



Bimetallic iron–aluminum particles for dechlorination of carbon tetrachloride

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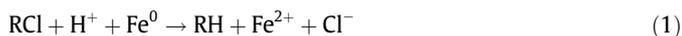
ABSTRACT

Bimetallic iron–aluminum (Fe/Al) particles were synthesized and tested for their reactivity toward carbon tetrachloride using batch reactors and a flow-through column at near neutral pH. Preparation of bimetallic Fe/Al particles was conducted under acidic conditions under which iron was readily deposited onto the aluminum surface. The SEM image showed clusters of iron on the aluminum surface at the measured Fe:Al molar ratio of about 2:3. Results showed that the presence of zero-valent aluminum successfully prevented the formation of a passive layer at the iron surface and maintained the reactivity of iron. The dechlorination of carbon tetrachloride by bimetallic Fe/Al particles produced chloroform (9%), dichloromethane (17%) and methane (38%). Kinetic analysis suggests that bimetallic Fe/Al particles increased the reactivity toward carbon tetrachloride degradation by a factor of 10 compared to zero-valent iron and possessed a comparable reactivity with nano-sized Fe. The effectiveness of bimetallic Fe/Al particles was further confirmed by the continuous flow column study from which an ageing of bimetallic particles was also observed.

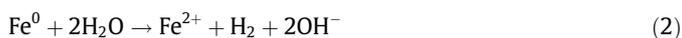
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1. Introduction

Zero-valent iron (ZVI) has been successfully applied for treatments of a large number of environmental contaminants including halogenated organic solvents (Gillham and O'Hannesin, 1994; Matheson and Tratnyek, 1994; Roberts et al., 1996; Lowry and Johnson, 2004; Lien et al., 2007), heavy metals (Blowes et al., 2000; Ponder et al., 2000; Lien and Wilkin, 2005), nitrate (Cheng et al., 1997; Alowitz and Scherer, 2002; Liou et al., 2005) and radionuclides (Gu et al., 1998; Morrison et al., 2001). Numerous *in situ* ZVI permeable reactive barriers (PRBs) have been in successful operation for many years (Puls et al., 1999; Wilkin et al., 2003; Puls, 2006). Main reactions involve iron corrosion and concurrent reduction of chlorinated organic compounds. Using a generalized chlorinated organic compound, RCl, as an example, ZVI-mediated reaction of RCl to the corresponding hydrocarbon, RH can be represented as



However, in aqueous environment, iron corrosion reaction inevitably leads to increase in solution pH and the formation of iron hydroxide precipitates:



The accumulation of hydroxide precipitates along with the deposition of insoluble mineral species on the metal surface causes the

loss of iron reactivity over time and eventually shortens the longevity of PRBs (Matheson and Tratnyek, 1994; Puls, 2006).

Many novel materials such as zero-valent bimetallics (e.g., Pd/Fe, Cu/Fe and Cu/Al) (Grittini et al., 1995; Fennelly and Roberts, 1998; Lien and Zhang, 2002) and nanoscale bimetallic particles (Lien and Zhang, 1999, 2001, 2005) have recently been shown to have enhanced reactivity toward chlorinated organic compounds compared to ZVI. Bimetallic particles consist of two types of zero-valent metals. The structure of bimetallics usually includes cluster-in-cluster and core-shell structures for nano-sized particles (Toshima and Yonezawa, 1998) while an island-like structure can be observed in micro-sized bimetallic particles (Liou et al., 2005). We have reported the use of bimetallic Cu/Al particles for the reductive degradation of chlorinated methanes (Lien and Zhang, 2002). Aluminum is an effective electron donor with a standard reduction potential of -1.662 V; however, the quick formation of aluminum oxide under neutral conditions limits its application as a reactive medium. As a result, we explored the aluminum-based bimetallic structure to overcome this drawback (Lien and Zhang, 2002; Lien and Lee, 2005; Lee et al., 2006).

