Submitted, accepted and published by
Fuel Processing Technology 110 (2013) 1-7

**Toluene and n-hexane adsorption and recovery behaviour on activated carbons derived
from almond shell wastes**

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Abstract

The objective of this work was to determine the adsorption capacity of activated carbons from almond shells in a fixed bed at low concentration of two solvents, n-hexane and toluene, as well as to study the desorption process in order to n-hexane and toluene recovery.

Activated carbons with different physicochemical characteristics were obtained by chemical activation of almond shells varying activation temperature, impregnation ratio and activation time, following an experimental design. Although a number of variables affect adsorption capacity under dynamic mode, such as adsorption temperature, initial concentration and spatial velocity, under the same operating conditions activated carbons exhibit quite different adsorption capacities. High adsorption capacities at low n-hexane and toluene concentration have been obtained: 253 mg toluene/g and 122 mg n-hexane/g.

However, the reduction of adsorption capacity comparing that obtained in static mode and dynamic mode does not follow a trend. This reduction it is not proportional either among the activated carbons for a single solvent or for one activated carbon with both solvents.

The n-hexane and toluene adsorption capacities obtained at low concentration do not correlate directly with textural characteristics and surface chemistry is involved in the adsorption process. The deviation of linearity of the Dubinin-Radushkevich model applied to solvent isotherms gives an appropriate idea of heterogeneity of the activated carbon, giving a range of deviation that maximizes n-hexane and toluene adsorption capacity.

Keywords: toluene adsorption, n-hexane adsorption, regeneration, solvent recovery, activated carbon, breakthrough curve

1. Introduction

Toluene and n-hexane are volatile organic compounds (VOCs) commonly used as solvents in the industry. According to the European Environmental Agency (EEA) around 40% of non-methane VOCs (NMVOCs) come from the solvents sector [1].

Apart from National Emission Ceilings Directive (NECD) target reduction of NMVOCs emissions [2], the control of VOCs emissions to the atmosphere by a non-destructive technology has the advantage of solvent recovery to be used again.

High surface area carbons are the most commonly employed adsorbents in gas phase separation. As they are a general adsorbent, they can adsorb all kind of molecules under a wide range of conditions [3, 4].

Most available data on adsorption systems are determined by the adsorption isotherm.

However, in real application the saturation capacity is never reached because gas streams has low concentration of VOCs that corresponds to the low relative pressure range in the adsorption isotherm.

Moreover, in dynamic mode equilibrium is difficult to reach. During dynamic adsorption of a VOC, adsorption occurs in a series of three steps. In the first step, the contaminant is transferred from the bulk gas stream to the external surface of the adsorbent material (mass transfer step). In the second step, the contaminant molecule diffuses from the relatively small area of the external surface into the macropores, transitional pores, and micropores within each adsorbent (diffusion step). Most adsorption occurs in the micropores, where the majority of available surface area is. In the third step, the VOC molecule adsorbs to the surface in the pore (adsorption step). First and second steps occur because of the concentration difference between the bulk gas stream passing through the adsorbent and the gas near the surface of the

adsorbent. This means that at low VOC concentration the concentration difference is low and consequently these steps are slow and the equilibrium under these conditions will be difficult to reach.

Although a number of variables affect adsorption capacity under dynamic mode, the characteristics of the adsorbent gas, the type of adsorbate, the adsorption temperature and the gas velocity are very important to determine the breakthrough capacity.

The adsorption capacity of a carbon will depend on surface area, pore volume and microporosity [3, 4]. Another important factor for the removal of polar compounds is surface chemistry [5, 6].

But VOCs generated from plants and factories are composed of organic compounds mixed each other with different dipole moment, so adsorption characteristics onto a sorbent were thought to be different and should be studied separately for design purposes before competitive adsorption process.

