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Thermodynamic and kinetic study on ammonium removal from a synthetic water solution using ion exchange resin

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Abstract Ammonium removal from the wastewater treatment effluents is mandatory considering the imposed discharge limits and the recycling/reuse requirements. Ion exchange represents a viable alternative for the biological processes of ammonium removal, although concurrent processes make modeling complex. This study reports on the performance of a commercial cation exchange resin, PUROLITE C150H, for ammonium removal from synthetic aqueous solutions. Thermodynamic and kinetic process parameters are calculated using the Langmuir model (thermodynamic study) and the shrinking core model (kinetic study); the data are correlated with the surface properties of the substrate, outlining the adsorption mechanism. For initial ammonium concentrations of 25–150 mg NH_4^+/L, removal efficiencies of 80–90 % were obtained.

Keywords Wastewater treatment · Ammonium · Ion exchange · Surface diffusion · Biot number

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Introduction

Water availability and its sustainable use are among the central problems of the twenty-first century, the unequal demand and use at global level, as well as pollution and insufficient treatment before discharge being important concerns. The Water Framework Directive 2000/60/EEC and Urban Wastewater Treatment Directive (91/271/EEC) (Hochstrat et al. 2008; Cailean and Teodosiu 2012) support sustainable water usage and, by 2015, the final objective is to achieve "good ecological and chemical status" of the EU waters, while water recycling and reuse are to be implemented "whenever appropriate." Nevertheless, the legislation mainly sets principles and not means on how to implement these concepts (Bixio et al. 2006), therefore water resources management, including recycling and reuse processes, is still to be optimized and expanded.

Considering the water quality targets set when including recycling and reuse, the wastewater has to undergo furthermore treatment steps, besides the conventional treatment (Teodosiu 2002). Thus, conventional treatment (mechanical, chemical, and biological) should be completed with advanced treatment options (chemical oxidation processes, adsorption, membrane processes, ion exchange, etc.) to efficiently remove the target pollutants (priority/persistent organic pollutants, toxic inorganic pollutants, N and P compounds) that are not easily/completely removed by conventional processes (Barjoveanu and Teodosiu 2009). Cost-effective solutions are also evaluated for various types of wastewater treatment plants (Hamad et al. 2003). To be accepted and scaled up, these solutions have to be efficient, low cost, and with low amounts of toxic/polluting by-products.

In Romania, as in many other countries, the concept of water reuse is mainly applied in agricultural irrigations.

Treated or partially treated wastewater effluents from the treatment plants are usually discharged into the rivers. In this context, the removal of priority pollutants that exceed the discharge limits becomes an important goal for advanced wastewater treatment. New and improved wastewater treatment technologies were developed for large scale wastewater treatment plants and also for on-site systems, providing more sustainable wastewater management options (Bradley et al. 2002). Nowadays, different advanced treatment methods are studied using advanced materials with tailored properties (Andronic and Duta 2008). Still, the use of traditional systems, like ion exchange, has the significant advantage of well-known technologies, requiring minimal initial investments for large scale applications.

Nutrients (nitrogen and phosphorous compounds) are pollutants with an important environmental impact due to their eutrophication potential along with their potential hazard to human beings; among them, ammonium is one of the most polluting species. Ammonium usual sources in water are the fertilizers, the industrial effluents, and animal dung.

According to the literature data, in industrial effluents the ammonium concentration can vary with the type and size of the facility, in a wide range of concentration. In Table 1 there are presented some significant types of industrial wastewater with the corresponding ammonium concentrations.

Ammonium removal is nowadays mainly done by air stripping or by biological treatment (nitrification) (Tchobanoglous et al. 2003). All these technologies, although efficient have the drawback of technological limitation, due to the wastewater pH (pH correction is required, for achieving alkaline pH), due to the sensitive microorganisms involved in the biological treatment and the formation of nitrate which should be further removed.

Table 1 Ammonium concentration in different types of industrial wastewater

Type of industrial wastewater	Ammonium concentration (mg/L)	References
Leakage waters of waste dumps	820	Farkaš et al. (2005)
Opto-electronic wastewater	567	Daverey et al. (2012)
Coal gasification wastewater	280	Ramakrishnan and Surampalli (2013)
Coal gasification wastewater	134	Wang et al. (2012)
Wool textile mill	54	Tchobanoglous et al. (2003)
Dairy wastewater	5.9–36.7	Tocchi et al. (2012)

Therefore, ion exchange can provide good response to shock loads, supplementary offering good chemical resistance, and a broad operating temperature range.

