60 mesh, inner diameter=5.5 mm, and length=5.89 cm). The concentration of inlet and outlet stream was detected by a gas chromatograph (FULI 9790, China) with an FID detector.

Fig. 1 Schematic flowchart of adsorption and desorption experiments. (1) air cylinder; (2) dryers; (3) ball valves; (4) mass flow controllers; (5) water baths; (6) water stream generator; (7) toluene stream generator; (8) rotor flow meter; (9) three-way valves; (10)

stream mixture; (11) oil bath; (12) adsorption tube; (13) hygrothermograph; (14) six-port valve; (15) gas chromatograph; (16) vacuum pump; and (17) exhaust gas adsorption tank

The temperatures of the chromatographic column, injector, and detector were 150 °C, 170 °C, and 180 °C, respectively. When the toluene concentration in the outlet stream was constant and equal to that in the inlet stream, the adsorption tube was saturated by toluene.

When the adsorption process was completed, the adsorption tube was removed from the oil bath. The oil bath was heated to the desired desorption temperature, and the adsorption tube was placed into the oil bath. Finally, the valves were switched and connected to a vacuum pump for desorption. During desorption, a stream of purge air was introduced to the adsorption tube. The chromatographic conditions for the detection of desorption gas were similar to those for adsorption gas.

Principle

Adsorption Amount and Desorption Rate

The amount of toluene adsorbed was calculated by the following formula:

$$q = \frac{F \times 10^{-9}}{W} \left(C_0 t - \int_0^t C(t) dt \right) \quad (1)$$

The desorption rate was measured by the gravimetric method and calculated by Eq. (2):

$$d_r = \frac{m_a - m_d}{m_a - m} \times 100\% \quad (2)$$

Yoon–Nelson Model

The Yoon–Nelson model was used to simulate the breakthrough curves of toluene [22].

$$\frac{C}{C_0} = \frac{1}{1 + \exp[k(t_{0.5} - t)]} \quad (3)$$

The length of mass transfer zone (MTZ) was calculated from breakthrough curves using the following equation [23]:

$$H_{MTZ} = H \times \frac{t_{0.5} - t_{0.05}}{t_{0.95}} \quad (4)$$

Adsorption Kinetic Model

The pseudo-zero-order model is presented as

$$\frac{dq}{dt} = k_0 \quad (5)$$

The pseudo-first-order model is presented as [24]

$$\frac{dq}{dt} = k_1 \times (q_e - q) \quad (6)$$

Adsorption Isotherms

The Langmuir adsorption isotherm describes homogeneous adsorption in which the adsorption enthalpy and activated energy are constant to each molecule (all sites show affinity to molecule) [25]. It is expressed as follows:

$$q_e = \frac{q_m \times b \times p}{(1 + b \times p)} \quad (7)$$

The Freundlich adsorption isotherm describes multilayer adsorption, which is presented as [26].

$$q_e = A \times p^{\frac{1}{n}} \quad (8)$$

The Langmuir–Freundlich adsorption isotherm was used to describe heterogeneous adsorption [27].

$$q_e = q_m \times \frac{b \times p^{\frac{1}{n}}}{(1 + b \times p^{\frac{1}{n}})} \quad (9)$$

The isosteric heat of adsorption was estimated by Clausius–Clapeyron equation [28].

$$\frac{\Delta H}{R} = \left[\frac{\partial \ln(p)}{\partial (1/T)} \right]_Q \quad (10)$$

Desorption Activation Energy

The desorption activation energy was estimated by the modified Polanyi–Wigner equation using TPD [29].

$$\ln \left(\frac{\beta_H}{RT_p^2} \right) = - \left(\frac{E_d}{RT_p} \right) - \ln \left(\frac{E_d}{k_0} \right) \quad (11)$$

Results and Discussion

Characterization of Adsorbents

Figure 2 illustrates the N_2 adsorption–desorption isotherms and the pore width distribution of USY. The steep increase in adsorbed amounts of N_2 was observed at low relative pressure ($p/p_0 < 0.05$), which suggested the large micropore volume. The hysteresis loops ($p/p_0 = 0.45$ – 0.95) indicated the mesopore volume. These phenomena suggested that USY possessed micro-mesopore structures, which are advantageous for both adsorption and desorption [30, 31]. With the increase in Si/Al ratios, the BET specific surface area and pore volume of USY initially increased and then decreased. The detailed parameters are shown in Table 1.