In this study, bimetallic zero-valent Fe/Al particles consisting of a core metal (aluminum) and a second metal (iron) are investigated. The bimetallic Fe/Al particles are designed to use aluminum as an electron source that can prevent the precipitation of iron corrosion products at the iron surface and thus maintain the surface reactivity of iron. We have previously examined the effect of iron content on the effectiveness of Fe/Al particles for the carbon tetrachloride degradation (Lien and Lee, 2005; Lee et al., 2006). A theoretic iron to aluminum ratio of 15% by weight corresponding to an

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initial molar ratio of Fe:Al = 6:94 was determined to have the optimum performance. As a part of our continuous research on bimetallic Fe/Al particles, this paper focuses on understanding the roles of iron and aluminum and the sustained performance of bimetallic Fe/Al particles. Again, carbon tetrachloride was selected as a model compound in this work. Like many other chlorinated organic compounds, carbon tetrachloride is a prevalent soil and groundwater contaminant. Based on the toxicity and carcinogenicity, it has been listed as a priority pollutant by the US EPA (1979). In this study, the structure of bimetallic Fe/Al particles was determined by X-ray diffraction (XRD) and SEM. Results from batch experiments on the rate and extent of carbon tetrachloride degradation by bimetallic Fe/Al particles are presented. A multi-cycle experiment of carbon tetrachloride addition in a batch reactor and a flow-through column test were conducted to examine the sustained performance of bimetallic Fe/Al particles.

2. Materials and methods

2.1. Materials and chemicals

All chemicals are analytic grade or better. Carbon tetrachloride (99.5%) was purchased from SHOWA. Chloroform (99%) and dichloromethane (99.9%) were obtained from Baker. A commercially available aluminum powder (99.5%, ~20 μm) and micro-sized iron powder (Baker analyzed reagent) were obtained from Alfa and Baker, respectively. Ferric chloride ($\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$, 98%) was purchased from Aldrich. A standard gas mixture for GC analysis was obtained from Supelco containing 1% each of ethane, ethylene, acetylene, and methane.

2.2. Preparation of bimetallic Fe/Al particles

Bimetallic Fe/Al particles were prepared using the zero-valent aluminum and ferric chloride as precursors in a fume hood under ambient conditions. Aluminum powder (5 g) was first washed by concentrated HCl (13 mL) in a 10 mL aqueous solution. The suspension was mixed with a magnetic stirrer and immediate fume evolution was observed. A small amount of distilled water was quickly added to dissipate heat. A 30 mL aqueous solution containing 3.6 g ferric iron ($\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$) was then quickly added into the suspension and mixed with a magnetic stirrer. Bimetallic Fe/Al particles were formed as the elemental iron deposited onto the aluminum surface. They were then washed by 2 L deionized water and harvested via vacuum filtration. About 1.0 ± 0.1 g ($n = 5$) bimetallic particles were recovered in each batch preparation. The initial molar ratio of precursors was Fe:Al = 6:94; however, the measured molar ratio of Fe to Al of about 2:3 was calculated based on the following equation:

$$\text{Fe} : \text{Al} = \frac{(\text{Applied Fe content} - \text{Residual Fe content})}{(\text{Applied Al content} - \text{Residual Al content})} \quad (3)$$

where the residual metal content was determined by multiplying the total volume of the filtering solution by the dissolved metal concentration measured by an inductively coupled plasma-optical emission spectrometry (ICP-OES). This indicated that the aluminum content in bimetallic particles was significantly reduced. The decrease in the aluminum content is because a vigorous dissolution of aluminum occurred during the acid-wash step.

2.3. Batch experiments

Batch experiments were conducted in 150 mL serum bottles containing 1 g bimetallic Fe/Al particles in a 100 mL aqueous solution under near neutral pH (6.7 ± 0.5). Measurements of oxida-

tion–reduction potential (ORP) indicated the reaction system quickly reached highly reducing conditions (ORP ~ -450 mV). The stock solution of carbon tetrachloride was prepared by adding 1 mL carbon tetrachloride in 10 mL reagent grade methanol. In a typical experiment, 20 μL methanol solution of carbon tetrachloride was spiked into a 100 mL aqueous solution to achieve an initial concentration of approximately 31.7 mg L^{-1} . The serum bottles were then capped with screw caps containing Teflon-lined septa and placed on a rotary shaker (50 rpm) at room temperature (22 ± 1 °C). The experiments were employed in duplicate. The solution pH and ORP were measured using a Sension 3 laboratory pH/mV meter (HACH) equipped with a combination pH electrode and a combination redox electrode, respectively.