Being strongly pH-sensitive, ammonium removal in ion exchange processes was intensively studied; literature (Thornton et al. 2007a, b; Kauspediene and Snukiskis 2006; Zheng et al. 2008; Miladinovic and Weatherley 2008; Wang et al. 2007), reports that pH values of 6–7 and below are best suited for ammonium removal and the process efficiency rapidly decreases at pH 8–10. The contribution to pH of the ion exchanged during the process is therefore important, and usually, the H^+ or the HO^- forms are avoided. If the ammonium removal mechanism is well understood, the process can be controlled and scaled up.

This study investigates the removal of ammonium from aqueous synthetic solutions, in the concentration range of 25–150 mg NH_4^+/L. The highest concentration considered for the optimization studies was fixed after a 1-year monitoring performed on the effluents of some small and medium wastewater treatment plants in Romania, when the maximum value of the ammonium concentration parameter was found to be 150 mg NH_4^+/L.

A commercial cation exchange resin (C150H) was used as sorbent. Based on the Langmuir model, the thermodynamic parameters were calculated. In order to investigate the sorption mechanism, the shrinking core model was applied to fit the kinetic data specific to the ion exchange process.

The presence of other compounds can influence the removal of ammonium ions due to different ions selectivity on different resins. However, if the ammonium removal mechanism is well understood, the process can be controlled and further tested at laboratory and pilot scale with "real" wastewater.

This study is part of a larger study aiming to develop a technical solution for advanced wastewater treatment, applicable to wastewater reuse in small and remote communities. Such effluents are closer to the "municipal" type in terms of wastewater quality indicators than to the specific industrial effluents (such as leacheates, opto-electronic effluents, coal gasification, etc.).

Ammonium equilibrium in water

The ion exchange process can be described according to the equilibrium equation:

$$\mathrm{R{-}Na} + \mathrm{NH_4}^+ \rightleftarrows \mathrm{R{-}NH_4} + \mathrm{Na}^+, \tag{1}$$

where R–Na is the ion exchange resin.

Equilibrium develops in aqueous solutions between non-ionized ammonia (NH_3) and ammonium, according to the following equation:

$$NH_4^+ + HO^- \rightleftarrows NH_3 + H_2O \tag{2}$$

In solutions, the ammonia–ammonium equilibrium is strongly pH-dependent and through ion exchange, only the ionic form (ammonium) can be removed.

Ammonia has limited solubility in water and its concentration in aqueous systems is temperature-sensitive; therefore experiments were done at constant temperature (22 ± 1 °C) and ammonium chloride was selected as precursor, also aiming at avoiding parallel equilibria which could be expected when using precursors containing weak acids anions.

Because ammonium chloride is a salt obtained from a strong acid (hydrochloric acid, HCl) and a weak base (ammonium hydroxide, NH_4OH), hydrolysis occurs in solution, according to Eq. (3):

$$NH_4Cl + HOH \rightleftarrows NH_4OH + (H^+ + Cl^-) \tag{3}$$

Using Eqs. (4)–(6), the hydrolysis constant and the solution pH were calculated, considering the maximum concentration set in this study. The corresponding values are: $K_h = 5.68 \times 10^{-20}$ mol/L, and pH 5.66.

$$K_h = \frac{K_w}{K_b} \tag{4}$$

$$[H^+] = \sqrt{\frac{K_w \cdot c}{K_b}} \tag{5}$$

$$\text{and pH} = -\log[H^+] \tag{6}$$

where K_w is the ionic product of water (10^{-14} mol^2/L^2); K_b the basicity constant of ammonium hydroxide (1.76×10^{-5}); c is the molar concentration (0.0083 mol/L = 150 mg/L).

These values confirm that ammonium chloride represents a good testing sample, since only a very small part of the ammonium cations is linked in ammonium hydroxide and the final pH is in the acidic range.

Experimental

The C150H cation exchange resin (Purolite Romania) was used for removing ammonium ions from a synthetic solution of wastewater. The chosen resin is largely used in industrial processes for removing water hardness or heavy metals, because it has a very good stability over pH, temperature (up to 120 °C) and time. Reuse (in successive cycles of adsorption/desorption) in full operation can be done over up to 10 years. So far, no testes for ammonium removal are reported. The main characteristics of the resin are presented in Table 2.