The preparation of activated carbons from biomass and agricultural wastes is widely known [7, 8]. However, some aspects have been developed in lower extent: the production of activated carbons related to their utilization, the recovery of solvents and VOC removal in low concentration streams. In this context, the objective of this study was to evaluate the breakthrough capacity of toluene and n-hexane at low concentration over activated carbons prepared by chemical activation of almond shells with phosphoric acid, according to an experimental design evaluated by the surface response methodology [9]. The influence of adsorption temperature as well as gas velocity on the breakthrough curves was evaluated. The breakthrough capacity was related with the characteristics of the different activated carbons. Finally, the behavior of some activated carbons along several cycles of adsorption-desorption was conducted in order to simulate real use of these carbons.

2. Experimental Methods

2.1. Activated carbons

Activated carbons have been obtained from the chemical activation with phosphoric acid of almond shells at different impregnation ratios (from 0.5 to 1.5), temperatures (from 400° to 800°C) and times (from 30 to 120 min). Samples were labelled indicating temperature of carbonization, followed by impregnation ratio and activation time. Example: AT400R05t120 (A: almond shell; T400: activation temperature of 400°C; R05: impregnation ratio of 0.5; t120: activation time of 120 min).

More details of the experimental design and procedure of preparation of the activated carbons can be found elsewhere [9].

2.2. Characterization

Samples were characterized by temperature programmed desorption (TPD), infrared spectroscopy (FTIR), Boehm titration and N₂ adsorption.

In a TPD experiment the amounts of CO and CO₂ evolved at each temperature were measured continuously with a quadrupole mass spectrometer from Pfeiffer.

Infrared spectra of the activated carbons were obtained in a Bruker Tensor 27 by directly dispersion of the activated carbon powder on the crystal.

The selective neutralization method was used to evaluate the acidic character of the surface of the activated carbons according to Boehm's procedure [10]. The amounts of various acidic oxygen functional groups (carboxyls, lactones, phenols and carbonyls) were measured by selective neutralization using bases of different strength.

Textural characterization was performed by N₂ adsorption-desorption at -196°C. Isotherms were obtained in an apparatus ASAP 2020 from Micromeritics. Prior to the analysis, samples were outgassed at 200°C up to a vacuum of 10⁻⁵ mm Hg. The volume of adsorbed nitrogen was measured from a relative pressure of 10⁻⁷ up to 0.995. Surface area was determined by BET method [11] applied to the adsorption branch of the isotherm. Pore volume corresponding to micropores was calculated using Dubinin-Radushkevich (D-R) equation applied to the adsorption branch of the N₂ isotherm [12]. Pore volume corresponding to mesopores was calculated with Barret-Joyner-Halenda (BJH) equation applied to the desorption branch of the N₂ isotherm [13]. The total pore volume was taken from the measure of adsorbed nitrogen at a relative pressure of 0.995. The percentage of microporosity can be obtained as the ratio between total micropore volume (calculated by applying D-R equation to the adsorption branch of the N₂ isotherm) and volume adsorbed at relative pressure of 0.995 [14]. Pore size distribution was evaluated by density functional theory (DFT) method [15]. More details of the characterization procedure are given in [9].

2.3. Toluene and n-hexane adsorption-desorption

The adsorption-desorption isotherms of toluene or n-hexane vapours in static mode were obtained using a gravimetric analyzer from VTI Corporation (Miami, USA). This apparatus is fully computer controlled and measures adsorption and desorption on a gravimetric microbalance. The sample temperature (25°C) is constantly monitored throughout the duration of the experiments and the variation was found to be 0.5°C. A pressure transducer in the range of 0-100 mm Hg (accurate to ±0.12%) is used to monitor the vapour pressure in the system. Approximately 100 mg of a sample of activated carbon was placed into a bucket made from stainless steel mesh and was outgassed in situ at 150°C under vacuum to a constant weight.

Pressure steps in the range of p/p_0 values 0-0.95 were used to obtain the isotherms. After the equilibrium was reached, the organic vapour pressure was increased to the next set pressure value, and the subsequent uptake was measured until equilibrium was re-established. The reverse procedure was used to study the desorption process.