2.4. Column tests

An up-flow column experiment was operated with a 2.5 cm inner diameter by 30 cm length glass column. The column was filled with bimetallic Fe/Al particles and quartz sand mixture. A well-homogenized bimetallic Fe/Al particles (15 g) and sand (230 g) mixture were funneled into the column in five increments to ensure a homogeneous packing of the column. Batch tests confirmed that the removal of carbon tetrachloride by quartz sand is negligible. The porosity was determined to be about 0.51. The influent solution containing 25 mg L^{-1} carbon tetrachloride was pumped through the column at rates of 0.75 mL min^{-1} using a HPLC pump. Volumetric flow rates were measured periodically throughout the experiment to ensure consistency. Samples were directly collected from the outlet at selected intervals.

2.5. Analytic methods

Measurement of carbon tetrachloride and its intermediates was conducted by the headspace GC method. At selected time intervals, a 50- μL headspace gas aliquot was withdrawn by a gastight syringe for GC analysis. A HP4890 GC equipped a flame ionization detector (FID) and a DB-624 capillary column (J&W, $30 \text{ m} \times 0.32 \text{ mm}$) was used for the analysis of chlorinated methanes. Temperature conditions for oven, injection port and detector were set at 45, 250 and 300 °C, respectively. The operation time of the oven was 5 min. Concentrations of hydrocarbons were measured by a HP4890 GC-FID equipped with a GS-GASPRO capillary column (J&W, $30 \text{ m} \times 0.32 \text{ mm}$). A same temperature program was used for the hydrocarbon analysis except that the oven temperature was set at 35 °C for 5 min. An external standard method using calibration curves was carried out to determine the concentration of chlorinated methanes. Calibration curves for each compound were made initially and the variability was checked daily before analysis (<15%). Peak areas were measured in duplicate with relative percent differences less than 15%. In this study, the detection limit of carbon tetrachloride was approximately $20 \mu\text{g L}^{-1}$.

Concentrations of dissolved iron and aluminum were measured by ICP-OES analysis. The wavelength of iron and aluminum was set at 238.204 and 396.153 nm, respectively. Prior to analysis, samples were filtered through 0.2 μm filters.

2.6. Solid-phase characterization

XRD measurements were performed to characterize the surface composition of bimetallic particles using a X-ray diffractometer (Siemens D5000) with a copper target tube radiation ($\text{Cu K}\alpha$) producing X-ray with a wavelength of 1.54056 Å. Samples were placed on a quartz plate and were scanned from 20° to 80° (2θ) at a rate of $5^\circ 2\theta \text{ min}^{-1}$. Morphological and elemental analysis of bimetallic Fe/Al particles was performed by SEM using a Hitachi S-4300

microscope (Hitachi Science Systems, Ltd.) with energy-dispersive X-ray (EDX) analysis (at 10 kV). A specific surface area of the particles was determined by Brunauer–Emmett–Teller N_2 method using a COULTER SA 3100 surface area analyzer (Coulter).

2.7. Kinetics analysis

The rate of transformation for carbon tetrachloride in a batch system is described as a pseudo first-order rate model. It has been recognized that the degradation rate is directly proportional to the amount of available iron surface (Johnson et al., 1996) and the kinetic equation can be expanded as follows:

$$\frac{dC}{dt} = -k_{\text{obs}}C = -k_{\text{SA}}\rho_m a_s C \quad (4)$$

where C is the concentration of carbon tetrachloride (mg L^{-1}); k_{obs} is the observed rate constant (h^{-1}); k_{SA} is defined as the surface area normalized rate constant ($\text{L m}^{-2} \text{h}^{-1}$); ρ_m is the metal loading (g L^{-1}); a_s is the specific surface area of metals ($\text{m}^2 \text{g}^{-1}$) and t is time (h). Recently, the pretreatment of iron that may affect its surface reactivity toward chlorinated organic compounds has been reported (Lin and Lo, 2005). The complication of the iron reactivity seems not simply to be explained by the effect of surface area alone. Another aspect of this observation is the likelihood that the specific surface area probably changes over time as the iron undergoes reactions. However, because the surface area normalized rate constant has widely been used in determining the iron reactivity, we still applied it in this study for comparison purpose.