Table 2 Cation exchange resin characteristics

Physical–chemical characteristics	C150H
Polymer structure	Macroporous polystyrene, crosslinked with divinylbenzene
Functional group	Sulphonic acid
Appearance	Spherical beads
Ionic form	$-Na^+$
Total capacity (Na^+ form) (eq/L)	1.81
Moisture retention (Na^+ form) (%)	50–54
Specific weight (g/mL)	1.18
Particle radius (mm)	0.59

The cation exchange resin was converted into the R-Na form using NaCl 10 % solution, by passing 1.5 bed volume (BV) of sodium chloride solution over the resin, followed by washing using 2 BV of distilled water, and by drying in open atmosphere.

Ammonium synthetic solutions were prepared using a stock solution of ammonium chloride 1,500 mg/L (NH_4Cl Scharlau S.A, analytical pure) dissolved in distilled water. For pH correction NaOH 0.1 N was used, under stirring. The pH was measured using a Hanna Instruments pH-meter.

The conventional stirred tank (batch reactor) method was used to investigate the thermodynamic and kinetic performance of the C150H cation exchanger in removing ammonium ions from aqueous solutions. The batch reactor consists of a glass container in which the resin-solution systems were stirred at 300 rot/min, at 22 ± 1 °C. The behavior of the cation exchange resin C150H in distilled water was studied in systems containing 1 g of resin in contact with 100 mL distilled water, for 90 min.

During the ammonium adsorption, the processes described in Eqs. (2) and (3) are running in a system that is no longer at equilibrium, leading to slight pH modifications, therefore, this property was measured, during adsorption, each 10 min. The regeneration (desorption) step is correlated with the ammonium load of the treated wastewater, according to the exchange capacity (also high for a cation exchange resin).

The ammonium concentration was evaluated based on the molecular spectrometric method (Romanian standard, STAS 8683-70): the ammonium ions form a yellow amido-oxy-dimercuric iodide complex with the Nessler Reagent, with an absorbance maximum at 400 nm. A Perkin-Elmer Lambda 25 spectrophotometer using 10 mm glass cuvettes was used for spectral measurements, at room temperature.

The surface of the C150H resin particles was investigated by scanning electron microscopy (SEM, Hitachi, S-3400 N type II Model, Secondary Electrons, High Vacuum, 10–3 Pa, 3 nm at 30 kV).

The energy dispersive X-ray spectroscopy (EDS/EDX) analysis was performed using Thermo Ultra Dry, Noran System 7, NSS Model (2,000,000 counts/s) to outline the surface composition before and after the removal processes.

Adsorption modeling

The removal efficiency (RE, %) was calculated using Eq. (7):

$$\mathrm{RE}\,(\%) = \frac{(c_0 - c)}{c_0} \times 100 \tag{7}$$

where c_0 is the initial concentration (mg/L) and c the equilibrium concentration (mg/L).

The ion exchange process can be modeled using different types of isotherms. For this study, experimental data were fitted to the Langmuir model, Eq. (8), considering the monolayer chemisorption, applicable to the process in the selected concentration range (Thornton et al. 2007b):

$$\chi = \chi_{\max} \frac{\alpha \cdot c}{1 + \alpha \cdot c} \tag{8}$$

where χ is the adsorption coefficient (mol/g ion exchanger), $\chi_{\max}$ the maximum adsorption coefficient (mol/g ion exchanger), c the equilibrium concentration (mg/L), and α is the Langmuir parameter.

By linearization and plotting $\chi/c = f(c)$, the maximum adsorption coefficient $\chi_{\max}$ was evaluated. Using the linear equation, the intercept and the slope of the linearized Langmuir isotherm, the adsorption enthalpy was calculated using Eq. (9):

$$\Delta H = \frac{RT}{\ln a} \tag{9}$$

where R is the universal constant (J mol^{-1} K^{-1}), T the temperature (K), a is the intercept.

The ammonium uptake (q) at the current moment (t) is calculated using Eq. (10):

$$q = \frac{(c_0 - c_t) \cdot V}{m} \tag{10}$$

where q is the adsorption coefficient (mol/g ion exchanger), c_t the residual solution concentration at the current moment (mg/L), c_0 the initial concentration (mg/L), V the solution volume (mL), and m is the mass of ion exchanger.

Several simplified kinetics models can be applied for batch operation (Öztürk and Ennil Köse 2008; Kang et al. 2004; Lin and Juang 2007), among these, being the shrinking core model (Inglezakis and Poulopoulos 2006). The overall exchange rate is considered as a combination of the diffusion rate of the ammonium ion in the fluid film, the diffusion rate in the solid, and the chemical reaction rate. Specific equations are used for calculating the corresponding coefficients for each rate-controlling process. In all equations, the fractional conversion X_B, (the solid-phase concentration), is used.

