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The interaction effect of magnetism on arsenic and iron ions in water

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ABSTRACT

Recently, attention has been focused on the use of physical methods, such as the application of magnetic fields, to reduce mineral impurities in water. The purpose of this study was to survey the effects of the magnetic fields on the interaction of arsenic and iron ions in aqueous solutions. In this study, an experimental setup was designed, and also a circular ferrite magnet with the mean magnetic flux density of 10 mT was used to apply the magnetism. The dissolved arsenic content was analyzed by inductively coupled plasma. The results of the study indicated that the arsenic level of the samples without iron fillings was reduced. The removal efficiencies of arsenic after exposure to the magnetic fields over contact times of 5, 10, and 15 min were 42.06%, 49.06%, and 55.26%, respectively. Moreover, passing the samples through the magnetic column caused the separation of AsO_{2-} ions from arsenic-iron complexes and, the soluble arsenic was therefore increased. When placed in magnetic fields, a force was applied to the multi-ionic species; the bond between the ions was then weakened and they were dissociated. Subsequently, the arsenic ions were deviated and reacted with a spiral metal inside a column. It can be concluded that the dissociation and dissolution of the ions in the process were due to the mechanisms of the Laplace–Lorentz force and the Hall effect.

Keywords: Arsenic; Laplace–Lorentz force; Hall effect; Magnetic flux density

1. Introduction

In recent years, many studies on the effects of magnetic fields on the water have been reported. Magnetic separation is a purification technique that has been applied to dissolved chemicals in the water. Magnetic water treatment or physical water treatment is an attractive but still controversial issue. The technology of magnetic water has been widely studied in the field of hard waters, but its application in the treatment of water polluted with other chemicals such as arsenic is very limited. The occurrence of arsenic in natural water resources has currently become a major environmental problem in the world [1]. Arsenic is a toxic metalloid and exists in nature in the two organic and mineral forms [2]. The excessive and prolonged human intake of inorganic arsenic, through drinking water and food, causes arsenicosis, which includes skin disorders, skin cancer, vascular diseases, and diabetes [3]. The World Health Organization (WHO) guideline value for arsenic in drinking water is set as 10 μg/L [4]. Several reports on the existence of increased levels of arsenic in groundwater have been made in different countries [3]. Water treatment using the magnetic field is recently taken into consideration [5]. Magnetic field has been successfully applied for separation purposes [6]. Magnetism is a unique physical method that facilitates

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applications such as water treatment by affecting the physical properties of impurities in water [6]. This physical method helps avoid the use of chemicals, which can be detrimental to human life or distractive to the environment. Magnetic technologies are implemented as either permanent magnets or electromagnetic devices [6]. Reports have been published on the use of magnets in water treatment in many countries such as Russia, China, Poland, and Bulgaria [7]. Magnetic water treatment is used in both static and dynamic forms. In static applications, water in a reservoir is in contact with a static magnetic field, and in dynamic forms, it is exposed to an alternating magnetic field, or water passes through a static magnetic field [8]. Magnetic water purification increases the speed of chemical reactions [9]. Magnetic treatment can accelerate or suppress nucleation depending on the solution chemistry [6]. Several researchers have presented theories for the effects of magnetic fields on water based on Faraday's law, according to which a conductive fluid moving at a higher velocity through and perpendicular to strong magnetic fields will produce an electromotive potential called the "Laplace–Lorentz force" [6]. Based on this phenomenon, when ions carrying water pass through a magnetic field, a force is exerted on each ion. The ions of opposite charge experience forces in opposite directions and consequently redirect them. Redirection of particles enhances the frequency with which ions of opposite charge collide and combine to form a new molecule [7]. Another theory that is proposed in the field of the magnetic treatment of water and dissociation of ions is the Hall effect. The principal of the Hall effect is almost similar to that of Laplace–Lorentz force, which causes the separation of multi-ionic compounds. The Hall effect is particularly pronounced in electric fields [10]. Ambashta and Sillanpää [11] conducted a review study on water purification using magnetism. Ma et al. [12] investigated arsenic removal using sulfide ions in the presence of an external magnetic field. In another study, Coey and Cass [10] carried out a study on the application of a magnetic field in the treatment of hard waters. Sun et al. [13] reported results about the combined effect of weak magnetic fields and anions on arsenite sequestration by zerovalent iron from the viewpoint of the kinetics and mechanisms of the reactions. Moreover, Li et al. [14] considered improving the reactivity of zerovalent iron by taking advantage of its magnetic memory, and investigated its implications for arsenite removal. In the former studies, arsenic removal from water was investigated only in the presence of iron ions, but in this study, it is surveyed along with magnetic force lines. The interaction of magnetic fields with arsenic, ferrite, and ferrous ions was a new approach to the treatment of the impurities in the research. Since the presence of arsenic in water resources, especially groundwater, has become a major problem, and low-cost treatment methods such as physical methods have been considered. Magnetic field technology is a physical treatment method that is very convenient for numerous types of physicochemical treatments. Understanding the magnetic field effects observed on water and aqueous solutions is still a controversial issue, although the effects have been reported for at least half a century. In this study, the effects of the magnetic fields on the reduction of arsenic from aqueous solutions in the presence of iron filings were considered.

