Full Length Article

Kinetics and thermodynamics of aluminum oxide nanopowder as adsorbent for Fe (III) from aqueous solution

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ABSTRACT

Batch adsorption of Fe (III) from aqueous solution by aluminum oxide nanopowder was studied in batch system. The removal efficiency (99.9\%) was obtained at pH 4 and 50 min contact time. The results indicate that the process follows Langmuir isotherm and pseudo-second-order kinetics model. As well as the thermodynamic data indicated that the exothermic nature process. The values of enthalpy ($\Delta H$), mean free energy ($E$) and activation energy ($E_a$) indicate that the adsorption process is physical sorption.

1. Introduction

In the Middle East, ground water is one of the important sources of drinking water. Iron is the most common contaminant in groundwater. The World Health Organization (WHO) has set a guideline value of 0.3 mg/l of iron in drinking water (WHO, 2003). The presence of high concentrations of iron in water causes harmful effects to human and technological problems in many industries. Iron ions precipitate a dark sludge on walls of pipes when contact with air, which lead the corrosion of the pipes (Komewska et al., 2007). The presence of iron ions in ground water above a certain limit makes the water un-usable for aesthetic considerations such as metallic taste, odour, staining of laundry and plumping fixtures (Magda et al., 2013). A number of researches have been developed for the removal of iron from water and wastewater. These processes include: chemical precipitation (Bhattachayya et al., 1980), coagulation/flocculation (Daniels, 1975; Hadj et al., 2014), solvent extraction (McDonald and Bajwa, 1977), electrochemical operation (Knocke et al., 1978), membrane processes (Kim, 1984) and adsorption (Youssef et al., 2008). Carbon and modified activated carbons obtained from agricultural wastes are low cost and available adsorbent materials. These materials give better performance in the adsorption of heavy metals from water and wastewater. Recently, interest has increased...
on nano-particle materials as adsorbent for removal of heavy metals owing to its effectiveness in separation of hazardous metal ion from aqueous solutions, mainly due to their high surface area to volume ratio (Arezoo et al., 2014). The use of aluminum oxide nanoparticles for separation of heavy metals has been investigated due to its low cost, high surface area, surface reactivity, porosity, mechanical strength, and thermal stability (Ahmadpour et al., 2014). The objective of the present work is to evaluate of nano-Al$_2$O$_3$ as adsorbent material for adsorption of Fe (III) ions from aqueous solution in batch process. Adsorption kinetics, isotherms and thermodynamics of Fe (III) ions on nano-Al$_2$O$_3$ were studied.

2. Material and methods

2.1. Adsorbent material

Aluminum oxide nanopowder (Nano-Al$_2$O$_3$) used in this study was obtained from Beijing China Mainland (Model Number: DK420). The characteristics of nano-Al$_2$O$_3$ were listed in Table 1. The XRD analysis and environmental scanning electron microscope (ESEM) of Aluminum oxide nanopowder is also performed before and after adsorption.

2.2. Preparation of iron stock solution

A stock solution containing 1000 mg/l prepared by dissolving certain amount of FeCl$_3$ in distilled water and then diluted to appropriate concentrations. All chemicals used were of AR grade (Sigma–Aldrich, Germany). 0.1 N HCl and 0.1 N NaOH were used for pH value adjustment.

2.3. Adsorption experiments

2.3.1. Batch technique

All batch experiments were carried out to study the ability of adsorb Fe (III) onto Nano-Al$_2$O$_3$ and to determine the optimum parameters of the adsorption process (contact time, pH, initial concentration, adsorbent dose and temperature). 60 ml of 25 mg/l of Fe (III) solutions with a range of pH values from 2 to 10 was transferred to a conical flask contain 25 mg of Nano-Al$_2$O$_3$. The solution was shaken at 200 RPM in a thermostatic shaker water bath for different interval time (0–120 min) at different temperatures (303 K, 313 K, 323 K and 333 K). The samples were withdrawn and centrifuged at 5000 RPM for 5 min and the supernatant solutions were analyzed using an atomic absorption spectrophotometer (Perkin Elmer, A 800).