The film diffusion control step is described by Eq. (11):

$$X_B = \frac{3bk_f}{\rho_B r_0} \int_0^t C_A \mathrm{d}t \tag{11}$$

and $\rho_B = q_{\max} \rho_p$

where k_f is the mass transfer coefficient in the film surrounding the particle (mm/min), $b = 1$ represents the stoichiometric coefficient, C_A the fluid phase bulk concentration of ammonium (mg/L), r_0 the radius of the particle (mm), ρ_B the molar density of originally found in the solid phase (moles sodium/g resin), $q_{\max}$ the maximum exchange capacity (mg/g), ρ_p is the particle density (g/mL).

The solid diffusion control is described by Eq. (12):

$$1 - 3(1 - X_B)^{2/3} + 2(1 - X_B) = \frac{6bD_s}{\rho_B r_0^2} \int_0^t C_A \mathrm{d}t \tag{12}$$

where D_s is the effective diffusion coefficient of ammonium in solid (mm^2/min).

The reaction kinetics control is described by Eq. (13):

$$1 - (1 - X_B)^{1/3} = \frac{bk}{\rho_B r_0} \int_0^t C_A \mathrm{d}t \tag{13}$$

where k is the first-order rate constant (mm/min).

Based on the coefficients calculated for each rate-controlling step, the Biot number can be calculated using Eq. (14):

$$\mathrm{Bi} = \frac{k_f d_p c_0}{2D_s q_{\max}} \tag{14}$$

where Bi is the Biot number and d_p the particle diameter (mm).

Results and discussion

Resin interaction with water

Since pH has a major influence on the process, initial studies were done to investigate the interaction between the cation exchanger and distilled water that might lead to an increase/decrease in the H$^+$ concentration.

The resin–distilled water system was studied for three consecutive contact cycles of 90 min. After each cycle, the resin was removed from the system by filtering, followed by drying in open atmosphere for 24 h. During each cycle,

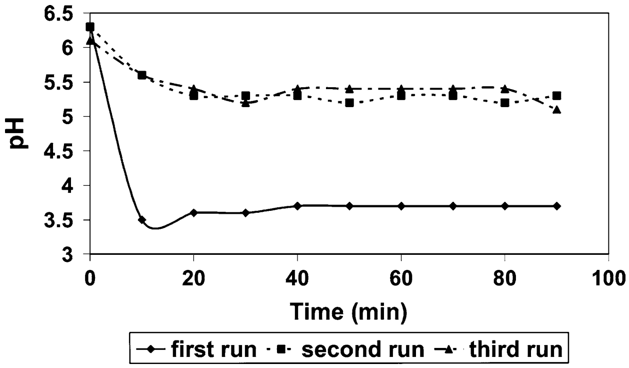

Fig. 1 pH evolution in the water–C150H system

the pH values were monitored and the results are presented in Fig. 1.

The results show a drastic pH decrease during the first cycle, in the first 10 min, followed by a steady-state plateau reached after 40 min. For the second and third run, the drop in the pH value is about 0.5–1 pH units in the first 20 min, than the steady-state is reached at similar values during both runs. The data show that a pre-conditioning step is necessary, for getting reproducible results, due to the interaction of the C150H resin with water, either as a result of a Na^+/H^+ exchange equilibrium but more likely as a result of a reversible water swelling in the resin on the sites located in the micropores.

Considering these data and the literature recommendations, further experiments were done at pH 6.5, which also is close to the natural pH of the ammonium polluted waters; to test the resin applicability limits, a parallel group of experiments were done at pH 10.

Effect of resin dosage on the process

The influence of the cation exchanger dosage was studied using 100 mL ammonium chloride synthetic solution (150 mg/L) and different amounts of resin: 0.25, 0.5, 1, 2, and 4 g; the removal efficiency data are presented in Fig. 2.

The results show that the removal efficiency increases with the resin dosage, up to 1 g resin/100 mL solution; these results can be anticipated because a larger amount of resin provides an increased number of sorption sites for a fixed initial concentration as long as the process is under kinetic control. Increasing the amount of substrate above 1 g brings no significant improvement (the process being under diffusional control) therefore, the optimum resin dosage in further sorption experiments was set at 1 g.