The breakthrough curves for toluene and n-hexane were obtained in a home-made experimental system used for dynamic mode. A scheme of the experimental installation is given in Figure 1. It consists of a fixed bed adsorber with an internal diameter of 1 cm coupled to a mass spectrometer (MS) from Pfeiffer. Toluene and n-hexane vapours were obtained from cylinders containing either toluene/Ar or n-hexane/Ar to obtain a concentration in the range 500-1000 ppmv. The flow rate was in the range 30-60 ml/min and the adsorption temperature was 25-100°C. Samples were used without previous degasification. Before starting an experiment the gas stream was bypassed the adsorber bed in order to allow either toluene or n-hexane concentration measurement.

For some samples, adsorption-desorption experiments were carried out. After an adsorption experiment, once the activated carbon reached saturation, it was heated up to 150°C and maintained at this temperature up to no solvent is evolved (followed by MS). After this, the activated carbon is cooled down up to the adsorption temperature, and a new adsorption experiment is carried out.

3. Results and Discussion

3.1. Influence of operating conditions on breakthrough curves

Figures 2, 3 and 4 depict the influence of operating conditions on breakthrough curves for activated carbon labelled as AT400R1t75 using n-hexane as adsorbate. Similar results were

found for toluene adsorption as can be follow in Figure 5, which represents the amount of each VOC adsorbed at different operating conditions.

Figure 2 shows the influence of temperature adsorption on breakthrough curves at initial n-hexane concentration of 1000 ppm and spatial velocity of 2900 h⁻¹. The breakthrough time decreases as the adsorption temperature increases. The vapour pressure of the adsorbate increases at increasing temperatures, raising the energy level of the adsorbed molecules. Adsorbed molecules now have sufficient energy to overcome the van der Waals' attraction and migrate back to the gas phase. Molecules already in the gas phase tend to stay there due to their high vapour pressure.

At increasing temperature the breakthrough curve becomes steeper. With the increase of temperature the pore diffusion coefficient is higher, which favours fast pore diffusion [16]. Moreover the predominant step during dynamic adsorption changes with the temperature regime, and at lower temperature the adsorption rate constant is predominant whereas adsorption capacity is predominant at higher temperature [17, 18].

Figure 3 shows the breakthrough curves for three different initial n-hexane concentrations at 25°C and spatial velocity of 2900 h⁻¹. Breakthrough time decreases at increasing initial concentration, because the high n-hexane concentration saturated the activated carbon more quickly. With increasing n-hexane initial concentration the curves are steeper, resulting in the decrease of the time required to reach its effective bed load [18].

Figure 4 shows the effect of different spatial velocities on the breakthrough curves at 25°C and an n-hexane initial concentration of 1000 ppm. As can be seen at higher spatial velocities the breakthrough occurs earlier. The lower spatial velocity corresponds to the longer contact time through the bed and accordingly the greater is the probability of a molecule of n-hexane to reach an available adsorption site. The steepness of the curves also increases with

increasing spatial velocity. This fact can be explained in terms of reduction of the thickness of the mass transfer boundary layer, leading to reduced external mass transfer resistance [19].

3.2. Influence of activated carbon characteristics on breakthrough curves

Table 1 reports the results of porosity characterization of the 12 activated carbons. N_2 adsorption-desorption isotherms are given elsewhere [20] and the influence of the preparation conditions on the porosity was studied previously [9].

Table 2 shows the results of the oxygen surface chemistry characterization. The CO_2 and CO evolution profiles are given in [9] and the IR spectra are given in [20]. The influence of the preparation conditions on the oxygen surface groups was studied previously [9].

Table 3 reports the adsorption capacity obtained by Langmuir model for toluene and n-hexane from the adsorption isotherms in static experiments. Previous study [20] has shown that adsorption capacity in static mode (relative pressures near 1) depends both on the porosity and surface groups content.