3. Results and discussion

3.1. Characterization of bimetallic Fe/Al particles

Figure 1 presents a SEM image of bimetallic Fe/Al particles (Fig. 1a). The SEM image indicated that bimetallic Fe/Al particles exhibited knobs deposited on the surface. The arrows in Fig. 1a pointed out areas without knobs at the aluminum surface corresponding to EDX mapping of aluminum (Fig. 1b). As shown in Fig. 1b and c, EDX mapping analysis suggested the spherical knobs were individual iron particles having particle sizes in a range of 0.5–1.0 μm . The EDX analysis performed on the bimetallic Fe/Al particles also resulted in a spectrum with distinct peaks for Al

and Fe indicating both elements are present (Fig. 2). In addition, an oxygen peak was detected in the spectrum, which is likely due to the over oxidation during the sample preparation. Nevertheless, the atomic ratio of Fe to Al was about 2:3.5, similar to that determined by ICP-OES analysis.

The XRD result for fresh bimetallic Fe/Al particles is shown in Fig. 3. The characteristic peaks of aluminum appear at 38.6, 44.9, 65.2, and 78.5° where the main diffraction peak is near at the diffraction angle (2θ) of 38.6°. The peaks assigned to iron are at the positions at 44.7° (main peak) and 65.0°. The diffraction angle of peaks shown in Fig. 3 is 38.6, 44.8, 65.2, and 78.4° indicating that bimetallic Fe/Al consisted of zero-valent aluminum and ZVI. It should be pointed out that bimetallic Fe/Al particles prepared under acidic conditions resulted in no formation of aluminum hydroxide/oxyhydroxides such as bayerite ($\text{Al}(\text{OH})_3$) that is a major byproduct for bimetallic Cu/Al particles during alkaline synthetic processes (Lien and Zhang, 2002).

3.2. Dechlorination rates and products

Figure 4 shows the transformation of carbon tetrachloride by bimetallic Fe/Al particles at near neutral pH. Acid-washed iron prepared based on the experimental procedure of Matheson and Tratnyek (1994) was used as a control test under identical pH conditions. The metal loading for bimetallic Fe/Al particles and Fe powder was 10 and 200 g L^{-1} , respectively. More than 97% of car-

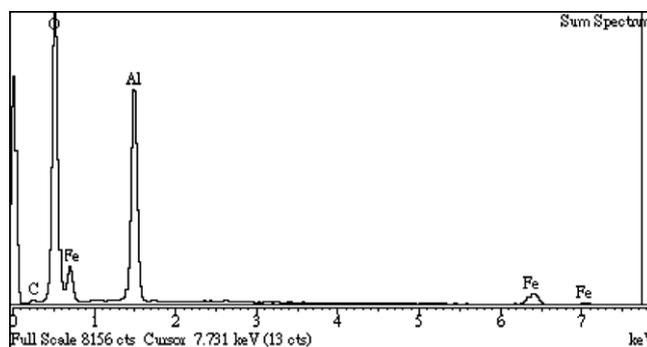


Fig. 2. SEM-EDX spectrum of bimetallic Fe/Al particles.

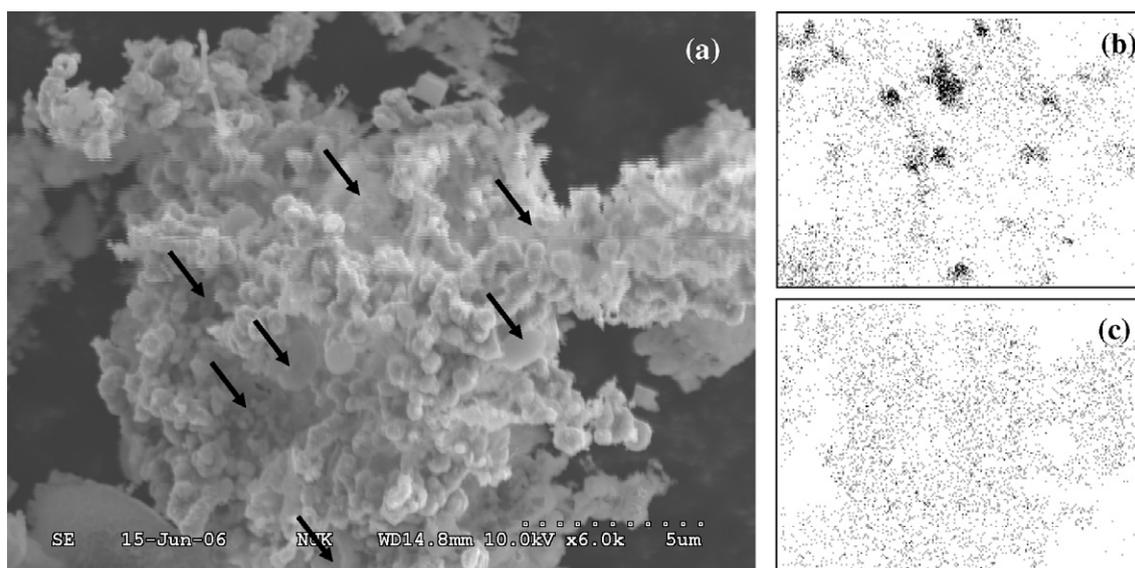


Fig. 1. (a) SEM micrographs of bimetallic Fe/Al particles. (b) and (c) are EDX mapping images of Al and Fe, respectively.