The pH value does not significantly influence the adsorption efficiencies, with a slight advantage for the 6.5 pH value.

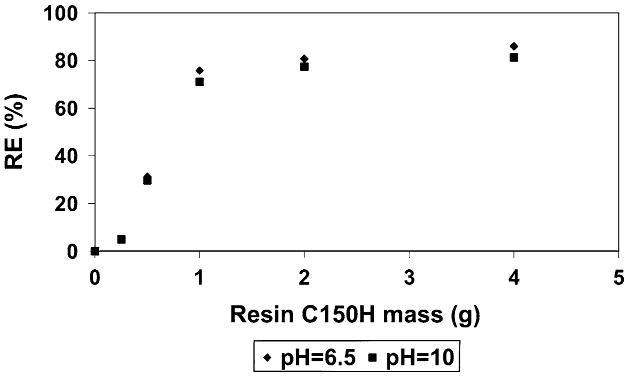

Fig. 2 Effect of resin dosage on the removal efficiency of ammonium at two pH values

Effect of contact time

A fixed amount of cation exchange resin (1 g) and 100 mL of ammonium solution at pH 6.5 and 10 were placed in the batch reactor and stirred. Aliquots of 0.5 mL of ammonium solution were taken at fixed moments and analyzed, allowing setting the optimal contact time, Fig. 3.

The data show that equilibrium is firstly reached after 40 min for both solutions. Better efficiencies are registered for pH 6.5, with about 10 % higher comparing to the results obtained in alkaline media, as result of the ammonium/ammonia equilibrium, which decreases the amount of cations at pH 10. It is also important to notice removal efficiency fluctuations after 40–80 min, stronger at alkaline pH, proving that the equilibrium steady-state needs a longer contact time (90 min), and supporting the idea of comparable affinities of the NH_4^+ and Na^+ cations for the C150H resin.

Considering these results, for further sorption experiments a 90-min contact time was used.

Effect of initial concentration

A fixed amount of C150H resin (1 g) was placed in a batch reactor with 100 mL of ammonium solution at different concentration. The experiments were performed for the already tested pH values: 6.5 and 10, using solutions at initial concentration in the range of 25–300 mg NH_4^+/L and the previously optimized contact time (90 min).

The results presented in Fig. 4 show higher removal efficiency for pH 6.5 than pH 10 on the entire concentration range. At pH 6.5 removal efficiencies above 65 % are obtained for a broad concentration range, up to 200 mg/L. Over this value the amount of active sites and/or the exchange rate are limiting the process and lead to an efficiency decrease. The results obtained in the experiments at pH 10 are consistent with the lower amount of ammonium

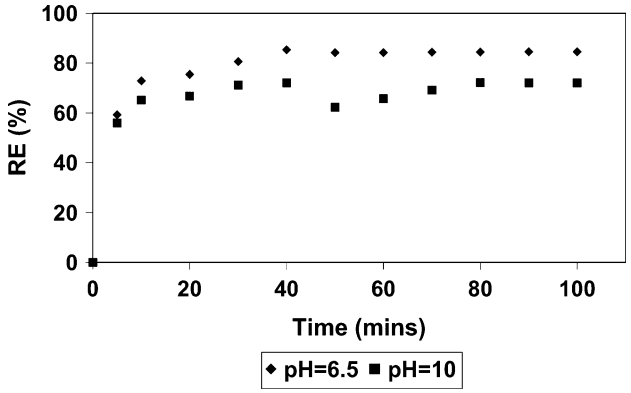

Fig. 3 Effect of contact time on ammonium removal at different solutions

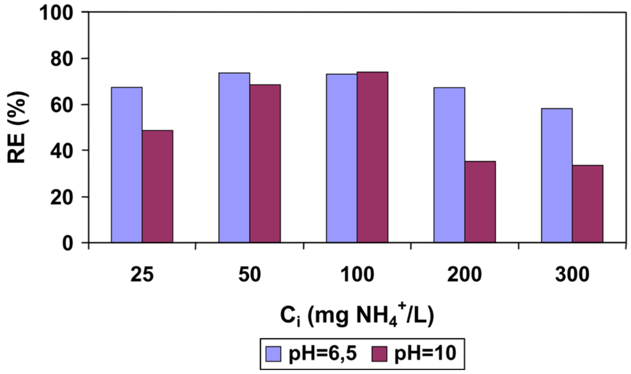

Fig. 4 Effect of initial concentration

cations, actually involved in ion exchange, showing lower efficiency at low ammonium chloride concentrations, when the ammonium cation diffusion toward the substrate is the limiting step in the mechanism. Significant higher salt concentrations lead again to lower (and almost constant) efficiencies, proving also a possible interaction of the substrate with the sodium cations from the NaOH added for pH control.