In dynamic experiments the equilibrium is difficult to reach and operating conditions, apart from the characteristics of the activated carbons, are involved in the final performance of an activated carbon. So, in present study, the breakthrough curves of toluene and n-hexane were obtained at fixed operating conditions: initial concentration of 500 ppm, total flow of 30 ml/min and adsorption temperature of 25°C. Figure 6 and 7 depict the toluene and n-hexane breakthrough curves, respectively, for some activated carbons as example. In general, the high slope of the curves indicates that the adsorption is very quick and there are not limitations to mass transfer. The breakthrough times are lower for n-hexane than for toluene. This is not only because of the characteristics of each activated carbon but also because of the relative pressure used for n-hexane and toluene. The initial gas concentration for each adsorbate is the

same; however, their relative pressures are different because they have different saturation pressures. Thus, relative pressure corresponding to 500 ppm for toluene is 1.3×10^{-2} and for n-hexane is 2.5×10^{-3} . These values correspond to the low relative pressure region in the adsorption isotherm obtained by static experiments, as can be deduced from Figures 8 and 9. The activated carbon adsorption capacity for each sample was obtained by the integration of the breakthrough curves and these values are presented in Table 3. The adsorption capacity of some of these activated carbons is higher than that reported by Yanxu et al. [21] with a semi-coke from an anthracite, Pei and Zhang [22] and Chiang et al. [23] and comparable with the adsorption capacity obtained by Kim et al. [24]. However, the reduction of adsorption capacity comparing those obtained in static mode and dynamic mode does not follow a trend. This reduction it is not proportional among the activated carbons for a single solvent. For example, this reduction is in the case of toluene adsorption of 51.8% for sample AT400R05t120 and 42.1% for sample AT400R1t75. Moreover, the reduction of adsorption capacity is not the same for one activated carbon with both adsorbates. For example, this reduction is in the case of toluene adsorption of 51.8% for sample AT400R05t120 and 40.3% in the case of n-hexane adsorption for the same sample. This fact could be explained in terms of the nature of both molecules and the interaction of them with the surface of the activated carbon at conditions different from equilibrium.

Since Table 2, it is evident that the activated carbons have different polarity coming from the different type and amount of surface groups. The heterogeneity of the activated carbon surface could give preferred sites for the adsorption in dynamic mode. This heterogeneity should be a compromise between adsorption potential distribution in micropores and surface chemistry.

The heterogeneity of the surfaces can be studied by inspection of the deviation from linearity of the D-R model applied to either n-hexane or toluene isotherms at high relative pressures [25]. When a polar adsorbate is adsorbed onto a surface containing polar sites there is a thermal effect on the orientation of the molecule on the adsorbent. So the distribution of the adsorbed volumes with $-\Delta G$ for such a system should not be representative solely of the physical nature of the surface but will also be markedly affected by its chemical nature.

In the present case, all the isotherms modeled by D-R equation exhibit a positive deviation, as can be seen in Figure 10 for some activated carbons as example.

At the lowest relative pressures, the adsorption capacities are strongly influenced by electronic properties of the adsorbate and also with the energy of interaction with the adsorbent. This fact is in line with adsorption capacities being associated with strong interaction between adsorbent and adsorbate at the early stages of adsorption, corresponding to primary micropore filling. During the later stages of adsorption, as micropores of bigger size are being filled, at higher relative pressures, the adsorption capacities are determined mainly by molecular size, the hydrophilic character of the adsorbate and polarity. The importance of these properties indicates that polar as well as non-polar interactions between adsorbate molecules play a key role in the adsorption mechanism at this stage. At high relative pressures range the adsorption capacity is affected by both mechanism [26].

These positive deviations at high relative pressures (low $\log^2 p_0/p$) from the D-R equation indicate that the adsorption process is dominated by surface heterogeneity rather than volume filling of micropores. At low surface coverage adsorption is dominated by differences in surface heterogeneity among a large population of adsorption sites (such as polar surface groups). The role played by both the chemical nature of the surface and the microporosity in the deviation of the D-R plots may be quantified by calculating the differences between the

slope of the portion of the plot corresponding to high relative pressures (low $\log^2 p_0/p$) and the slope of the portion of the plot corresponding to low relative pressures (high $\log^2 p_0/p$). So, the difference between both slopes could give an idea of both surface chemistry and porosity in a single parameter.

