Perchlorate removal using granular activated carbon supported iron compounds: Synthesis, characterization and reactivity

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Abstract

Synthesis and use of the iron compounds supported on granular activated carbon (ICs/GAC) have shown significant environmental implications for perchlorate (ClO₄⁻) removal. ICs/GAC was synthesized via hydrolyzing FeSO₄·7H₂O on GAC, reduced by NaBH₄ solution in polyethylene glycol 6000 and ethanol solution, dried in vacuum condition and exposed to air. Synthesized ICs/GAC was characterized using transmission electron micrograph (TEM), Brunauer-Emmett-Teller, X-ray photoelectron spectroscopy (XPS). ICs/GAC was determined to be containing a large amount of FeOHSO₄, Fe₂O₃ and a small amount of zero-valent iron (ZVI) nanoparticles according to TEM and XPS measurements. Batch static kinetic tests showed that 97% of ClO₄⁻ was removed within 10 hr at 90°C and 86% of ClO₄⁻ was removed within 12 hr at 25°C, at ICs/GAC dosage of 20 g/L. The experimental results also showed that FeOHSO₄ and Fe₂O₃ nanoparticles have the function of perchlorate adsorption and play important roles in ClO₄⁻ removal. The activation energy (Eₐ) was determined to be 9.56 kJ/mol.

Key words: perchlorate removal; ICs/GAC; activation energy; synthesis

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Introduction

Over many years, perchlorate (ClO₄⁻) has been widely used in the areas such as rocket propellants (Urbansky, 1998), fireworks manufacturing, arm industry, automobile airbags, the safety flash board in highway, thereby it has been widely and increasingly found in groundwater, surface water, and soil (Bao and Gu, 2004; Dasgupta et al., 2004). Because ClO₄⁻ can disrupt the production of thyroid hormone by interfering with iodine uptake, the adverse health effects of ClO₄⁻ are reportedly more profound for newborns, children, and pregnant women (Wolff, 1998; Blount et al., 2006). Great attentions are required for ClO₄⁻ removal from groundwater and surface water. Various treatment technologies of ClO₄⁻ removal from water have been developed in recent years, including biological reduction (Logan and Lapoint, 2002; McCarty and Meyer, 2005; Wu et al., 2008), ion exchange (IX) (Xiong et al., 2006), tailored activated carbon adsorption (Chen et al., 2005), filtration (Yoon et al., 2003), chemical reduction (Moore et al., 2003; Xiong et al., 2007).

For chemical reduction technology, nanoscale zerovalent iron (nZVI) was employed as reductant for perchlorate removal. nZVI has great potential environmental applications due to its extremely small particle size, large surface area, and high in situ reactivity. However, the nanoparticles without a stabilizer are actually agglomerated in the micron scale, various methods have been developed to modify their surface properties and enhance their reactivity. Gao et al. (2007) have prepared nZVI by modified liquid phase reduction method. He and Zhao (2005) and He et al. (2007) have prepared nZVI by applying a food-grade water-soluble starch or sodium carboxymethyl cellulose (CMC) as a stabilizer to maximize the reactivity of nZVI. Xiong et al. (2007) have studied that the starch and CMC-stabilized nZVI degraded perchlorate faster than no-stabilized nZVI. Wang et al. (2006, 2009) have reported that nZVI modified in aqueous ethanol solution can enhance the removal rate of bromate and nitrate. For the adsorption technology, Xiong et al. (2007) have reported that the surface of ZVI nanoparticles was oxidized to iron oxides (Fe₂O₃) which could rapidly adsorb perchlorate from water. In a word, nZVI and Fe₂O₃ from iron salt can remove perchlorate from water. However, nZVI, HFO and Fe₂O₃ nanoparticles are unable in fixed beds or any flow through systems because of excessive pressure drops and poor mechanical strength of the nanoparticles. To overcome the foregoing problems, Choi et al. (2008) have developed an effective strategy.
to employ a series of innovative granular activated carbon (GAC) composites incorporated with iron/palladium (Fe/Pd) bimetallic nanoparticles. Zhu et al. (2009) have reported that nZVI was supported on GAC for arsenic removal. For HFO particles, Jang et al. (2006, 2008) and Zhang et al. (2008) reported HFO particles incorporated into diatomite, GAC and anion exchange resin D-201 to enhance their mechanical strength. The objectives of this work were: (1) to introduce the synthesis method of iron compounds supported on GAC (ICs/GAC), (2) to analyze the synthetic route and characterize ICs/GAC; (3) to determine the rate of perchlorate removal and the activation energy (Ea) of ICs/GAC.