These results recommend an environmental-friendly pH value, close to 6.5; if required by the wastewater content, pH 10 can be used for average polluted waters, with ammonium overall concentrations up to 100 ml/L.

Equilibrium studies: isotherm modeling

Considering the ion exchange particularity (direct chemical interaction of the pollutant species with ion exchange sites), the Langmuir model was applied to fit the experimental data. The study was performed in a batch reactor, where 1 g of cation exchanger was stirred for 90 min with 100 mL solution of different initial concentrations.

The linear form of the Langmuir plot is presented in Fig. 5, along with the experimental data and confirms that chemisorption is the mechanism that governs the process. Obviously, this is valid for ion exchange, but the results also prove that no other side reactions are significant in the mechanism.

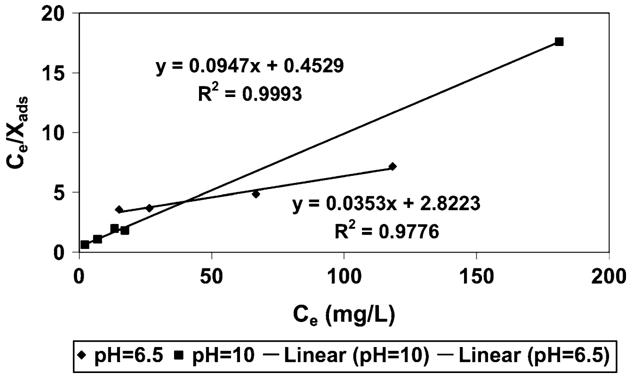

Fig. 5 Fitted Langmuir isotherm for C150H–ammonium at pH 6.5 and 10

Based on the linear plots in Fig. 5, the Langmuir parameters are calculated and are presented in Table 3.

The results show that the amount of adsorption active sites on the cation exchanger depends on pH, as already proved in the preliminary tests. The data also show a higher adsorption affinity in acidic media, confirming that investigations on the substrate are compulsory, even for the highly homogeneous cation exchanger resins. The low values registered for the adsorption heat give evidence that the energy required for regeneration is reduced, and C150H cation exchange resin can be successfully used for ammonium removal.

Kinetic study

For the kinetic study, 1 g of C150H cation exchange resin was added in 100 mL of 150 mg/L NH_4^+ solution. Considering the results obtained in the equilibrium study, the system C150H–ammonium at pH 6.5 was investigated. Aliquots of 0.5 mL were taken at 10 min and the momentary concentrations were evaluated. On these data, the shrinking core model was applied.

The integral values, Eqs. (11)–(13), were plotted against X_B. The data presented in Fig. 6a, b show that during the first 20 min all three processes are running in parallel, followed by a steady-state, reached by all three processes at

Table 3 Values obtained for Langmuir isotherms for C150H–ammonium system at different pH

pH	Correlation coefficient	Maximum adsorption capacity (mg/g)	ΔH (J/mol)	ΔH (cal/mol)
6.5	0.9776	28.225	−2569.373	−612.197
10	0.9993	10.560	−1961.501	−467.361