The amount of toluene and n-hexane adsorbed at 50% of the breakthrough is plotted as a function of the D-R slope difference in Figure 11. First noticeable observation is that the differences of D-R slope obtained from n-hexane and toluene isotherms were higher for the first adsorbate than for the second one, indicating that the interaction of each adsorbate with the activated carbons is quite different. Adsorption forces include dispersion forces (van der Waals, attractive), short range repulsive forces and electrostatic (coulombic) forces if either the solid or the gas is polar. Dispersion forces arise from the rapid fluctuation in electron density within each atom. This induces an electrical dipole moment in neighboring atoms, leading to an attraction between the atoms. Both solvents are non-polar, but the dipole moment of toluene is four times higher than that for n-hexane. On the other hand, the affinity coefficient β in D-R equation is similar for n-hexane and toluene [27], so the value of characteristic adsorption energy E_0 for each system (n-hexane-activated carbon and toluene-activated carbon) is the main factor explaining differences of the slope D-R. This influence is more pronounced at low relative pressures (high $\log^2 p_0/p$) [28]. As can be seen from Figure 11, low D-R slope differences lead to low adsorption capacities for both solvents studied. On the other hand, high D-R slope differences lead to high adsorption capacities for both solvents studied. However, as it has been stated before, the range of D-R slope differences is different for n-hexane and toluene, indicating that lower E_0 favours n-hexane adsorption up to a level. This level is determined by the surface of the activated carbon: the polarity character of the activated carbons is detrimental for n-hexane adsorption.

3.3. Adsorption-desorption cycles

The regeneration of the activated carbons is an important issue to investigate, because the recovery of solvents is one of the attractive of the adsorption process.

In industrial uses, fixed-bed adsorption systems usually involve multiple beds. One or more beds treat the process exhaust, while the other beds are either being regenerated. The functions of the two beds are switched periodically based either upon a time cycle or when the adsorption bed approaches saturation and the solvent concentration in the purified stream increases to some predetermined level.

Table 4 reports the toluene and n-hexane adsorption capacities at breakthrough of 90% along several adsorption-desorption cycles for some activated carbons. Small differences of adsorption capacities along the adsorption-desorption cycles can be found. It seems that adsorption capacities follow a decreasing trend along cycles. Two different explanations can arise from this fact. Despite the temperature used for desorption is higher than boiling temperature of both solvents, the interaction between solvent and activated carbon could leave some remaining amount of solvent on the adsorbent after desorption and so, some sites for further adsorption occupied, slightly decreasing the amount desorbed in a new cycle. On the other hand, the desorption step at 150°C in presence of an organic specie adsorbed could lead to a change on the activated carbon textural characteristics by a mild gasification. However, textural data obtained from N₂ isotherms after toluene desorption at 150°C did not exhibit significant changes either surface area or pore volume.

In order to test first hypothesis, some sample coming from the toluene adsorption-desorption isotherm in static mode was submitted to a TPD of the remainder toluene after desorption.

With this procedure, sample has been desorbed at 25°C, but it has not undergone the treatment at 150°C.

This TPD experiment was carried out at a heating rate of 5°C/min under a flow of 30 ml/min of Ar. Figure 12 shows DTA curve and fitted DTA curve as well as curvefitting peaks for TPD experiment with sample AT400R1t75, as example. Table 5 gives the temperature for maximum toluene evolution during TPD experiments. As can be seen three desorption peaks of toluene can be obtained. Lower temperature peaks correspond to weakly adsorbed toluene, which would be easily removed by heating before to next adsorption cycle. However, the presence of high temperature peak indicates that toluene is strongly adsorbed in some sites of the activated carbon and it is not evolved even at the boiling point of toluene. This residual amount of toluene cannot be removed at the temperatures of desorption used in this work, and this is the reason because the amount of toluene adsorbed slightly decreases along the cycles used in this work.