Effect of Si/Al Ratios on Adsorption

Figure 3 shows the breakthrough curves of toluene at different relative humidities. In Fig. 3a, the USYs with different Si/Al ratios presented similar adsorption performance when toluene vapor lacked moisture. However, the USYs with different Si/Al ratios showed a remarkable difference in adsorption at the relative humidity (RH) of 50%, (Fig. 3b). The breakthrough time improved with the increase in Si/

Fig. 2 Nitrogen adsorption–desorption isotherms and pore width distribution (insets) of USYs with different Si/Al ratios: **a** Si/Al = 11; **b** Si/Al = 25; **c** Si/Al = 40

Table 1 Main characteristics of different USYs

Adsorbent	BET surface area (m ² /g)	Micropore volume (cm ³ /g)	External volume (cm ³ /g)	Total pore volume (cm ³ /g)
USY-11	748	0.284	0.124	0.408
USY-25	881	0.315	0.150	0.465
USY-40	848	0.303	0.141	0.444

Fig. 3 Breakthrough curves of toluene at different relative humidities: **a** RH=0%; **b** RH=50%; initial concentration: 1500 mg/m³; feed flow rate: 450 mL/min; adsorption temperature: 25 °C

Al ratios. The USY with Si/Al ratio of 40 presented great hydrophobicity. When the relative humidity was 50%, the adsorption ratio of toluene reached 98.6%. Therefore, USY (Si/Al=40) is an excellent adsorbent with good adsorption performance and hydrophobicity.

Effects of Adsorption Conditions

The adsorption properties of toluene at different adsorption conditions are shown in Fig. 4. The breakthrough time decreased from 140 min to 80 min, and the adsorbed amount decreased from 0.223 to 0.183 g/g as the bed temperature increased from 15 to 35 °C. These results indicated that increasing bed temperature negatively influenced toluene adsorption. This conclusion was consistent with that of a former study [32].

Feed flow rate also presented a significant influence on adsorption. The breakthrough time reduced from 265 to 85 min as feed flow rate increased from 200 to 700 mL/min. However, the adsorption capacity increased from 0.181 to 0.224 g/g. This result indicated that increasing feed flow rate enhanced the adsorption capacity of VOCs.

Besides feed flow rate, the initial concentration also influenced adsorption. The breakthrough time decreased

Fig. 4 Effects of operation conditions on adsorption: **a** initial concentration: 1500 mg/m³; feed flow rate: 450 mL/min; **b** adsorption temperature: 25 °C

from 115 min to 75 min with the increase in initial toluene concentration from 1500 to 2700 mg/m³. However, the amount of adsorbed toluene increased from 0.204 to 0.231 g/g, which was attributed to the enhanced driving force to diffusion.

Yoon–Nelson model can well fit the breakthrough curves of toluene. The length of mass transfer zone (H_{MTZ}) was estimated via the toluene breakthrough curves. The detailed fitting parameters of the Yoon–Nelson model and H_{MTZ} are presented in Table 2. A high rate constant k was gained under low bed temperature, high feed flow rate, and high initial toluene concentration. However, the length of mass transfer zone increased with bed temperature and feed flow rate.

Adsorption Kinetics

The adsorption kinetic curves of toluene are shown in Fig. 5. During adsorption, the adsorbent bed underwent a stable state, breakthrough state, and saturation state successively. In the stable state, the mass transfer zone did not reach the boundary of the adsorbent bed. Toluene molecules were steadily adsorbed on USY, so the amount of toluene adsorbed linearly increased with time. Hence, it could be

Table 2 Fitting parameters of the Yoon–Nelson model and H_{MTZ}

Adsorption conditions			q_e (g/g)	k	R^2	H_{MTZ} (cm)
Bed temperature (°C)	Feed flow rate (mL/min)	Initial toluene concentration (mg/m ³)				
15	450	1500	0.223	0.102	0.991	0.825
25	450	1500	0.204	0.092	0.996	1.019
35	450	1500	0.183	0.073	0.994	1.302
25	200	1500	0.181	0.070	0.992	0.713
25	700	1500	0.224	0.126	0.997	1.049
25	450	2700	0.231	0.197	0.998	0.813

Fig. 5 Adsorption kinetic curves of toluene on USY at various inlet conditions

fitted by the pseudo-zero-order model. Table 3 shows the detailed fitting parameters. Increasing the feed flow rate or initial toluene concentration elevated the adsorption rate.

The breakthrough state was fitted by the pseudo-first-order model, also shown in Table 3. Increasing the feed flow rate or initial concentration can also enhance the adsorption rate.