1 Materials and methods

1.1 Synthesis of materials

The synthesis of ICs/GAC included four steps. Firstly, mesoporous GAC was sieved with a 20 mesh sieve, and then 20 g of mesoporous GAC was put into 100 mL deionized (DI) water. The GAC solution was heated and boiled on the stove for 5 min, then washed with DI water and dried overnight at 120°C. Secondly, 15 g of FeSO₄·7H₂O was mixed with 15 g of GAC by adding 50 mL DI water, then the mixture was heated and agitated to be hydrolyzed for 15–20 min. Ten gram of polyethylene glycol 6000 as dispersing agent was added to the mixture of FeSO₄·7H₂O and GAC, which were immersed in 100 mL of ethanol/DI water (70/30, V/V). Then solution pH was adjusted above 6.5 using 1 mol/L NaOH. Thirdly, to reduce Fe(III) to zerovalent iron, 2 g of NaBH₄ was prepared in 100 mL DI water. Then NaBH₄ solution was added slowly to the pH adjusted solution and the mixture was stirred until no significant H₂ production was observed (approximately 2 hr). After the solid materials were recovered by filtering and washed with copious amount of ethanol, they were loaded in a 500 mL flask attached to a 25 mL sample loop. A degassed 20 mmol/L sodium hydroxide solution was used as eluent. The detection limit was 4 μg/L. Sulfate and chloride were analyzed using an AS11 column, an AG11 guard column, and a 250 mL sample loop. A degassed 20 mmol/L sodium hydroxide solution was used as the eluent. The eluent flow rate was set at 1.0 mL/min. The Fe ion concentration was determined by graphite furnace atomic absorption spectroscopy (AA400, PerkinElmer, USA).

1.2 Characterization

Transmission electron micrograph (TEM) images were obtained using electron microscopes (H-800, Hitachi, Japan). The sample preparation of the TEM foils was as follows: ICs/GAC materials were milled and were added to ethanol solution, which was dispersed by ultrasonic, at last, the mixture solution was used to prepare the sample foils. The specific surface areas of ICs/GAC were measured by Brunauer-Emmett-Teller (BET) N₂ method and the pore sizes were calculated by BJH (Barrett, Joyner, and Halenda) N₂ adsorption/desorption isotherm method. X-ray photoelectron spectroscopy (XPS) analysis was performed with a RBD upgraded. PHI-5000C ESCA system (PerkinElmer, USA) with Mg Kα radiation (hν = 1253.6 eV). XPS spectrum was obtained at several angles, primarily at 90° and 35° with respect to the sample surface plane. Binding energies were calibrated by using the containment carbon (C₁s = 284.6 eV).

1.3 Batch reactions

Batch kinetic tests were carried out using 250 mL glass vials. Four gram of each ICs/GAC materials and 200 mL of water solution containing 4 mg/L perchlorate were distributed to each of a series of 250 mL glass vials. Then the glass vials were placed in thermostat water bath cauldrons which were set at the desired temperature in the range of 25–100°C. Control experiments were carried out without ICs/GAC at 90°C, but under otherwise identical conditions. For each time interval, 5 mL of aqueous sample was taken. At earlier time of the experiment, the interval time of taking samples was shorter than the later time. Because iron ions of the aqueous sample would pollute the ion chromatography, iron ions of the aqueous sample were precipitated by adding alkali solution and were filtered through a 0.45 μm membrane filter to remove iron ions of the aqueous sample. For determining Fe amount on GAC and the stability of ICs/GAC materials, 0.2 g of ICs/GAC materials were added to 100 mL of HCl solution (2 mol/L) and 100 mL of DI water, respectively. Then the two mixture solutions were placed in a rotary shaker at 200 r/min for 4 hr.