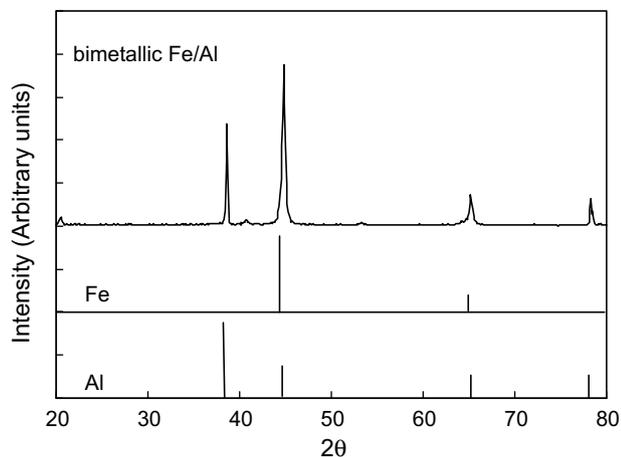


Fig. 3. XRD pattern of fresh bimetallic Fe/Al particles.

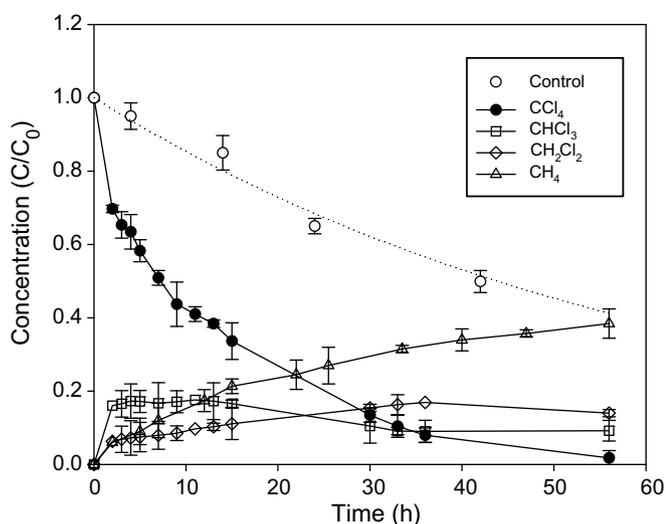


Fig. 4. Transformation of 31.7 mg L^{-1} carbon tetrachloride by bimetallic Fe/Al particles at near neutral pH. Iron powder was used as a control. The metal loading for Fe/Al particles and Fe powder was 10 and 200 g L^{-1} , respectively.

bon tetrachloride was degraded by bimetallic Fe/Al particles in the contact period of 60 h. Compared to bimetallic Fe/Al particles, ZVI alone showed a relatively slow degradation in reaction with carbon tetrachloride. The observed rate constant of metals was estimated using Eq. (4). Results indicated the degradation of carbon tetrachloride follows the behavior of first-order kinetics ($R^2 > 0.98$) in the presence of either bimetallic Fe/Al particles or iron powder. The observed rate constant for bimetallic Fe/Al particles and iron powder was calculated to be approximately 0.13 and 0.017 h^{-1} , respectively. The specific surface area of bimetallic Fe/Al particles and iron powder was 11.8 ± 2.5 and $0.7 \pm 0.2 \text{ m}^2 \text{ g}^{-1}$ ($n = 4$), respectively. The surface area normalized rate constant (k_{SA}) was then determined to be 1.1×10^{-3} and $1.2 \times 10^{-4} \text{ L m}^{-2} \text{ h}^{-1}$ for bimetallic Fe/Al particles and iron powder, respectively. It has been reported that the k_{SA} value of micro-sized iron, nano-sized iron and nano-sized Pd/Fe for the carbon tetrachloride degradation is 1×10^{-4} , 5.3×10^{-4} , and $9 \times 10^{-3} \text{ L m}^{-2} \text{ h}^{-1}$, respectively (Lien and Zhang, 1999). It is clear that bimetallic Fe/Al particles increased the reactivity toward carbon tetrachloride degradation by a factor of 10 compared to ZVI. Although the reaction rate of bimetallic Fe/Al particles is about eight times less than that of nano-sized Pd/Fe, still, bimetallic Fe/Al particles possess a com-

parable reactivity with nano-sized Fe. It should be pointed out that the degradation of carbon tetrachloride by zero-valent aluminum is negligible as it has been reported in the study of bimetallic Cu/Al particles (Lien and Zhang, 2002).

