Adsorption mechanism of recovering potassium from seawater by modified-clinoptilolite using microwave
Hao Guo, Chang-Sheng Peng, Chang-Jiang Kou, Jian-Yun Jiang, Fan Zhang and He-Tao Yuan

ABSTRACT

The adsorption capacity and mechanism of K⁺ ion onto modified-clinoptilolite (MC) for recovering potassium from seawater has been investigated in this paper. The maximum value of K⁺ adsorption capacity is 36.3 mg/g (1.92 times of raw-clinoptilolite) while the modifying condition of microwave power is 450 W and heating time is 60 min. Specific surface area and pore size of absorbent has also been advanced with employing microwave. The kinetic data followed the pseudo-second-order model kinetic model, and the equilibrium data were well fitted to the Langmuir model, showing monolayer coverage of K⁺ ions on the surface pores of MC. Thermodynamic parameters, including Gibbs free energy (∆G), enthalpy changes (∆H), and entropy changes (∆S) were also calculated. The results demonstrated that K⁺ ion was absorbed onto MC spontaneously and exothermically in nature. Thus, MC could be employed as efficient and suitable adsorbent for recovering potassium from seawater.

Key words | adsorption amount, isotherm, kinetics, modified-clinoptilolite, potassium, thermodynamic parameters

INTRODUCTION

Potassium is an important resource for agricultural production. However, the potassium resource on land is very limited, therefore recovering potassium from seawater has great prospects (Yuan et al. 2012). The total reserve of potassium in seawater is about 500 trillion tons (Shahmansouri et al. 2015). This amount is approximately 30 thousand times that of the land reserve, however the K⁺ ion concentration in seawater is only 399 mg/L, and coexists with more than 80 kinds of chemical elements. The technologies of extracting potassium from seawater using zeolite as adsorbent have gained a great deal of public attention. At present, using raw-clinoptilolite (RC) as adsorbent has been put into industrial operation (Jin et al. 2014). However, the K⁺ ion adsorption capacity from seawater is only 14–20 mg/g due to the low purity and disproportionate quality of RC (Yuan et al. 2006). In order to enhance the K⁺ ion adsorption capacity of RC, many modification experiments were carried out. After modifying, the characteristics of porosity and surface activity have been obviously improved.

The molecular structure of clinoptilolite consists of frameworks elements and exchangeable ions. The modification of clinoptilolite principally relates to replacement of non-skeleton and framework elements. The replacement of non-skeleton elements aimed at replacing the exchangeable ions of clinoptilolite, such as sodium, potassium, calcium and magnesium cations. Peng et al. (2001) used thermal sodium chloride solution soaked zeolites, the internal
holes were developed and then the specific surface area was increased. Ćurković et al. (1997) used 2.0 mol/L sodium chloride solution soaked zeolites at 22 and 70 °C respectively, the heavy metals removal efficiency was enhanced distinctly. Wang et al. (2002) used ammonium bicarbonate soaked clinoptilolite, the performance of K⁺, Rb⁺ and Cs⁺ ion adsorption capacity was improved obviously. The replacement of framework elements aimed at replacing the aluminum ion of clinoptilolite with a hydrothermal process, and the adsorption capacity to polar molecules and ions increased with the SiO₂/Al₂O₃ ratio of molecular composition decreasing (Chang et al. 1984). Yang & Xu (1996) used sodium aluminate soaked zeolite β in order to supplement aluminum atoms on zeolite molecules, and characterized the samples with X-ray diffraction and nuclear magnetic resonance. Xie et al. (2002) also used sodium aluminate soaked zeolite β and compared catalytic activity of the samples before and after modifying, since the adsorption capacity of zeolites mainly depends on the degree of aluminum atoms replacing silicon atoms. For this reason, the replacement of framework elements is the fundamental method to modify zeolites and researched extensively (Tang & Chen 2009).

A microwave radiation heating method is capable of generating equivalent thermal effects simultaneously at different depths of absorbent inner holes (Liu et al. 2006). In addition, the profound heating effect was quicker and more even in contrast to the hydrothermal method, which is extensively employed in the absorbent modification, which can improve the molecular structure and advance the adsorption capacity (Liu et al. 2012). The organic matters in the absorbent inner holes were decomposed thoroughly with microwave heating. Consequently, the inner holes were dredged and the outside of the absorbent particles were cleaned (Zhang et al. 2009). With adopting microwave modification instead of a hydrothermal method, the heating time and modification effects were improved greatly (Tang & Chen 2009). The purpose of the present research was to make use of microwave modifying RC to enhance the K⁺ ion adsorption amount. The effect of microwave power and heating time on adsorption amount was investigated. Then the modified-clinoptilolite (MC) was used as adsorbent to recover potassium from seawater.