4. Conclusion

High n-hexane and toluene adsorption capacities from dynamic experiments at low solvent concentration can be obtained with almond shell based chemically activated carbons. There is not a direct relationship between nor textural characteristics neither surface chemistry and adsorption capacities and a balance between both features should be include to explain high adsorption capacities in some cases.

The deviation of linearity of the Dubinin-Radushkevich model applied to solvent isotherms gives an appropriate idea of heterogeneity of the activated carbon, giving a range of deviation that maximizes n-hexane and toluene adsorption capacity.

Recovery of solvents along several cycles adsorption-desorption has been tested and only a slight decrease of the adsorption capacity was found. This decrease has been attributed to residual solvent strongly adsorbed to the activated carbon that is not removed at the desorption temperatures.

Acknowledgements

The financial support from Spanish Ministry of Environment (contracts 439/2006/3-11.2 and B030/2007/2-11.2) is duly recognized.

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FIGURE CAPTIONS

Figure 1. Experimental installation for dynamic toluene and n-hexane adsorption experiments

Figure 2. Effect of adsorption temperature on n-hexane breakthrough curves (initial concentration 1000 ppm; spatial velocity 2900 h^{-1})

Figure 3. Effect of n-hexane initial concentration on breakthrough curves (adsorption temperature 25°C ; spatial velocity 2900 h^{-1})

Figure 4. Effect of spatial velocity on n-hexane breakthrough curves (adsorption temperature 25°C ; initial concentration 1000 ppm)

Figure 5. Amount of (●) n-hexane and (■) toluene adsorbed for different operating conditions

Figure 6. : Toluene breakthrough curves (operating conditions: temperature of adsorption 25°C , initial concentration C_0 500 ppm, total flow 30 ml/min) for samples: 1-AT400R1t75; 2-AT400R15t30; 3-AT467R117t45; 4-AT600R1t30; 5-AT800R15t120

Figure 7. n-hexane breakthrough curves (operating conditions: temperature of adsorption 25°C , initial concentration C_0 500 ppm, total flow 30 ml/min) for samples: 1-AT400R1t75; 2-AT400R15t30; 3- AT467R117t45; 4-AT600R1t30; 5-AT800R15t120

Figure 8. Isotherms for n-hexane adsorption at 25°C (dashed line indicates the relative pressure for 500 ppm).

Figure 9. Isotherms for toluene adsorption at 25°C (dashed line indicates the relative pressure for 500 ppm).

Figure 10. Dubinin-Radushkevich plot for some activated carbons from a) toluene adsorption isotherm at 25°C and b) n-hexane adsorption isotherm at 25°C .

Figure 11. Amount adsorbed at 50% breakthrough (initial concentration of 500 ppm, total flow of 30 ml/min and adsorption temperature of 25°C) against D-R slope difference.

Figure 12. DTA and DTA fitted curve of toluene from TPD experiment onto desorbed AT400R1t75 sample at 25°C.

Table 1. Textural characterization of the samples.

Sample	S_{BET} m^2/g	V_{p} cm^3/g	V_{meso} cm^3/g	V_{micro} cm^3/g	$D_{\text{p,H-K}}$ (Å)	Microporosity %
AT400R05t120	626	0.376	0.124	0.335	8.6	89.1
AT400R1t75	1128	0.670	0.385	0.521	9.5	77.8
AT400R15t30	789	0.482	0.268	0.342	9.6	71.0
AT467R067t90	785	0.497	0.259	0.392	9.0	78.9
AT467R117t45	1117	0.724	0.494	0.513	9.6	70.9
AT533R083t60	891	0.571	0.341	0.426	12.5	74.6
AT533R083t60(2)	903	0.593	0.378	0.427	13.1	72.0
AT600R05t75	502	0.301	0.106	0.261	8.3	86.7
AT600R1t30	926	0.624	0.375	0.435	9.0	69.7
AT667R067t45	624	0.440	0.176	0.314	8.4	71.4
AT800R05t30	723	0.425	0.147	0.378	8.2	88.9
AT800R15t120	990	0.694	0.511	0.448	15.3	64.6

Table 2. Oxygen functional groups characterization: total amount of CO and CO₂ evolved up to 1100°C in TPD experiments, area of IR regions 1600 cm⁻¹ and 1100 cm⁻¹ and results from Boehm titration.