2. Materials and methods

2.1. Magnetic column fabrication

A circular magnet with the intensity of magnetization of 10 mT, outer diameter of 7 cm, and inner diameter of 3 cm was primarily placed around a glass column with the height of 28 cm and diameter of 1.5 cm. The magnetic flux density at the center and at several points inside the magnet was measured by a Gauss meter and its average was considered. In addition, a spiral iron with the length of 6 cm was located in front of the magnet inside the column. Also, a switching valve was applied at the end of the column for the discharge velocity adjustment, with the discharge velocity of 2 mm/s (Fig. 1).

2.2. Sample preparation

The synthetically arsenic-polluted water samples were prepared by diluting 0.1 N sodium arsenite solution Merck Company (Darmstadt, Germany) with de-ionized water. In addition, to prevent the oxidation of arsenite to arsenate the required solutions were prepared on a daily basis at 0.5 and 2 mg/L concentrations.

2.3. Iron filing procurement

The required iron filings were prepared in the turning workshops of Tehran, Iran. The iron filings were passed through a sieve with pores of 2 mm and were made wet using deionized water. Also, ferric hydroxide precipitation was allowed to be formed on the surface of the filings. Iron filings used in this study were heterogeneous and non-uniform in structural geology and existed mostly in semi-cylindrical forms.

2.4. Experiments

The prepared arsenite solutions at 0.5 and 2 mg/L concentrations were reacted with the iron filings adsorbent at 2.5 and 5 g/L dosages in contact times of 5, 10, and 15 min within a beaker with the volume of 100 mL on the shaker at the velocity of 400 rpm. Half of the sample (50 mL) was then passed through the column at the velocity of 2 mm/s, and a control sample (without iron filings) was considered for each sample. The control sample was also passed through

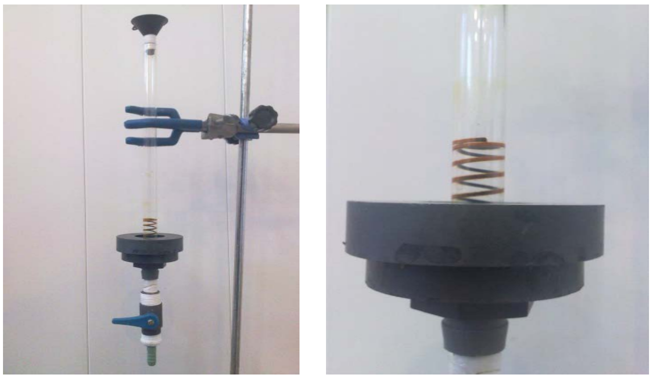

Fig. 1. Overview of the magnetic column.

the column at the same velocity. The samples before and after the column were then passed through a filter with pores of 0.45 mm and their pH was reduced to below 2 using the intact concentrated nitric acid. The arsenic concentration of the samples was measured by the inductively coupled plasma (ICP) system. Furthermore, the electrical conductivity of the samples was measured by EC meter. All the experiments were accomplished at a room temperature of 25°C. They were carried out with three times of repetition and the number of the samples reached a total of 108. The data was analyzed by the statistical test of paired *t*-test and one-way analysis of variance (ANOVA) in SPSS11.5 software.

3. Results

The magnetic field effects on the arsenic removal efficiency have been shown in Tables 1 and 2. According to the Tables, at the arsenic concentration of 0.5 mg/L, at the iron filings dosage of 0 g/L, and over contact times of 5, 10, and 15 min, the removal efficiencies before passing through the column were 31.26%, 35.46%, and 38.06%, and after passing through the column, 42.06%, 49.06%, and 55.26%, respectively. Also, at the iron filings dosage of 2.5 g/L at the same contact times before passing through the column, the removal efficiencies were 87%, 73.46%, and 75.73%, and after passing through the column they were 62.46%, 60.06%, and 71.4%, respectively. Finally, the removal efficiencies for 5 g/L dosage of iron filings were reported at 85.73%, 91.13%, and 78.46% at the pre-column samples, and at 73.2%, 84.2%, and 72.73% post-column samples, respectively. Moreover, in Table 1, the influence of the magnetic field on removal efficiency based on the arsenic concentration of 2 mg/L has been shown.