Recovering potassium from seawater is a physicochemical process that involves mass transfer of a solute from liquid phase to the adsorbent surface (Hao et al. 2015). Adsorption kinetics were performed to assess the uptake rates and contact times needed for completion of adsorption reactions in treatment systems. Pseudo-first-order, pseudo-second-order and Weber–Morris models were generally used to describe the adsorption isotherms (Liu et al. 2016). The Langmuir isotherm assumes that the surface of the solid is homogeneous and one specific site within the adsorbent can only match a molecule without access to others, that is, the form of adsorption is monolayer. However, the Freundlich isotherm describes the process of multilayer adsorption on uneven solid surfaces (Li et al. 2016). In this research, the equilibrium data of using MC to recover potassium have been fitted by different kinetics and isotherm models. The thermodynamic parameters of entire adsorption process were also calculated.

**MATERIALS AND METHODS**

**Instruments and reagents**

The particle size of RC was 0.5–1.0 mm and was purchased from Jinyun County, China. Analytical-grade KCl, NaOH and Al(OH)₃ were purchased from Shanghai Sinopharm Chemical Reagent Co. Ltd, Shanghai. The microwave digestion furnace (JK-MDA-23, Shanghai JKI) was used to treat MC. The atomic adsorption spectroscopy (AAS, TAS-990, Purkinje general instrument) measured the concentration of K⁺ ion in seawater and solution. The constant temperature vibrator (THZ-D, China Taicang Instruments, China) was employed in adsorption kinetics and isotherm experiments. The specific surface area and pore size was measured by a surface area and pore size analyzer (Autosorb-1, Quantachrome Instruments, USA). The pH at the zero point of charge (pHŽPC) was determined by Zeta potential analyzer (Zetasizer Nano ZS90, Malvern Instruments, UK).

**Preparation of modified clinoptilolite**

MC was prepared from 1.0 g KCl and 2.0 g NaOH dissolved in 25 mL deionized water and stirred until well mixed. Then,
1.0 g Al(OH)$_3$ was added to the above mixture and stirred continuously to room temperature (20 °C). After that, 5.0 g RC was added to the mixture which was then continually stirred for 2 hours. The above mixture was heated by the microwave digestion furnace using microwave power of 75, 150, 225, 300, 375, 450, 525, 600, 675 and 750 W, and heating times of 10, 20, 30, 40, 50, 60, 70, 80, 90, 100 min; the MC was separated from the hydrothermal mixture, thoroughly rinsed with deionized water and dried in an evaporating dish. Finally, the MC was calcined for 2 hours at 400 °C in a crucible.

In a beaker, 1.0 g of MC was added to 100 mL seawater (Bohai Bay, China) then it was stirred at room temperature for 30 min. After solid phase and liquid phase were separated, the concentration of K$^+$ ion in the liquid phase was measured by AAS, and then the liquid phase was abandoned and fresh seawater was added into the solid phase for the next adsorption process. This operation was repeated three times after adsorption saturation. The K$^+$ ion adsorption amounts of MC in different modifying conditions were calculated as follows:

$$q_e = \frac{l[(C_0 - C_1) + (C_0 - C_2) + (C_0 - C_3)] \times V}{m}$$  \hspace{1cm} (1)

where $q_e$ is the K$^+$ ion adsorption amount (mg/g) of MC at equilibrium; $C_0$ is the concentration of K$^+$ ion (399 mg/L) in seawater; $C_1$, $C_2$ and $C_3$ represent the residual concentrations (mg/L) of K$^+$ ion after the first, second and third adsorption process respectively; $V$ and $m$ are the volume (L) of seawater and dosages (g) of MC.

**Adsorption kinetics**

One gram of MC was added to 100 mL seawater and blended evenly. The concentration of K$^+$ ion ($C_0$) in the seawater was 399 mg/L. At 20 °C, the mixture was oscillated in a constant temperature vibrator at 120 rpm. The concentration of K$^+$ ion ($C_i$) in supernatant was measured by AAS at different times (20, 40, 60, 80, 100, 200, 400 and 600 min). The adsorption amounts of K$^+$ ion ($q_i$) were calculated based on the K$^+$ ion mass conservation. The adsorption kinetics was respectively fitted by pseudo-first-order, pseudo-second-order and Weber–Morris models.