1.4 Chemical analysis

Perchlorate was analyzed using a Dionex ion chromatograph (DX-120) equipped with a suppressed conductivity detector, using an AS20 column, an AG20 guard column, and a 250 mL sample loop. A degassed 35 mmol/L sodium hydroxide solution was used as eluent. The detection limit for perchlorate was 4 μg/L. Sulfate and chloride were analyzed using an AS11 column, an AG11 guard column, and a 25 mL sample loop. A degassed 20 mmol/L sodium hydroxide solution was used as the eluent. The eluent flow rate was set at 1.0 mL/min. The Fe ion concentration was determined by graphite furnace atomic absorption spectroscopy (AA400, PerkinElmer, USA).

2 Results and discussion

2.1 Analysis of synthetic route

ICs were supported on mesoporous GAC via a hydrolyzed and reduced method. DI water of 50 mL was added to the mixture of GAC and FeSO₄, which can make FeSO₄ solution immerse into all the pores of GAC, the pH value of the solution was 3–4. Alkaline ferrous (FeOHSO₄) was deposited on GAC by heating the mixture of FeSO₄ and GAC in DI water at pH 1–2 on the stove (Reaction (1)). Some FeOHSO₄ on GAC was reduced by NaBH₄ solution, and then ZVI was produced as Reaction (2).

FeSO₄ + H₂O → FeOHSO₄ + H⁺  
4Fe³⁺ + 3BH₄⁻ + 9H₂O → 4Fe⁰ + 3H₂BO₃⁺ + 12H⁺ + 6H₂  
(1)  
(2)

According to Reaction (1), pH adjustment of FeOHSO₄/GAC to above 6.5 was needed since the
acidic environment was adverse for the reduction of FeOHSO$_4$.

Gao et al. (2007) have prepared nZVI with a modified method of reduction in liquid phase, in which polyvinlypyrrolidone (PVP k-30) and ethanol were added to change the physical property of nZVI surface. Wang et al. (2009) have reported that nZVI modified by 90% aqueous ethanol had a maximum surface area of 67.51 m$^2$/g and nZVI modified in 70% aqueous ethanol solution had a high efficiency of bromate reduction. Therefore, the materials in this research were prepared in 70% aqueous ethanol solution and polyethylene glycol 6000 solution. Polyethylene glycol 6000 (a kind of macromolecule of dispersant) in this experiment is similar to polyvinylpyrrolidone (PVP k-30), which plays a very important role in the dispersibility of nano iron particles by changing the distribution of the surface and generates the effect of electrostatic stabilizing, space steric electrostatic and space steric stabilizing. Furthermore, the ethanol and water solution has many free and strong polar hydroxyl groups which chelate to FeOH$\cdot$SO$_4$ and nZVI particles, and then cover them tightly to limit ZVI and FeOH$\cdot$SO$_4$ sizes for enhancing their reactivity.

A lot of researches have been carried out on drying nano materials. Qi et al. (2005) have prepared nano composites in vacuum environment. Vacuum and storage time have a significant impact on the nanowire formation and morphology. Wu et al. (2006) have prepared the necklace-like hollow carbon nanospheres and dried the materials under vacuum for 3 hr. Vacuum environment is favorable for the formation of nano material. Furthermore, nZVI is a kind of material with heat sensitive and volatile trait. The materials in this research were dried in vacuum environment and then ZVI nanoparticles were bond on the GAC tightly. Due to the materials exposure to air, some nZVI was oxidized to Fe$_2$O$_3$.

2.2 Characterization of ICs/GAC

2.2.1 TEM characterization

Figure 1a shows that there are some nanoparticles on GAC at scale bar 100 nm. The sizes of the nanoparticles are in the range of 10–100 nm. Figure 1b, c shows the morphology of Fe$_2$O$_3$ and its diffraction pattern. Diffraction analysis reveals that Fe$_2$O$_3$ has tetragonal structure. This result is in agreement with the structure of Fe$_2$O$_3$. Figure 1d, e also shows the morphology of FeOH$\cdot$SO$_4$ and its diffraction pattern. Diffraction analysis reveals that FeOH$\cdot$SO$_4$ has orthorhombic structure. This result is also in agreement with the structure of FeOH$\cdot$SO$_4$. Diffraction analysis illustrates nZVI was completely oxidized to Fe$_2$O$_3$ in air or a little on GAC, namely less than resolution.