As shown in Fig. 4, carbon tetrachloride (31.7 mg L^{-1}) was transformed to chloroform and dichloromethane, and methane by bimetallic Fe/Al particles. Concentrations in Fig. 4 are expressed as the molar ratio to the initial carbon tetrachloride concentration. Concentrations of chloroform increased continuously to about 18% of the initial carbon tetrachloride after 1 h and then gradually decreased to about 9% of the carbon tetrachloride lost. Peak concentration of dichloromethane ($\sim 17\%$) was observed at about 36 h. Methane accounted for 38% of the carbon tetrachloride lost. The mass balance of carbon was about 64%. Studies have indicated that concurrent adsorption and reduction of chlorinated organic compounds took place in the presence of ZVI or bimetals (e.g., Burris et al., 1995; Kim and Carraway, 2000). Lin and Lo (2005) reported that about 13–37% of trichloroethylene disappearance was resulted from the adsorption onto the surface of iron with various pretreatments. The remaining carbon could therefore be attributed to adsorption and its transformation products onto the metal surface.

3.3. Repetitive addition experiment and column test

Experiments with repetitive spiking of carbon tetrachloride into batch bottles were conducted to determine the capacity of bimetallic Fe/Al particles for the degradation of carbon tetrachloride. Figure 5 shows the results of an experiment during which a dose of 20–40 μmol carbon tetrachloride was repeatedly spiked into a 100 mL solution containing 1 g bimetallic Fe/Al particles. The total operation time was about 320 h. The added carbon tetrachloride was completely degraded within about 60 h for each cycle. Small amounts of chlorinated intermediates (chloroform and dichloromethane) were produced but no significant accumulation was observed until 40 μmol carbon tetrachloride was added. The accumulated amount of dichloromethane and methane accounted for about 10% and 18% of the total addition of carbon tetrachloride in the four cycles of the experiments. As mentioned previously, the adsorption may be involved in the bimetallic Fe/Al system. The contribution of adsorption to the overall treatment efficiency of carbon tetrachloride needs further investigation. Currently, our study indicated that the adsorption effect of aluminum hydroxide formed from the aluminum oxidation of bimetallic Fe/Al is minor.

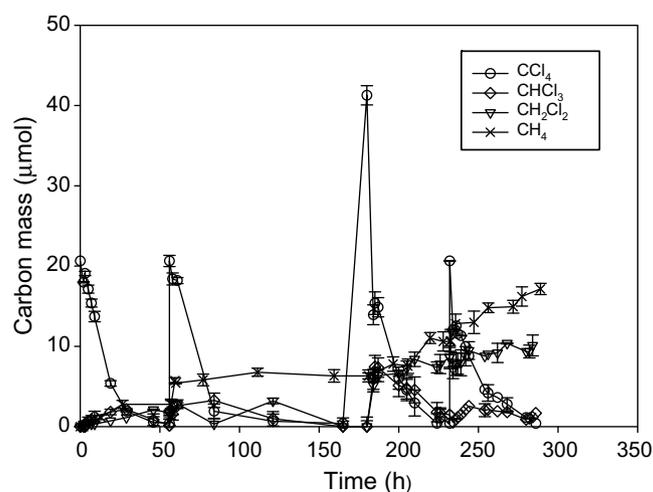


Fig. 5. Repetitive addition of carbon tetrachloride (20–40 μmol) in reaction with bimetallic Fe/Al particles. The metal loading for Fe/Al particles was 10 g L^{-1} .

Insignificant removal of carbon tetrachloride (<5%) was found in the presence of aluminum hydroxide alone prepared by completely oxidation of zero-valent aluminum at 40 °C for 24 h. This can be attributed to the hydrophilic surface of aluminum hydroxide that causes the adsorption affinity of chlorinated organic compounds onto its surface is negligible.