**Adsorption isotherm and thermodynamic calculating**

One gram of MC was added to 100 mL KCl solution with different initial concentrations of K$^+$ ion (0.01, 0.02, 0.03, 0.04, 0.05, 0.06, 0.07 and 0.08 mol/L). The K$^+$ ion was adsorbed by MC in constant temperature vibrator at 120 rpm lasting 80 min. The concentration of K$^+$ ion in supernatant ($C_e$) was measured by AAS, and the equilibrium concentration of K$^+$ ion onto MC ($q_e$) was calculated based on the K$^+$ ion mass conservation. The adsorption isotherm was measured at different temperatures (283, 293, 313 and 333 K) and fitted by Langmuir and Freundlich isotherm models respectively. Finally, the thermodynamic parameters such as $\Delta G^0$, $\Delta H^0$ and $\Delta S^0$ were calculated.

**RESULTS AND DISCUSSION**

**Effect of pH value to adsorption amount**

The K$^+$ ion adsorption amount with different pH values is shown in Figure 1. The results indicate that the maximum K$^+$ ion adsorption amount onto MC is at pH 6.0–8.0. The K$^+$ ion adsorption amount was severely influenced in acidic conditions when the concentration of KCl solution was 0.001 mol/L. However, the K$^+$ ion adsorption amount was barely influenced by the change of pH value when the concentration of KCl solution was 0.01 and 0.1 mol/L. Consequently, neutral conditions were chosen to carry out the adsorption reactions. In addition, the pH value of seawater was impossibly adjusted in the case where the MC was employed in the engineering due to economy and the complexity of the seawater, because the treatment scale of seawater is enormous and most plants cannot afford the high requirements of acid or alkali.

**Effect of microwave power and heating time**

Figure 2 shows the K$^+$ ion adsorption amount of MC with different microwave power and heating time modifying conditions. It is evident that the maximum value of the K$^+$ ion adsorption amount is 36.3 mg/g, with microwave power of 450 W and heating time of 60 min. It also can be observed
that when the microwave power and heating time was greater or less than 450 W and 60 min, the $K^+$ ion adsorption amount curve declined quickly. This is because when using lower microwave power and less heating time, the soaking solution temperature is also lower. This will affect the aluminum-silicon replacing velocity and exchange extent. However, using higher microwave power and longer heating time, the soaking solution temperature raised quickly and the solution was boiling, the solid-liquid ratio of reaction system was changed and the internal water of MC escaped. The structure of the MC molecule was destroyed and the conversion ratio declined with elapsing time (Querol et al. 1997).

Adsorption capacity of RC and MC

As shown in Figure 3, the potassium adsorption capacity of RC and MC is 18.9 and 36.3 mg/g respectively. With microwave modification, the increment of adsorption capacity reached 92%. Consequently, the adsorption capacity of potassium by MC was significantly improved from the results.

Adsorption kinetics

In order to understand the transfer mechanism of $K^+$ ion from liquid phase to solid phase, three adsorption kinetics models were used to describe the $K^+$ ion transfer process from seawater onto MC. The linear form of pseudo-first-order kinetic model is shown in the following equation (Hao et al. 2015):

$$\ln \left( \frac{q_e - q_t}{C_0} \right) = \ln \left( \frac{q_e}{C_0} \right) - k_1 t$$

(2)

where $q_e$ (mg/g) is the adsorption amount of $K^+$ ion at equilibrium (36.3 mg/g), $q_t$ is the adsorption amount of $K^+$ ion at time $t$ (min), $k_1$ (1/min) is the rate constant of the pseudo-first-order kinetic model.

The linear form of the pseudo-second-order kinetic model is expressed by Equation (3):

$$\frac{t}{q_t} = \frac{t}{q_e} + \frac{1}{k_2}$$

(3)
Moreover, the initial adsorption rate $h$ when $t = 0$ is defined in the following equation (Cardoso et al. 2004):

$$ h = k_2 q_e^2 $$

(4)

where $k_2$ (g/(mg·min)) is the rate constant of pseudo-second-order kinetic model, and the intercept of Equation (3) was applied to calculate the $k_2$ value.

In accordance with the Weber–Morris model, the intra-particle diffusion stage controls the adsorption rate and the stage from liquid to adsorbent surface can be neglected. The model is expressed by the following Equation (5) (Tsai et al. 2005):

$$ q_t = k_p t^{1/2} + C $$

(5)

where $k_p$ (g/(mg·min)) is the rate constant of Weber–Morris, $C$ value is the intercept of this plot. If the intra-particle diffusion stage is the rate-limiting step, the plot of $q_t$ against $t^{1/2}$ should go through the origin, the value of which is equal to zero.