The uptake of Fe (III) onto Nano-Al$_2$O$_3$ increased with time and attained a maximum value at 50 min. The removal of Fe (III) was studied at different pHs in the range 2–10 at initial Fe (III) concentration of 25 mg/l, 303 K and adsorbent dose 0.1 g. It was found that adsorption capacity was highly dependent on pH. The maximum Fe (III) adsorption was obtained at pH 4 (Fig. 3). The competing of H$^+$ with Fe (III) for the adsorption sites on nano-Al$_2$O$_3$ lead to decreasing the removal percent of Fe (III) at low pH. The increase in Fe (III) removal may be due to decrease in competition between H$^+$ and Fe (III) and consequently more negatively charged sites were made available and this facilitated greater Fe (III) ion uptake. Above pH 4, the removal efficiency decreases as pH increases, this is due to the presence of Fe (III) on the surface of nanopowder indicates that aluminum oxide nanopowder has the adsorption ability for removal of Fe (III) ions from aqueous solutions.

3. Results and discussion

3.1. Characteristics of adsorbent

The XRD analysis of nano-Al$_2$O$_3$ in Fig. 1 indicates that the diffraction peaks of particles perfectly matched with the data of the joint committee on powder diffraction standards, and almost observed no change in the structure of the nano-Al$_2$O$_3$ before and after the uptake of Fe (III) ions. This result deduces that the adsorption process of Fe (III) ions onto nano-Al$_2$O$_3$ may be a physical in nature. Environmental scanning electron microscope (ESEM) of aluminum oxide nanopowder is studied before and after the adsorption process to see the presence of Fe (III) on the surface of Nano-Al$_2$O$_3$ which is shown in Fig. 2.

3.2. Adsorption dynamics

The uptake of Fe (III) onto nano-Al$_2$O$_3$ increased with time and attained a maximum value at 50 min. The removal of Fe (III) was studied at different pHs in the range 2–10 at initial Fe (III) concentration of 25 mg/l, 303 K and adsorbent dose 0.1 g. It was found that adsorption capacity was highly dependent on pH. The maximum Fe (III) adsorption was obtained at pH 4 (Fig. 3). The competing of H$^+$ with Fe (III) for the adsorption sites on nano-Al$_2$O$_3$ lead to decreasing the removal percent of Fe (III) at low pH. The increase in Fe (III) removal may be due to decrease in competition between H$^+$ and Fe (III) and consequently more negatively charged sites were made available and this facilitated greater Fe (III) ion uptake. Above pH 4, the removal efficiency decreases as pH increases, this is due to the presence of Fe (III) on the surface of nanopowder indicates that aluminum oxide nanopowder has the adsorption ability for removal of Fe (III) ions from aqueous solutions.

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**Table 1 – Characteristics of aluminum oxide nanopowder.**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purity</td>
<td>99.9%</td>
</tr>
<tr>
<td>Particle size</td>
<td>20 nm</td>
</tr>
<tr>
<td>Appearance</td>
<td>White powder</td>
</tr>
<tr>
<td>Nanoparticles (Al$_2$O$_3$) morphology:</td>
<td>Spherical</td>
</tr>
<tr>
<td>Density</td>
<td>3.97 g/cm$^3$</td>
</tr>
<tr>
<td>BET surface area</td>
<td>&gt;138 m$^2$/g</td>
</tr>
</tbody>
</table>

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**Fig. 1 – XRD analysis of raw and loaded nano-Al$_2$O$_3$.**
hydrolysis effect (Pavani and Sunil, 2013). On changing the initial Fe (III) concentration from 25 to 100 mg/l at 50 min, dose 0.1 g, 303 K and pH 4, the adsorption capacity increased from 14.32 to 57.30 mg/g. In order to obtain the optimal dose of nano-Al2O3 for the adsorption of Fe (III) ions, the adsorption experiments were carried out by adding doses 0.1, 0.2, 0.3, 0.4 and 0.5 g of nano-Al2O3 to a series of 60 ml 25 mg/l Fe (III) solutions at pH 4.0. When the amount of nano-Al2O3 reached to 0.2 g, the removal percentage of Fe (III) on nano-Al2O3 was close to 99.99%. Therefore, 0.2 g of nano-Al2O3 was the optimum dose for the uptake of Fe (III). The effect of temperature was studied at pH 4, dose 0.2 g, contact time 50 min and initial concentration of 25 mg/l. Increase in temperature from 303 K to 333 K was found to decrease the removal efficiency of Fe (III) ions. This is probably due to the effect of temperature on the interaction between the shell surface and the metal ions in solution (Urbain et al., 2013).