![Fig. 1 TEM image of ICs/GAC (a), Fe$_2$O$_3$ (b), diffraction pattern of Fe$_2$O$_3$ (c), TEM image of FeOH$\cdot$SO$_4$ (d) and diffraction pattern of FeOH$\cdot$SO$_4$ (e).]
capability. FeOHSO$_4$ and Fe$_2$O$_3$ nanoparticles tend to agglomerate rapidly in a few minutes because the surface of the nanoparticles is lack of neighboring ligand atoms and has a high nano-energy to agglomerate (Phenrat et al., 2007; Gao et al., 2007). However, because the surface of GAC is very rough and has a lot of pores, GAC can prevent the nanoparticles from agglomerating by the nano-energy between the nanoparticles.

### 2.2.2 BET characterization

Figure 2 shows the nitrogen adsorption-desorption isotherms of GAC and ICs/GAC materials. According to the International Union of Pure and Applied Chemistry (IUPAC) classification, GAC and ICs/GAC materials exhibited a typical type II isotherm, which suggested that the materials were microporous materials (Mulik et al., 2008). The data about the BET characteristics of GAC and ICs/GAC materials are shown in Table 1. The BET surface area (591 m$^2$/g) and the BJH adsorption pore volume (0.147 cm$^3$/g) of ICs/GAC were about 0.638 and 0.83 times lower than those of the plain GAC (BET 925 m$^2$/g, BJH 0.177 cm$^3$/g), respectively. The results have shown that ICs supported on the small pores of GAC decreased the surface area and the pore volumes of GAC, that is to say, the pore volumes of GAC decreased were caused by FeOHSO$_4$, Fe$_2$O$_3$ and nZVI nanoparticles filling only. Furthermore, the pore sizes of ICs/GAC materials (BJH, 2.554 nm) are 1.08 times larger than those of plain GAC (BJH, 2.36 nm), because FeOHSO$_4$, Fe$_2$O$_3$ and nZVI nanoparticles have deposited on GAC surface and filled or covered most of the cavities and hydrolyzing FeSO$_4$·7H$_2$O on GAC have trimmed the uneven pores to enhance the pore sizes of GAC.

![Figure 2](image-url)

**Figure 2** $N_2$ adsorption-desorption isotherms of ICs/GAC and GAC materials.

### 2.2.3 XPS characterization

The overall XPS spectrum of ICs/GAC is illustrated in Fig. 3a. The main elements on ICs/GAC surface are iron, oxygen, sulfur and carbon. An enlargement of Fe 2p binding energy region (Fig. 3a) is shown in Fig. 3b. Since the position of Fe 2p3 peak in this study at 712.2 eV is higher than 710.8 eV reported by Fiedor and Bostick (1998), Fe$^{3+}$ is the predominant surface species. Some Fe$^{3+}$ comes from the residue of FeOHSO$_4$; some Fe$^{3+}$ comes from Fe$_2$O$_3$, which is oxidized by nZVI. The position of another Fe 2p3/2 peak at 707.8 eV conforms to nZVI peak reported by Sun et al. (2007), which certifies that nZVI is the predominant surface species. In a word, the overall XPS spectrum of ICs/GAC materials has shown that there are a large amount of Fe$^{3+}$ (FeOHSO$_4$ and Fe$_2$O$_3$) and a small amount of nZVI on GAC. Consequently, ICs/GAC materials contain FeOHSO$_4$, Fe$_2$O$_3$ and ZVI nanoparticles based on TEM and XPS measurements.

### 2.3 Kinetics and activation energy of perchlorate removal

Figure 4 shows the perchlorate removal kinetics using 20 g/L of ICs/GAC at temperature ranging from 25 to 90°C in thermostat water bath cauldrons. The initial concentration of perchlorate was 4 mg/L. The rate of the perchlorate removal increased with temperature. 86% of perchlorate was removed in 12 hr at 25°C and 97% of perchlorate was removed in 10 hr at 90°C.

Figure 5 shows that linearized plots (ln($C/C_0$) vs. time) of the experimental and model-simulated kinetic data. Table 2 gives the fitted model parameters. The kinetics of perchlorate removal conformed to the pseudo first-order model Eq. (3). Fairly good model fitting ($R^2 > 0.97$) was obtained.

$$
\frac{dC_{\text{ClO}_4^-}}{dt} = -K_{\text{obs}}C_{\text{ClO}_4^-}
$$

(3)

where, $C_{\text{ClO}_4^-}$ (mg/L) is the perchlorate concentration in water at time $t$ (min), $K_{\text{obs}}$ (min$^{-1}$) is the observed pseudo first-order rate constant.