On the basis of equilibrium data of the $K^+$ ion adsorption amount, Figure 4 shows the effect of different times on the adsorption amounts of $K^+$ ion onto MC in (a) seawater, (b) linear fit of pseudo-first-order, (c) pseudo-second-order and (d) Weber–Morris models. As can be seen from Figure 2(a), the overall trend was an increase in adsorption amount with elapsing time. It was observed that the $K^+$ adsorption rate was rapid from the beginning of the experiment and before 80 min, thereafter it proceeded with a slower rate and finally reached saturation.

The linear fit parameters of three kinetics models are listed in Table 1. Judging from the $R^2$ value, we can see that the pseudo-second-order in Figure 4(c) gives the best fitting result for all cases. This suggests that the $K^+$ ion adsorption process should mainly be involving exchange or sharing of electrons between $K^+$ cations and functional groups. In addition, the linear fit of Weber–Morris Figure 4(d) models can be classified into two phases, also showing that intra-particle diffusion is not the only rate-limiting step in the adsorption process.

### Adsorption isotherm

To clarify the adsorption mechanism of $K^+$ ion onto MC, two commonly used types of isotherm models, Langmuir and Freundlich, were applied to explain the $K^+$ ion adsorption process (Kumar 2007). The Langmuir model assumes that the process of monolayer adsorption on a homogeneous solid surface, where one specific site within the adsorbent can only match a molecule without access of others and the model is given by the following linear equation:

$$ \frac{C_e}{q_e} = \frac{1}{b q_m} + \frac{C_e}{q_m} $$

(6)

where $q_e$ (mg/g) is the adsorption amount of $K^+$ ion onto MC surface at equilibrium and $C_e$ (mg/L) is the concentration of KCl solution at equilibrium, $q_m$ (mg/g) and $b$ (L/mg) are the amount of maximum adsorption amount and Langmuir constant, respectively.

Moreover, $R_L$ value reflects the tendency of the adsorption process, when the value of $R_L$ is between 0 and 1, it indicates the adsorption process is favorable, otherwise, it is unfavorable. The $R_L$ value can be inferred as follows:

$$ R_L = \frac{1}{1 + bC_0} $$

(7)

The Freundlich model is an empirical model, describing the process of multilayer adsorption on an uneven solid surface. The Freundlich linear model is expressed by the following equation (Li et al. 2016):

$$ \log q_e = \log K_f + \frac{1}{n} \log C_e $$

(8)
where $q_e$ (mg/g) and $C_e$ (mg/L) represent the adsorption amount of K$^+$ ion onto MC and K$^+$ ion concentration of KCl solution at equilibrium, $K_f$ and $n$ are the constant of the model, expressing the adsorption amount and the intensity of the adsorption process. In addition, $1/n$ reflects the tendency of the adsorption process, when the value of $1/n$ is between 0.1 and 0.5, this indicates that the adsorption process is favorable, if the $1/n$ value is greater than 2, the adsorption process becomes difficult (Li et al. 2016).

On the basis of equilibrium data of K$^+$ ion adsorption amount onto MC, Figure 5 shows the linear fit of (a) the Langmuir model and (b) the Freundlich model at different temperatures (283, 293, 313 and 333 K).

The parameters of two isotherm models are listed in Table 2. Because the $R^2$ values of the Langmuir model are closer to 1 than the Freundlich model, it can be deduced that the Langmuir model fits the equilibrium data better than the Freundlich model. Therefore, the Langmuir model...
The model is in better accordance with the process of K\(^+\) ion adsorption. In addition, the RL values of the Langmuir model are between 0 and 1, and the 1/n values of the Freundlich equation are between 0 and 0.5, indicating that the adsorption process is favorable. The range of qm is between 58.82 and 71.43 mg/g, and the maximum qm occurs at 283 K, it is also shown that the value of qm increases with decreasing temperature. This feature corresponds with physisorption characteristics because the lower temperature could promote the rate of physisorption process.