3.3. Adsorption isotherms

Adsorption isotherm studies are important to determine the efficacy of adsorption and in the design of adsorption process. Freundlich, Langmuir and Dubinin–Radushkevich (D–R) isotherms were used to determine the adsorption equilibrium between the adsorbent and metal ions in the solution at equilibrium.

3.3.1. Langmuir isotherm

The maximum adsorption capacity corresponding to complete monolayer coverage on the adsorbent surface is expressed by Langmuir equation as follow (El-Dien et al., 2013):

\[ q_e = \frac{q_{max} K_L C_e}{1 + K_L C_e} \]  

(3)

The linear form of the above equation after rearrangement is given by:

\[ \frac{C_e}{q_e} = \frac{1}{q_{max} K_L} + \frac{C_e}{q_{max}} \]  

(4)

The constants \( q_{max} \) and \( K_L \) can be determined from the slope and intercept of plotting \( C_e/q_e \) against \( C_e \), respectively. The essential features of a Langmuir isotherm can be expressed in terms of a dimensionless constant separation factor or equilibrium parameter, \( R_L \), which is defined by equation (Vadivelan and Vasanth, 2005):

\[ R_L = \frac{1}{1 + K_L C_0} \]  

(5)

The value of \( R_L \) indicates the shape of the isotherms to be either unfavorable (\( R_L > 1 \)), linear (\( R_L = 1 \)), favorable (\( 0 < R_L < 1 \)) or irreversible (\( R_L = 0 \)).

3.3.2. Freundlich isotherm

Freundlich model (Nethaji et al., 2013), is used to estimate the adsorption intensity of the adsorbent towards the adsorbate and is given by:

\[ q_e = K_F C_e^{1/n} \]  

(6)

The above equation is conveniently used in linear form as:

\[ \ln q_e = \ln K_F + \frac{1}{n} \ln C_e \]  

(7)

The constants \( K_F \) and \( n \) can be determined from the slope and intercept of plotting \( \ln C_e \) against \( \ln q_e \), respectively, indicates the conformation of the Freundlich adsorption isotherm.

3.3.3. The Dubinin–Radushkevich (D–R) isotherm

The Dubinin–Radushkevich isotherm model was used to predict the nature of adsorption processes as physical or chemical by calculating sorption energy (Vadivelan and Vasanth, 2005). The linear form of this model is described as:

\[ \ln q_e = \ln Q_0 - K_D (RT \ln(1 + 1/C_0))^2 \]  

(8)

The slope of the plot of \( \ln q_e \) versus \( [RT \ln(1 + 1/C_0)]^2 \) gives \( K_D \) (mol²/kJ²) and the intercept yields the adsorption capacity \( Q_0 \) (mg/g).
The results of plots of three isotherms at different temperature in Table 2, indicate that the Langmuir isotherm appears to be the best fitting model for adsorption of Fe (III) onto aluminum oxide nanopowder than other isotherms (Freundlich and Dubinin–Radushkevich isotherm) because it gives the highest correlation coefficient value than other isotherm, indicating that monolayer surface adsorption may exist (Figs. 4 and 5) and the calculated values of the dimensionless factor (Rl) are 0 < Rl < 1 indicate the favorable adsorption of Fe (III) onto aluminum oxide nanopowder under consideration. This means that the equilibrium isotherms can be well described by the Langmuir model, and the adsorption process is monolayer adsorption onto a surface with a finite number of identical sites, which are homogeneously distributed over the adsorbent surface. The constant K0DR gives an idea about the mean adsorption energy (E) (kJ/mol) of adsorption per mole of the adsorbate using the following relationship:

\[ E = \frac{1}{\sqrt{2K_{DR}}} \]  \hfill (9)

If the value of E = 8–16 kJ/mol then the adsorption process flows by chemical ion-exchange, and if E < 8 kJ/mol the adsorption process is physical in nature, whereas if the value is more than 16 kJ/mol, the adsorption process is chemisorption in nature (Youssef et al., 2008). The values of the rate constant (K0DR) of Dubinin and Radushkevich isotherm present in Table 2 showed that E value was lower than 8 kJ/mol, indicating that the adsorption of Fe (III) onto nano Al2O3 is physisorption in nature.