The removal enhancement at various temperatures can be easily revealed when the experimental data are plotted.

**Table 1** BET characteristics of GAC and ICs/GAC materials

<table>
<thead>
<tr>
<th>Name</th>
<th>Surface area (m$^2$/g)</th>
<th>Pore volume (cm$^3$/g)</th>
<th>Pore size(nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BET Micro BJH</td>
<td>Total Micro BJH Ave BJH</td>
<td></td>
</tr>
<tr>
<td>GAC</td>
<td>925  591  574  299</td>
<td>0.457  0.433  0.177</td>
<td>1.97  2.36</td>
</tr>
<tr>
<td>ICs/GAC</td>
<td>591  574  230</td>
<td>0.305  0.272  0.147</td>
<td>2.06  2.554</td>
</tr>
</tbody>
</table>

Micro: $t$-plot micropore; BJH: cumulative pores between 1.7 and 300 nm from BJH adsorption branch; total: single point adsorption total pore volume at $P/P_0 > 0.99$ (corresponding to less than 200 nm pores); ave: adsorption average pore width (4 V/A by BET).

**Table 2** Observed pseudo first-order rate constants of perchlorate removal by ICs/GAC

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>$K_{\text{obs}}$ (min$^{-1}$)</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>0.0025</td>
<td>0.9746</td>
</tr>
<tr>
<td>60</td>
<td>0.0036</td>
<td>0.9941</td>
</tr>
<tr>
<td>90</td>
<td>0.005</td>
<td>0.9883</td>
</tr>
</tbody>
</table>
is the absolute temperature. By analyzing the relationship of various temperatures and the observed first-order rate constants, the activation energy ($E_a$) of 9.56 kJ/mol and an $A$ value of 0.1176 were obtained for ICs/GAC materials according to the Arrhenius equation (Fig. 6). At the same time, the observed pseudo first-order rate constant ($K_{obs}$) increased from 0.0025 to 0.005 min$^{-1}$ when the temperature increased from 25 to 90°C, thereby the effect of temperature was not distinct on ClO$_4^-$ removal for ICs/GAC materials.

It is generally known that perchlorate reduction requires conditions in which a Cl–O bond is broken and the oxygen atom is transferred to the reductant, so a great amount of energy should be provided for them and the temperature is an important factor for the perchlorate reduction by nZVI. Xiong et al. (2007) have reported that the observed pseudo first-order rate constants ($K_{obs}$) were improved by 82 times using the CMC-stabilized nZVI when the ambient temperature increased from 25 to 110°C. Cao et al. (2005) have reported that an activation energy of non-stabilized ZVI particles at various ZVI dose (1.0–20.0 g/L) for perchlorate removal (200 mg/L) was 79.02 kJ/mol. Xiong et al. (2007) reported the activation energy ($E_a$) of (52.597 + 8.41) kJ/mol for reduction of ClO$_4^-$ (10 mg/L).
by CMC-stabilized ZVI particles at an iron dosage of 1.8 g/L. However, the overall ClO$_4^-$ adsorption on porous solid is a kind of physical transport process, so little energy is needed for ClO$_4^-$ adsorption on ICs/GAC.

Consequently, much lower activation energy of ICs/GAC materials can be attributed to three factors. Firstly, ICs/GAC materials contain a large amount of FeOHSO$_4$ and Fe$_2$O$_3$, which have the function of ClO$_4^-$ adsorption. Sulfate concentration increased while ClO$_4^-$ concentration decreased, because sulfate of the FeOHSO$_4$ was released to the solution in the course of ClO$_4^-$ adsorption. This result shows that sulfate of FeOHSO$_4$ has exchanged with ClO$_4^-$ as Reaction (5):

$$\text{FeOHSO}_4 + 2\text{ClO}_4^- \rightarrow \text{FeOH(ClO}_4)_2 + \text{SO}_4^{2-}$$  \hspace{1cm} (5)