**Thermodynamic parameters**

The data obtained from the temperature study were used for thermodynamic analysis. Thermodynamic analysis focused on Gibbs free energy (\(\Delta G\)), which can also be expressed using enthalpy changes (\(\Delta H\)) and entropy changes (\(\Delta S\)). These parameters imply the feasibility of the adsorption process and are obtained using Equations (9)–(11) (Gupta et al. 2012):

\[
\ln K_L = \frac{\Delta S}{R} - \frac{\Delta H}{RT}
\]

(9)

\[
K_L = \frac{M_K \cdot \times 55.6b}{C_0}
\]

(10)

\[
\Delta G = \Delta H - T\Delta S
\]

(11)

where \(K_L\) (L/g) represents the Langmuir constant, \(R\) (J/(mol · K)) is the universal gas constant, 8.314 J/(mol·K), \(\Delta S\) (J/(mol·K)) and \(\Delta H\) (kJ/mol) were calculated from the slope and intercept of ln\(K_L\) against 1/T plot as shown in Figure 6, \(\Delta G\) (kJ/mol) values with different temperatures were calculated from Equation (11), \(M_K\) (g/mol) is the atomic mass of potassium.

The calculated thermodynamic parameters are listed in Table 3. Negative \(\Delta G\) and \(\Delta H\) indicates that the adsorption of K\(^+\) ion onto MC was an exothermic reaction. A positive value of \(\Delta S\) suggests that an increased randomness occurs at the solid solution interface in the internal structure. The \(\Delta G\) value obtained was relatively low (<20 kJ/mol),

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**Table 2** Parameters of the Langmuir and Freundlich equations

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>qm (mg/g)</th>
<th>b</th>
<th>R(^2)</th>
<th>RL</th>
<th>Kf</th>
</tr>
</thead>
<tbody>
<tr>
<td>283</td>
<td>71.43</td>
<td>0.0035</td>
<td>0.996</td>
<td>0.08–0.42</td>
<td>7.00</td>
</tr>
<tr>
<td>293</td>
<td>66.67</td>
<td>0.0033</td>
<td>0.996</td>
<td>0.09–0.44</td>
<td>6.30</td>
</tr>
<tr>
<td>313</td>
<td>62.50</td>
<td>0.0031</td>
<td>0.997</td>
<td>0.09–0.45</td>
<td>5.47</td>
</tr>
<tr>
<td>333</td>
<td>58.82</td>
<td>0.0029</td>
<td>0.996</td>
<td>0.10–0.47</td>
<td>4.99</td>
</tr>
</tbody>
</table>

**Figure 5** | Linear fit of (a) the Langmuir model and (b) the Freundlich model.
suggesting that the adsorption process follows a physisorption mechanism (Hameed et al. 2007). Furthermore, the decrease in the values of $\Delta G$ with increasing temperature revealed the adsorption was naturally more spontaneous at lower temperatures (Liu et al. 2012).

**Surface characteristics and pHZPC of RC and MC**

The surface characteristics of adsorbent significantly affected the adsorption capacity. The specific surface area and pore size was measured by a surface area and pore size analyzer. The properties comparison between RC and MC are compared in Table 4. The results indicate that the specific surface area (including external surface area and micro-pore area) was increased after microwave modification. However, the average pore of MC was slightly increased. Consequently, the adsorption capacity of potassium was increased with the specific surface area increasing.

Chemical properties of the adsorbent were also rather important for adsorption. The pH at the zero point of charge (pHZPC) was determined by a Zeta potential analyzer, 0.25 mol/L HCl and 0.25 mol/L NaOH were prepared to adjust the pH value of the KCl solution to 2, 3, 4, 5, 6, 7 and 8. As shown in Figure 7(a) and 7(b), the plots of Zeta potential against pH indicated that the pHZPC of RC and MC was 5.1 and 4.3, respectively.

**CONCLUSIONS**

The present work shows that the K$^+$ ion adsorption capacity of MC reached 36.3 mg/g (1.92 times of RC) when recovering potassium from seawater. The optimum modification conditions of microwave power and heating time for modifying clinoptilolite are 450 W and 60 min respectively. On account of employing microwaves to promote the modifying
process, the specific surface area and pore size of absorbent has also been advanced. The adsorption kinetics follows the pseudo-second-order model, and the equilibrium data were well fitted to the Langmuir model, showing monolayer coverage of K⁺ ion onto the surface pores of MC. Thermodynamic parameters, including Gibbs free energy (ΔG), enthalpy changes (ΔH), and entropy changes (ΔS), were also calculated. The results demonstrated that K⁺ ion was naturally absorbed onto MC spontaneously and exothermically. Thus, the MC is applicable for recovering potassium from seawater as adsorbent.

ACKNOWLEDGEMENTS

This research was supported by Beijing Municipal Science and Technology Project (Z16110000716006), Beijing Association for Science and Technology Golden Bridge Project (No. ZZ15024) and Shandong Province Key Research and Development Program (2016GSF115040).

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