An up-flow column reactor packed with a mixture of bimetallic Fe/Al particles and quartz sand was further carried out to test the sustained performance of bimetallic Fe/Al particles. The study was performed for 30 d at the flow rate of about 1080 mL d⁻¹ and the influent concentration of carbon tetrachloride was set at 25 mg L⁻¹. The result is shown in Fig. 6 indicating that bimetallic Fe/Al particles effectively degraded carbon tetrachloride in the testing period. The effluent concentration of carbon tetrachloride remained below 1 mg L⁻¹ for most of time while it began increasing to about 8 mg L⁻¹ after about 680 h. This revealed that ageing of bimetallic Fe/Al particles may occur. Nevertheless, it should be noted that only small amounts of bimetallic Fe/Al particles (15 g) were applied in this test.

3.4. Roles of aluminum and iron

Figure 7 shows the XRD patterns of reacted bimetallic Fe/Al particles taken after reacting with 31.7 mg L⁻¹ carbon tetrachloride for 24 h and 7 d. Compared to the XRD pattern of fresh bimetallic Fe/Al particles shown in Fig. 3, reacted bimetallic Fe/Al particles showed a significant change of their composition at the surface. The XRD pattern of reacted bimetallic Fe/Al particles at 24 h revealed the diffraction peaks at only 44.7° and 65.0° (Fig. 7). The characteristic peaks assigned to aluminum were disappeared. This indicated that only ZVI dominated at the metal surface for treated bimetallic Fe/Al particles. Furthermore, no iron corrosion products such as magnetite, maghemite, and hematite were found. These are common crystalline iron oxides observed in iron-mediated reactions (Ponder et al., 2000; Lien et al., 2007). This suggested that the use of aluminum as a core metal successfully maintains a fresh surface of iron. The disappearance of diffraction peaks of aluminum indicated the aluminum at the particle surface was consumed in contact with water during the reaction. Aluminum exhibits a strong tendency to donate electrons yielding dissolved aluminum ions that are subsequently formed a passive layer of aluminum hydroxide to stop a further oxidation of aluminum.

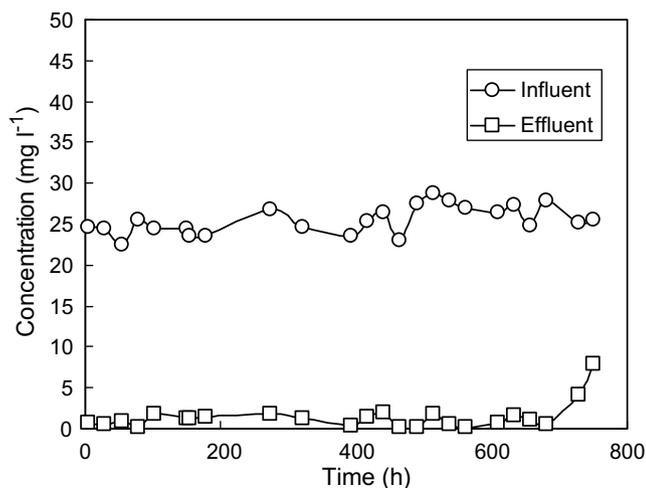


Fig. 6. Degradation of carbon tetrachloride through a continuous column packed with bimetallic Fe/Al particles (15 g) and quartz sand mixture (230 g). The influent concentration of carbon tetrachloride was 25 mg L⁻¹.

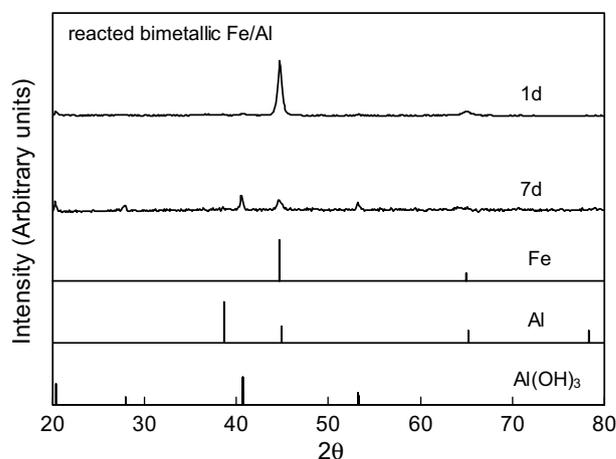


Fig. 7. XRD pattern of reacted bimetallic Fe/Al particles.