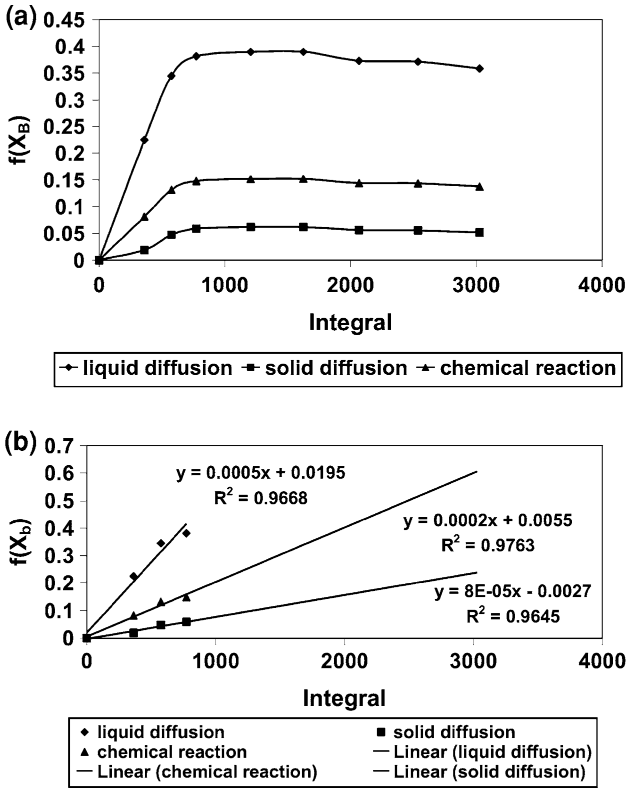

Fig. 6 **a** Shrinking core model for C150H–ammonium system and **b** linearization

the same time. Considering the overall mechanism, the most likely sequences is: liquid diffusion–chemical reaction–solid diffusion and the results show that the contribution of solid diffusion is very low, but not zero, indicating that beside ion exchange also regular adsorption can occur.

The parameters of each kinetic model are presented in Table 4 and support the conclusion that the chemical reaction is the fastest step, limited by film and/or solid diffusion.

Using Eq. (14), based on the kinetic coefficients, the Biot number was calculated. Biot number estimates the predominance of the external or internal diffusion control. If Bi < 0.5, film diffusion mechanism is dominant, and if Bi > 30 the solid diffusion mechanism is strongly dominant (Inglezakis and Poulopoulos 2006). For the studied C150H–ammonium system Bi $= 19.337$ confirming that mixed diffusion mechanism control the process.

Table 4 Mass transfer coefficients calculated for the kinetic models

Rate-controlling process	R^2	Mass transfer coefficient
Film diffusion	0.9668	$k_f = 2.7749$ mm/min
Solid diffusion	0.9763	$D_s = 0.3863$ mm^2/min
Chemical reaction	0.9645	$K = 6.6599$ mm/min

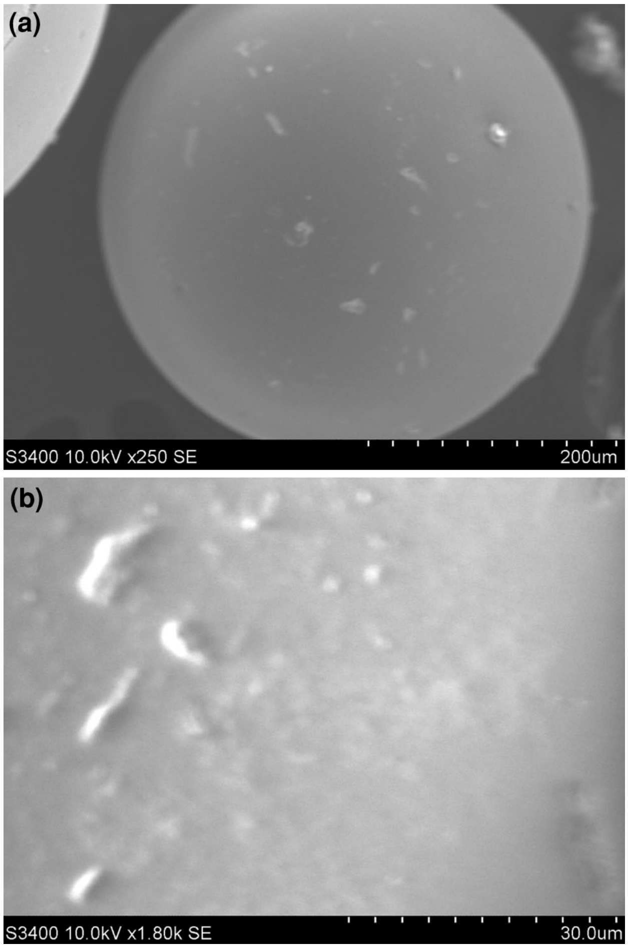

Fig. 7 Unreacted C150H resin particle

Surface analysis

Before and after reaction, the surface of the C150H resin particles were SEM investigated. In Figs. 7 and 8 the images of the unreacted, and respectively, reacted resin particles are presented.

For C150H resin no significant modifications occur after ion exchange process in the surface aspect. Images presented in Fig. 8 are taken on a cracked particle, where the core can be studied. The regular and compact structure of the material supports the kinetic conclusion that the solid diffusion is the limiting step of the process.

The EDX analysis was used for elemental analysis on the pristine and used substrate's surface and the results of the elemental mapping are presented in Table 5.