### 3.4 Adsorption kinetic studies

Kinetics of Fe (III) adsorption nano-Al2O3 was analyzed using Pseudo-first order, pseudo-second order, and intraparticle diffusion kinetics models.

#### 3.4.1 Pseudo-first-order model

The pseudo first order kinetic model (Lagergren, 1898; Mohamed, 2013), was given by equation:

\[ \log(q_e - q_t) = \log q_e - \frac{k_1}{2.303} t \]  \hfill (10)

The linearized form of the pseudo-first-order model for the sorption of Fe (III) ions onto nano Al2O3 at different temperature is given in Fig. 6. The calculated results of the first-order rate equation are given in Table 3. It is found that correlation coefficient values are low, showing the bad quality of linearization. Additionally, the qe value acquired by this method contrasts with the experimental value. So the reaction cannot be classified as first-order.

#### 3.4.2 Pseudo-second-order model

The sorption data were also analyzed in terms of pseudo-second order model (Ho and Mckay, 1999), given by the equation:

\[ \frac{t}{q_t} = \frac{1}{h} + \frac{1}{q_e} t \]  \hfill (11)

If the initial adsorption rate, h (mg/g min) is:

\[ h = K_3 q_e^2 \]  \hfill (12)

The linearized form of the pseudo-second order model is given in Fig. 6. The values of the correlation coefficients were all extremely high showing the best quality of linearization. Besides, the calculated qe values agreed very well with the experimental data (Table 3). This result indicates that the adsorption process shows a better compliance with the pseudo second order model.

#### 3.4.3 The intraparticle diffusion model

In order to determine the adsorption mechanism involved in the uptake Fe (III) onto nano-Al2O3, the experimental data were studied by the intraparticle diffusion model. The intraparticle diffusion shows that the adsorption process occurs in three steps as follows (Nethaji et al., 2013):

- Mass transfer across the external boundary layer film of liquid surrounding the outside of the particle.
- Adsorption at a site on the surface (internal or external) and the energy will depend on the binding process (physical or chemical), this step is often assumed to be extremely rapid.
- Diffusion of the adsorbate molecules to an adsorption site either by a pore diffusion process through the liquid filled pores or by a solid surface diffusion mechanism.

The intraparticle diffusion model is expressed as:

\[ q_e = K_d t^{0.5} + C \]  \hfill (13)

Fig. 7 shows that the plot of qe versus t^{0.5} at different temperature, was multi-linear, indicate that more than one rate-limiting step affected the uptake Fe (III) onto nano-Al2O3. Based on these plots, the adsorption processes of the three steps are comprised by two phases, suggesting that the intraparticle diffusion is not the rate-limiting step for the

### Table 2 – Parameters of Langmuir, Freundlich and Dubinin–Radushkevich isotherms at different temperatures (pH 4, 50 min, 0.1 g, 25 mg/l Fe (III) solution).

<table>
<thead>
<tr>
<th>Isotherms</th>
<th>Temperature (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>301</td>
</tr>
<tr>
<td><strong>Langmuir isotherm</strong></td>
<td></td>
</tr>
<tr>
<td>qmax (mg/g)</td>
<td>14.28</td>
</tr>
<tr>
<td>KL (L/mg)</td>
<td>0.098</td>
</tr>
<tr>
<td>RL</td>
<td>0.289</td>
</tr>
<tr>
<td>r²</td>
<td>0.997</td>
</tr>
<tr>
<td><strong>Freundlich isotherm</strong></td>
<td></td>
</tr>
<tr>
<td>KF (mg/g)</td>
<td>3.281</td>
</tr>
<tr>
<td>n</td>
<td>5.290</td>
</tr>
<tr>
<td>r²</td>
<td>0.947</td>
</tr>
<tr>
<td><strong>D–R model isotherm</strong></td>
<td></td>
</tr>
<tr>
<td>Q0 (mg/g)</td>
<td>3.658</td>
</tr>
<tr>
<td>K10 (10⁻⁶ mol⁻² kJ⁻¹)</td>
<td>0.100</td>
</tr>
<tr>
<td>E (kJ/mol)</td>
<td>2.230</td>
</tr>
<tr>
<td>r²</td>
<td>0.553</td>
</tr>
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</table>
The initial part of the plot indicated an external mass transfer, whereas the second linear part is due to intraparticle diffusion. Due to the double nature of intraparticle diffusion (both film and intraparticle diffusion), Boyd’s model was used to determine whether the main rate-limiting step for the resistance to mass transfer is in the thin film surrounding the adsorbent particle, or in the resistance to diffusion inside the pores. This model is expressed as (Nethaji et al., 2013):