Because Fe$_2$O$_3$ in the solution can form HFO nanoparticles, Fe$_2$O$_3$ has the function of ClO$_4^-$ adsorption and can form inner-sphere complexes with ClO$_4^-$. Generally speaking, ClO$_4^-$ adsorption activation energy is lower than ClO$_4^-$ reduction activation energy ($E_a$), because ClO$_4^-$ adsorption on ICs/GAC materials is a kind of physical transport process. Perchlorate adsorption of FeOHSO$_4$ and Fe$_2$O$_3$ plays an important role in ClO$_4^-$ removal. Therefore, the activation energy of ICs/GAC materials is very low. Secondly, the materials prepared in polyethylene glycol 6000 and ethanol-water solution can limit the sizes of FeOHSO$_4$, Fe$_2$O$_3$ and nZVI particles to enhance their reactivity. Hence, FeOHSO$_4$ and Fe$_2$O$_3$ nanoparticles have high ClO$_4^-$ adsorption capacities. Thirdly, a small amount of nZVI supported on GAC can constitute the micro-cell corrosion in solution, nZVI as the anode and GAC as the anode, then the formation of the micro-cell corrosion of ICs/GAC materials accelerates the electron gain and loss rate. Electrochemical studies of corrosion of pitting of iron electrodes in ClO$_4^-$ media have been published, for example, Prinz and Strehblow (1998) concluded that ClO$_4^-$ ion decomposed on the surface of iron electrodes during the pitting process and chloride was the main product. In this research, sulfate of the FeOHSO$_4$ released to the solution can form electrolyte solution and ICs/GAC in ClO$_4^-$-laden solution undergo Reaction (6):

$$\text{ClO}_4^- + 4\text{Fe}^0 + 8\text{H}^+ \rightarrow 4\text{Fe}^{2+} + \text{Cl}^- + 4\text{H}_2\text{O}$$  \hspace{1cm} (6)

In fact, the change of chloride concentration was insignificant, because a large amount of ClO$_4^-$ was adsorbed by FeOHSO$_4$ and Fe$_2$O$_3$ nanoparticles. The results show that nZVI is easy to become Fe$_2$O$_3$, and ClO$_4^-$ adsorption on FeOHSO$_4$ and Fe$_2$O$_3$ is the most important role in ClO$_4^-$ removal.

2.4 Loading Fe amount and stability of ICs/GAC

Determined Fe ion concentration of ICs/GAC in HCl solution (2 mol/L) is 16.7 mg/L, therefore, the loading Fe amount on GAC is 0.83%. Fe ion concentration of ICs/GAC materials in DI water is 1.2 mg/L, which has shown that some iron ion of the GAC-ICs materials is easily soluble and some FeOHSO$_4$, Fe$_2$O$_3$ and ZVI nanoparticles are bond on GAC tightly. Furthermore, the stable structure of GAC can preclude the crumbling phenomenon and commensurate backwashing to overcome the poor mechanical strength of nZVI, FeOHSO$_4$ and Fe$_2$O$_3$ nanoparticles. Hence, ICs/GAC materials can be applied to the fixed beds or any flow through systems.

3 Conclusions

On the basis of the results, major findings and conclusions are summarized.

1) ICs/GAC can be successfully synthesized via hydrolyzing FeSO$_4$·7H$_2$O on GAC, reduced by NaBH$_4$ solution in polyethylene glycol 6000 and ethanol solution, dried in vacuum condition and exposed to air.

2) ICs/GAC materials contain a large amount of FeOHSO$_4$, Fe$_2$O$_3$ and a small amount of ZVI nanoparticles. Perchlorate adsorption on FeOHSO$_4$ and Fe$_2$O$_3$ plays an important role in perchlorate removal. Perchlorate removal can reach 86% within 12 hr at 25°C and 97% within 10 hr at 90°C.

3) The effect of temperature is not distinct on ClO$_4^-$ removal by ICs/GAC. The observed pseudo first-order rate constant ($k_{obs}$) was improved only by 2 times when the temperature increased from 25 to 90°C. The activation energy ($E_a$) was determined to be 9.56 kJ/mol.

Acknowledgments

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References


Fiedor J, Bostick W, 1998. Understanding the mechanism of magnesium removal from groundwater by zero-valent iron using...