The data confirm the $Na^+/NH4^+$ exchange by a reduction in the sodium concentration corroborated with the nitrogen increase. In a rough estimation, these values show that about 0.39 sodium units (e.g., equivalents) are replaced by 1.13 ammonium units, proving that ion exchange represents just one part of the removal process, the rest being

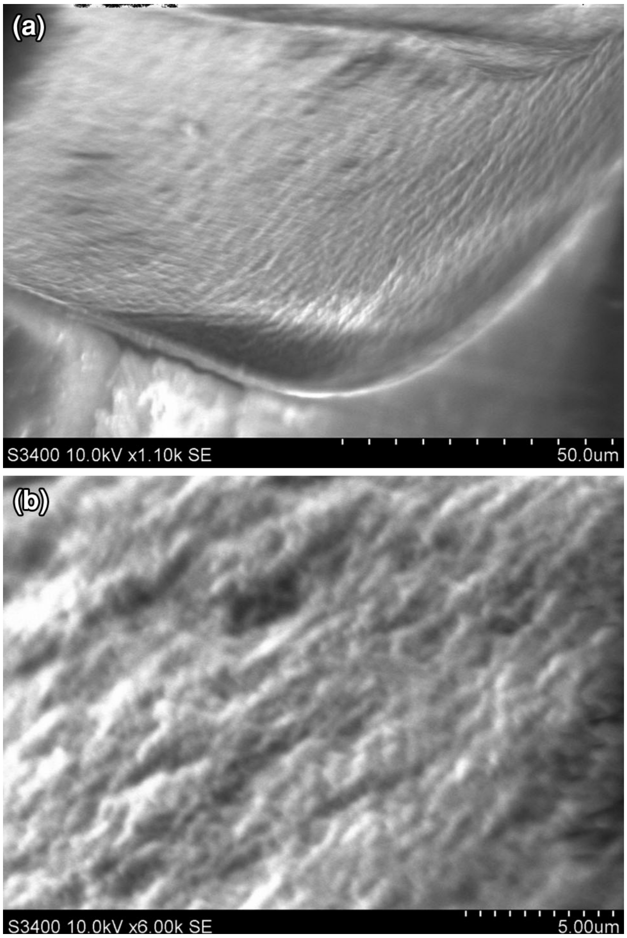

Fig. 8 Reacted C150H resin particle (cracked particle)

Table 5 Element's weight for C150H resin

Element	Unreacted resin (wt%)	Reacted resin (wt%)
C	38.24	37.34
O	22.22	25.47
Na	16.76	7.65
N	–	20.39

regular adsorption, on the low polar surface. The slight increase in the oxygen content also confirms a possible water trapping or oxidative processes involving ammonia (explaining also the cracks in some particles) but these assumptions will be detailed investigated in the future. Also the increase in the oxygen content can be generated by the physisorbed molecules as experiments were performed in open atmosphere. The carbon content is slightly decreased (0.9 wt%) as result of a possible CO_2 decrease in the water solution, with consequences on the CO_2 equilibrium established between the solved CO_2 and the adsorbed CO_2 on the ion exchanger grains.

Conclusions

The article shows that the cation exchange resin C150H can be successfully used for ammonium removal from aqueous solutions, on a broad concentration range, at pH 6.5. With careful concentration control, convenient efficiencies can be reached even in alkaline environments, at pH values of 10. For initial concentrations of 25–300 mg NH_4^+/L removal efficiencies of 80–90 % were obtained.

For reproducible results and for avoiding pH fluctuations, a resin pre-conditioning, with distilled water is recommended. The heat of adsorption indicates that resin regeneration can be easily performed, allowing simple regeneration methods. As diffusion is the predominant process, distended breakthrough curves will be obtained. This impediment can be overcome by increasing the amount of cation exchange resin.

The thermodynamic and kinetic parameters for C150H–ammonium system were investigated, using Langmuir isotherm model for the thermodynamic behavior and the shrinking core model for the ion exchange process kinetic, as input data for the further design of the ion exchange column.

For small and remote communities, the ion exchange advance wastewater treatment method can be a viable solution for wastewater reuse purposes. The process can be of lower cost as compared to the biological treatment, because the nitrification process involves difficult operation conditions due to the use of bacteria, the necessity of aerations, and involvement of large tanks for operation. Supplementary, the physical and chemical processes involve good wastewater pH control (e.g., for aeration process, adding pH correctors like sodium carbonate required on-line pH measurements, and surveillance), generating extra-costs.

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