Sample	CO mmol/g	CO ₂ mmol/g	A ₁₆₀₀	A ₁₁₀₀	Carboxyls mmol/g	Lactones mmol/g	Phenols mmol/g	Carbonyls mmol/g
AT400R05t120	1.985	0.569	0.25	4.35	0.350	0.800	0.800	1.900
AT400R1t75	2.170	1.322	0.28	4.51	0.350	0.850	0.988	2.012
AT400R15t30	1.798	0.754	0.33	3.90	0.375	1.075	1.750	1.525
AT467R067t90	2.587	1.036	0.52	4.75	0.425	1.025	0.900	2.412
AT467R117t45	2.181	1.177	0.35	4.60	0.450	0.650	1.100	2.175
AT533R083t60	2.232	0.387	0.40	4.94	0.450	0.800	0.875	2.625
AT533R083t60(2)	2.180	0.358	0.42	4.79	0.450	0.900	1.025	2.400
AT600R05t75	2.833	0.517	0.29	5.10	0.725	0.425	0.725	2.750
AT600R1t30	3.045	0.451	0.29	4.70	0.475	0.750	0.975	2.425
AT667R067t45	2.865	0.481	0.61	4.41	0.500	1.600	1.200	2.250
AT800R05t30	4.135	1.921	0.55	4.60	0.650	0.850	1.225	2.300
AT800R15t120	3.722	1.293	0.58	4.85	0.525	1.075	1.000	2.425

Table 3. Adsorption capacities from Langmuir model (W_m , static experiments at 25°C) and from breakthrough curves (W_{dyn} , dynamic experiments at initial concentration of 500 ppm, temperature of 25°C and spatial velocity of 2900 h⁻¹).

Sample	Toluene			n-hexane		
	$W_{m,tol}$ mmol/g	$W_{dyn,tol}$ mmol/g	t_b (h)	$W_{m,hex}$ mmol/g	$W_{dyn, hex}$ mmol/g	t_b (h)
AT400R05t120	3.65	1.89	22.5	2.82	1.13	13.8
AT400R1t75	6.54	2.75	32.9	5.73	1.46	15.2
AT400R15t30	7.44	2.15	25.2	5.44	1.22	14.0
AT467R067t90	4.02	2.40	23.3	3.55	1.05	7.4
AT467R117t45	6.89	2.29	27.9	5.55	1.32	16.2
AT533R083t60	4.95	2.22	27.7	4.23	1.18	12.5
AT600R05t75	2.53	1.46	14.7	2.06	0.78	3.1
AT600R1t30	6.50	2.31	28.5	4.54	1.11	11.2
AT667R067t45	3.37	1.39	11.5	2.84	0.91	7.3
AT800R05t30	2.68	1.19	12.0	2.12	0.78	2.9
AT800R15t120	6.10	1.72	20.6	5.00	0.98	11.2

Table 4. Adsorption capacities (mmol/g) at 90% breakthrough for some activated carbon along several adsorption-desorption cycles.

	n-hexane	toluene
AT400R1t75		
cycle 1		2.48
cycle 2		2.46
cycle 3		2.41
cycle 4		2.38
AT400R15t30		
cycle 1		2.20
cycle 2		2.19
cycle 3		2.14
cycle 4		2.15
AT467R117t45		
cycle 1	1.10	1.93
cycle 2	1.03	1.92
cycle 3	0.98	1.88
cycle 4	0.91	
cycle 5	0.90	

Table 5. Evolution temperatures (°C) from TPDs of toluene-activated carbons after desorption at 25°C.

	T1	T2	T3
AT400R1t75	58.2	99.5	159.8
AT400R15t30	59.8	99.5	160.7
AT467R117t45	59.0	99.2	159.9

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

Figure 12