Adsorption Isotherms and Isostatic Heat

The adsorption isotherms were obtained by adsorption experimental instruments (shown in Fig. 1) via kinetic adsorption. The toluene adsorbed amount increased with partial pressure of toluene, shown in Fig. 6a. The adsorption isotherm was simulated by different adsorption models.

The detailed fitting parameters are summarized in Table 4. The order of R^2 of various adsorption isotherm models was Langmuir–Freundlich > Langmuir > Freundlich. This result indicated that the adsorption surface of USY was heterogeneous, containing both homogeneous and multilayer adsorption.

The isosteric heat of toluene adsorption was calculated from adsorption isotherms by using the Clausius–Clapeyron equation, shown in Fig. 6b. The isosteric heat of toluene adsorption on USY was in the range of 54.3–69.8 kJ/mol, which suggested physical adsorption. The isosteric heat curve increased with rising adsorbed amount of toluene, which may be attributed to the interaction between toluene molecules [33].

Comparison of Various Desorption Methods

Figure 7 shows a comparison of different desorption methods. By use of VSA, the lowest desorption rate (12.6%) was obtained within 40 min because vacuum could hardly break the strong interaction between USY and toluene molecules. The desorption rate reached 80.9% within 40 min by TSA, which was attributed to the inhibition of the dynamic adsorption of toluene due to increasing adsorbent bed temperature. Thus, the adsorbed toluene molecules were removed by constant purge gas. However, TVSA presented the highest desorption rate (90.6%) and shortest removal time (10 min) possibly because vacuum weakened the interaction between toluene molecules and USY. Therefore, in comparison with TSA, toluene molecules were easily released. These results suggested that TVSA is a promising method for the removal

Table 3 Fitting parameters of pseudo-zero-order model and pseudo-first-order model

Model parameters	Pseudo-zero-order model				Pseudo-first-order model			
	k_0 (10 ⁻⁴ g/min)	t_0 (min)	q_0 (g/g)	R_0^2	k_1 (min ⁻¹)	t_1 (min)	q_e (g/g)	R_1^2
200 mL/min, 1500 mg/m ³	6	260	0.1556	0.9996	0.0208	380	0.1814	0.9278
450 mL/min, 1500 mg/m ³	14	110	0.1515	0.9998	0.0238	220	0.2047	0.9675
700 mL/min, 1500 mg/m ³	21	85	0.1750	0.9995	0.0365	170	0.2239	0.9635
450 mL/min, 2700 mg/m ³	24	75	0.1832	0.9997	0.0415	150	0.2312	0.9942

Fig. 6 Adsorption isotherm simulation (a) and isosteric heat of toluene (b)

of heavy VOCs, which could enhance the desorption rate and reduce the desorption time.

Desorption Activation Energy

To further investigate the mechanism of TVSA, the desorption activation energy of toluene at different pressure values was calculated via TPD. In this case, desorption was assumed to follow Arrhenius-like behavior and first-order kinetics. The activation energy was estimated by the modified Polanyi–Wigner equation. Figure 8a, b shows the toluene TPD spectra at heating rates from 3 to 15 K/min. The intensity of the TPD spectra and temperature corresponding to desorption peak increased with the heating rate. The calculated desorption activation energy results are also depicted

in Fig. 8c, d. The desorption activation energy at atmosphere pressure was 71.217 kJ/mol, which was higher than the isosteric heat of toluene adsorption. However, the desorption activation energy at 10 kPa was only 55.970 kJ/mol, which was 21% lower than that at atmosphere pressure. Vacuum clearly reduced the desorption activation energy. Therefore, TVSA presented better desorption performance than TSA.

Optimization of Desorption Conditions

To provide operational guidance for industry, the desorption conditions of TVSA were optimized. Vacuum pressure, bed temperature, and purge gas flow rate are important parameters in desorption. Low pressure is advantageous for desorption [10]. Therefore, the desorption process should be conducted at the lowest pressure permitted by the VOC purification plant. Considering the equipment factors, 10 kPa was set as the desorption pressure.