\[
F = \frac{1}{6} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp \left( -\frac{D_n \pi^2 m^2 t}{r^2} \right)
\]  

Or

\[
F = 1 - \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp( -m^2 B t )
\]  

where \( F \) and \( B \) are obtained by the following expressions:

\[
F = \frac{q_t}{q_e}
\]

\[
B = \frac{D m^2}{r^2}
\]

The expression \( Bt \) is given by the equation:

\[
Bt = -0.4977 - \ln(1 - F)
\]

The values of \( Bt \) can be determined from values of \( F \). The linear Boyd plot of \( Bt \) versus \( t \) (Fig. 7) was used to differentiate between the controlled mechanism of adsorption process (film diffusion or particle diffusion). If the particle-diffusion mechanisms is the rate-limiting step of adsorption processes, straight line passing through the origin of Boyd plot of \( Bt \) versus \( t \). Or else they are governed by film diffusion (Nethaji et al., 2013). From Fig. 7, it was observed that the plots were linear and does not pass through the origin at various temperatures, indicating the external mass transfer (film diffusion) controlled mechanism.

3.5. **Thermodynamic studies**

Thermodynamic parameters, such as an enthalpy variation (\( \Delta H^\circ \)), entropy variation (\( \Delta S^\circ \)) and change in Gibbs free energy (\( \Delta G^\circ \)), were calculated from the curve relating the distribution coefficient (\( K_D \)) as a function of temperature using the following equations (Mahmoud and El-Halwany, 2013):

\[
\ln K_D = \frac{\Delta S^\circ}{R} - \frac{\Delta H^\circ}{RT}
\]

\[
K_D = \frac{q}{C_e}
\]

\[
\Delta G^\circ = -RT \ln K_D
\]
The values of $\Delta H^\circ / C_{14}$, $\Delta S^\circ / C_{14}$ were determined from the slope and intercept values of the straight line of plotting $\ln K_D$ versus $1/T$, respectively (Fig. 8). From Table 4, the negative value of $\Delta H^\circ$ shows that the adsorption process is exothermic in nature. This is in accordance with decreasing adsorption equilibrium with increasing temperature. The value of $\Delta H^\circ$ may give an indication about the type of Fe (III) adsorption onto nano Al$_2$O$_3$ as follows (Mahmoud and El-Halwany, 2014):

\[
\Delta H^\circ = 2.1 - 20.9 \text{ kJ/mol \ (Physical adsorption)} \\
\Delta H^\circ = 80 - 200 \text{ kJ/mol \ (Chemical adsorption)}
\]

The value of $\Delta H^\circ$ is 12.34 kJ/mol which indicates that the uptake of Fe (III) onto nano Al$_2$O$_3$ could be attributed to a physical adsorption process. The negative values of $\Delta G^\circ$ confirm the feasibility and the spontaneous nature of the

![Fig. 6 – Pseudo-first order and pseudo-second order kinetics models of Fe (III) onto nano Al$_2$O$_3$ at different temperature.](image)

![Fig. 7 – Intraparticle diffusion and Boyd’s model kinetics models of Fe (III) onto nano Al$_2$O$_3$ at different temperature.](image)

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>Pseudo-first-order model</th>
<th>Pseudo-second-order model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$K_1$ (1/min)</td>
<td>$q_e$ (mg/g)</td>
</tr>
<tr>
<td>303</td>
<td>0.0156</td>
<td>43.47</td>
</tr>
<tr>
<td>313</td>
<td>0.0147</td>
<td>40.45</td>
</tr>
<tr>
<td>323</td>
<td>0.0143</td>
<td>34.61</td>
</tr>
<tr>
<td>333</td>
<td>0.0134</td>
<td>30.00</td>
</tr>
</tbody>
</table>
Adsorption process. The positive value of $\Delta S^\circ$ reflects an increase in the randomness at the interface between solid and solution interface during the uptake of Fe (III) onto nano-Al$_2$O$_3$ (Mahmoud and El-Halwany, 2013).