The formation of aluminum hydroxide was insignificant for reacted bimetallic Fe/Al at 24 h (Fig. 7). Only a group of small diffraction peaks appeared at 20.4°, 27.9°, 36.6°, and 40.7° was identified as the characteristic peaks of aluminum hydroxide (Al(OH)₃). This can be attributed to the fact that the crystallization of aluminum hydroxide/oxyhydroxides is a slow process that causes an either amorphous or poorly crystalline structure in most aluminum hydroxide/oxyhydroxides (Dixon and Weed, 1989). Nevertheless, after reacting with carbon tetrachloride in aqueous solutions for 7 d, aluminum hydroxide was clearly found at the bimetallic Fe/Al surface along with the iron consumption (Fig. 7).

Dissolved iron and aluminum ions were measured during the course of carbon tetrachloride degradation. Concentrations of dissolved aluminum ion initially increased to 2.1 mg L⁻¹ at 7 h and then it was removed from solution gradually with time to reach 0.04 mg L⁻¹ at 70 h. However, dissolved iron concentration quickly increased to about 8 mg L⁻¹ at 1 h while slightly decreasing to 5 mg L⁻¹ at the end of the experiment. Unlike ZVI increasing pH significantly in aqueous solutions (e.g., a typical increase in pH of 2–3 standard units) (Sun et al., 2006), bimetallic Fe/Al particles resulted in only minor change in the solution pH during the reaction. It was found that the solution pH increased from 6.7 ± 0.5 to 7.3 ± 0.5 at the end of the experiment. At the neutral pH, an insoluble form of polymeric aluminum hydroxide and dissolved ferrous iron dominate in reducing regions (Deltombe and Pourbaix, 1958; Stumm and Morgan, 1996). Consequently, a low concentration of dissolved aluminum and a relatively high concentration of dissolved iron can be found in the bimetallic Fe/Al aqueous system.

Based on the XRD study, product analysis of the carbon tetrachloride degradation, and the measurement of dissolved metals, a conceptual model accounting for the roles of aluminum and iron is proposed (Fig. 8). Carbon tetrachloride was first adsorbed at the

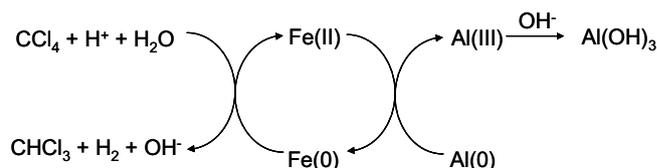


Fig. 8. Conceptual model accounting for the roles of aluminum and iron in the reductive dechlorination of carbon tetrachloride with bimetallic Fe/Al particles.

iron surface where a surface-mediated dechlorination took place (Matheson and Tratnyek, 1994). Iron oxidation was involved in the carbon tetrachloride degradation and water dissolution. The dechlorination and water dissolution are dynamic processes that should cause a continuous increase in dissolved iron concentrations at the near neutral pH. However, no continuous increment of the dissolved iron concentration in the solution and no iron corrosion products at the iron surface were found. They can be attributed to the presence of aluminum that serves as an electron source for the reduction of dissolved iron. Aluminum was oxidized to dissolved aluminum ions that were subsequently precipitated as aluminum hydroxide/oxyhydroxides.

4. Conclusions

The build-up of iron corrosion products at the iron surface declining its reactivity toward contaminants and the increase in solution pH during the iron-mediated reaction are the two major issues affecting the application of ZVI technology. Bimetallic Fe/Al particles have been developed to address these issues. Effective degradation of chlorinated organic compounds using the bimetallic Fe/Al particles was demonstrated under near neutral conditions under which the solution pH can be maintained without any significant change. The bimetallic Fe/Al particles dechlorinated carbon tetrachloride to chloroform (9%), dichloromethane (17%), and methane (38%), exhibiting a comparable reactivity with nano-sized ZVI. Reductive dechlorination coupled with the iron oxidation occurred at the iron surface. Nevertheless, the presence of aluminum reduced the dissolved iron to ZVI without the precipitation of iron corrosion products at the surface of bimetallic particles. The dissolved aluminum ion resulted from the aluminum oxidation was quickly precipitated out from solution leading to a relatively low residual of dissolved aluminum ($\sim 0.04 \text{ mg L}^{-1}$) in the solution.

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