The relationship between desorption rate and temperature is shown in Fig. 9. The desorption rate sharply increased within 5 min and remained stable after 10 min. A high desorption rate was obtained at high desorption temperatures. However, the desorption rates at 120 °C and 140 °C were similar to each other (90.6% and 91.7%, respectively). Therefore, considering energy consumption, desorption

Fig. 7 Comparison of different desorption methods: purge gas flow rate: 200 mL/(min·g_{adsorbent}); toluene amount adsorbed: 0.204 g/g

Table 4 Fitting parameters of different adsorption isotherms

Bed temperature (°C)	Fitting models	q_m (g/g)	k	A	$1/n$	R^2
25	Langmuir	0.2579	0.1085	—	—	0.9827
25	Freundlich	—	—	0.1252	0.1287	0.9386
25	Langmuir–Freundlich	0.2742	0.2688	—	0.6656	0.9916
35	Langmuir	0.2284	0.0889	—	—	0.9888
35	Freundlich	—	—	0.1103	0.1266	0.9436
35	Langmuir–Freundlich	0.2413	0.2132	—	0.7005	0.9960

Fig. 8 TPD curves and desorption activation energy of toluene at different desorption pressures: **a, c** 101.3 kPa; **b, d** 10 kPa

Fig. 9 Effect of temperature on desorption (Purge gas flow rate: 200 mL/(min·g_{adsorbents}); toluene amount adsorbed: 0.204 g/g)

temperature and desorption time were set at 120 °C and 10 min, respectively.

Figure 10 shows how the purge gas flow rate influences the desorption rate. A similar conclusion was obtained, in which increasing purge gas flow rate was found to be beneficial for desorption. The desorption rates were 86.7%, 90.6%, and 91.1% at the purge gas flow rates of 100 mL/

Fig. 10 Effect of purge gas flow rate on desorption (Desorption temperature: 120 °C; toluene amount adsorbed: 0.204 g/g)

Fig. 11 Adsorption performance of long-term cyclic utilization (Adsorption temperature: 25 °C; initial concentration: 1500 mg/m³; feed flow rate: 450 mL/min; desorption temperature: 120 °C; purge gas flow rate: 200 mL/(min·g_{adsorbent}); desorption pressure: 10 kPa; and adsorbent mass: 0.5 g)

(min·g_{adsorbent}), 200 mL/(min·g_{adsorbent}), and 300 mL/(min·g_{adsorbent}), respectively.

The initial outlet concentration of toluene was high and then sharply fell. After 3 min, the concentration of toluene gradually approached zero. Given that the initial outlet concentration was high, most of toluene was recycled by condensing. However, the initial outlet concentration of toluene sharply decreased with increasing purge gas flow rate. Low concentrations of toluene are disadvantageous for condensation recovery. Thus, considering both desorption rate and outlet concentration, the purge gas flow rate was determined as 200 mL/(min·g_{adsorbent}).

Long-Term Cyclic Utilization by TVSA

Stability is one of the most important properties in industrial applications. Hence, after optimizing the desorption conditions, long-term cyclic utilization experiments were carried out (Fig. 11). In the second recycle, the adsorbed amount decreased from 0.2 to 0.18 g/g, which was ascribed to the irreversible adsorption of toluene [34]. However, the adsorbed amount of toluene was maintained at 0.18 g/g during long-term recycling. The outlet concentration of toluene before breakthrough was detected as 0 mg/m³, which was lower than the national emission standard (15 mg/m³ from GB31571-2015). These results suggested that USY as adsorbent presents excellent adsorption stability.

Conclusions

USY is an excellent adsorbent for VOCs, which has large adsorption capacity and good hydrophobicity. Lowering the bed temperature and increasing the feed flow rate and

initial concentration are proven to be beneficial for VOC adsorption. The Yoon–Nelson model could fit the breakthrough curves of VOCs. The length of mass transfer zone calculated from the breakthrough curves increased with rising adsorbent bed temperature and feed flow rate. The adsorbed amount of toluene at stable adsorption state and breakthrough state was well fitted by the pseudo-zero-order and pseudo-first-order models, respectively. The adsorption isotherm of toluene on USY was fitted by the Langmuir–Freundlich model. The adsorption isosteric heat of toluene was in the range of 54.3–69.8 kJ/mol, indicating physical adsorption. TVSA method exhibited superior desorption performance compared with TSA and VSA methods. The desorption activation energy calculated by TPD was 71.217 kJ/mol at the desorption pressure of 101.3 kPa and 55.970 kJ/mol at the desorption pressure of 10 kPa. The optimal desorption conditions at laboratory scale were 10 kPa of desorption pressure, 120 °C of desorption temperature and 200 mL/(min·g_{adsorbent}) of purge gas flow rate. At these conditions, the desorption rate could reach 90.6% within 10 min. The long-term cyclic utilization results suggested that the adsorbed amount of toluene was stabilized at 0.18 g/g. Therefore, TVSA using USY as adsorbent is a promising way for the removal of heavy VOCs.

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