3.6. Determination of activation energy

Arrhenius equation is used to calculate the activation energy for the metal ion adsorption by using pseudo-second order rate constant (El-Halwany, 2013), as given below:

$$\ln K_2 = \ln A + \frac{E_a}{RT}$$

Activation Energy was determined from the slope of the straight line of plotting $\ln K_2$ versus $1/T$ (Fig. 8). The value of the activation energy may give another indication about the type of adsorption of Fe (III) adsorption onto nano Al$_2$O$_3$. In the physical adsorption the equilibrium is usually rapidly attained and easily reversible, because the energy requirement is small ($E_a = 0-40$ kJ/mol) and since the forces involved are weak. Chemical adsorption is specific and involves forces much stronger (chemical bonds) than physical adsorption. So the activation energy for chemical adsorption is of the same magnitude as the heat of chemical reactions which means that the rate varies with temperature according to finite activation energy ($E_a = 40-800$ kJ/mol) in the Arrhenius equation (Mahmoud and El-Halwany, 2014). The value of activation energy for Fe (III) onto nano Al$_2$O$_3$ was found as 25.29 kJ/mol. This value indicates that the adsorption of Fe (III) adsorption onto nano Al$_2$O$_3$ is Physical adsorption.

4. Conclusion

The present investigation showed that nano Al$_2$O$_3$ can be used as an effective adsorbent for Fe (III) adsorption from aqueous solution. The experimental data indicate that the process follows Langmuir isotherm and pseudo-second-order kinetics model and the thermodynamic data indicate that the processes is exothermic. The values of enthalpy ($\Delta H^\circ$), mean free energy ($E$) and activation energy ($E_a$) indicate that the adsorption process is physical sorption.

Nomenclature

- $A_0$: frequency factor of Arrhenius equation (g/mg. min)
- $B$: time constant of Boyd’s model (min$^{-1}$)
- $C_0$: initial concentration (mg/l)
- $C_e$: equilibrium concentration of Fe (III) in solution (mg/l)
- $C$: adsorption constant of intraparticle diffusion
- $D_l$: effective diffusion coefficient of Fe (III) in the adsorbent phase (cm$^2$/min)
- $E_a$: activation energy of adsorption (kJ/mol)
- $E$: mean free energy of adsorption (kJ/mol)
- $F$: fractional attainment of equilibrium at time t of Boyd’s model
- $K_L$: Langmuir constant (l/mg)
- $K_F$: Freundlich constant (mg/g)
- $k_1$: pseudo first-order adsorption rate constant (l/min)
- $k_2$: pseudo second-order adsorption rate constant (g/mg min)


\[ K_D \] distribution coefficient (cm³/g)  
\[ K_{DR} \] Dubinin–Radushkevich constant (mol²/kJ²)  
\[ K_{id} \] intraparticle diffusion constant (mg/g/min¹/²)  
\[ M \] weight of adsorbent (g)  
\[ m \] an integer that defines the infinite series solution  
\[ n \] Freundlich constant gives an indication about the favorability of the adsorption process  
\[ q \] adsorption capacity (mg of Fe (III)/g adsorbate)  
\[ q_e \] adsorption capacity at equilibrium (mg of Fe (III)/g adsorbate)  
\[ q_{max} \] Langmuir constant related to the maximum adsorption capacity (mg/g)  
\[ q_t \] adsorption capacity at time t (mg of Fe (III)/g adsorbate)  
\[ Q_0 \] the maximum adsorption capacity of Dubinin–Radushkevich isotherm (mol/g)  
\[ R \] gas constant (8.314 J/mol K)  
\[ R_e \] removal efficiency  
\[ R_L \] the essential features of a Langmuir isotherm  
\[ r^2 \] correlation coefficient  
\[ R \] radius of the sorbent particle (cm)  
\[ T \] temperature (K)  
\[ T \] contact time (min)  
\[ V \] volume of the solution (l)

**REFERENCES**


Lagergren S. About the theory of so-called adsorption of solution substances. Handlinge 1898;24:147–56.