4. Discussion

The results showed that the magnetic fields reduced the arsenic level of the samples without iron fillings but increased the arsenic level of the samples with iron fillings, which has been shown in Tables 1 and 2 and Figs. 2–6.

The ferric hydroxide ion was formed on the surface of the iron filings in the following equations:

$$Fe(o) \rightarrow Fe^{2+} + 2e^- \quad (1)$$

$$2e^- + H_2O + \frac{1}{2}O_2 \rightarrow 2OH^- \quad (2)$$

$$2Fe^{2+} + 5H_2O + \frac{1}{2}O_2 \rightarrow Fe(OH)_3 \downarrow + 4H^+ \quad (3)$$

Sodium arsenite ($NaAsO_2$) reacts with ferric hydroxide ($Fe(OH)_3$) and forms ferric arsenite ($Fe(AsO_2)_3$) on the surface of the iron filings. In addition, ferrous hydroxide ion is formed within the solution; it may react with sodium arsenite and ferrous arsenite, ($Fe(AsO_2)_2$) can be thus formed.

$$3NaAsO_2 + Fe(OH)_3 \rightarrow Fe(AsO_2)_3 + 3NaOH \quad (4)$$

Table 1
Arsenic removal efficiency before and after the magnetic field based on iron filings dose and contact time at the arsenic concentration of 0.5 mg/L

IF (g/L)	Time (min)	Before	After
		X ± S.D	X ± S.D
0	5	31.26 ± 2.19	42.06 ± 2.84
	10	35.46 ± 3.4	49.06 ± 1.84
	15	38.06 ± 0.3	55.26 ± 0.41
2.5	5	87 ± 7.51	62.46 ± 8.02
	10	73.46 ± 11.49	60.06 ± 10.6
	15	75.73 ± 9.81	71.4 ± 15.33
5	5	85.73 ± 4.9	73.2 ± 14.56
	10	91.13 ± 5.8	84.2 ± 13.42
	15	78.46 ± 34.88	72.73 ± 7.67

Table 2
Arsenic removal efficiency before and after the magnetic field based on iron filings dose and contact time at the arsenic concentration of 2 mg/L

IF (g/L)	Time (min)	Before	After
		X ± S.D	X ± S.D
0	5	34.35 ± 3.76	43.6 ± 3.93
	10	36.65 ± 2.52	50.86 ± 3.41
	15	39.8 ± 3.61	58.66 ± 4.53
2.5	5	61.3 ± 7.11	56.98 ± 7.35
	10	66.71 ± 4.71	63.1 ± 3.81
	15	65.58 ± 0.89	61.35 ± 3.77
5	5	63.18 ± 11.15	61.66 ± 6.18
	10	78.18 ± 5.69	70.48 ± 4.92
	15	90.75 ± 8.96	81.8 ± 6.06

$$2NaAsO_2 + Fe(OH)_2 \rightarrow Fe(AsO_2)_2 + 2NaOH \quad (5)$$

Based on the physicochemical Hall effect, when multi-atomic ions placed within a fluid pass through the external magnetic fields, the bond between the ions is weakened and they are dissociated, thus forming cations and anions. When the ionic species are placed in a magnetic field, a force called "Laplace–Lorentz force" is applied to the ions by the magnetic fields [5]. The maximum force happens when the magnetic field lines are perpendicular to the direction of the movement of ions [6]. The magnitude of this force depends on the following factors:

$$F = q \cdot v \cdot B \quad (6)$$

where F is the Lorentz force (Newton), q is the particle's charge (coulomb), v is the fluid or particle velocity (m/s), and B is the magnetic flux density (Tesla (T)).

As $NaAsO_2$ molecules of the samples without iron filings were passed through the magnetic fields according to

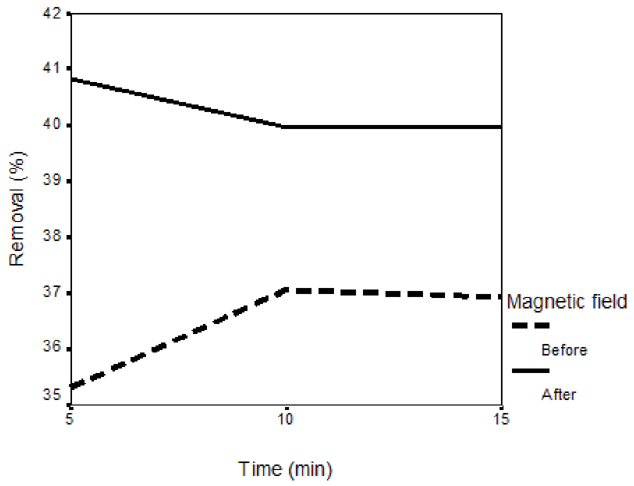

Fig. 2. Effects of the magnetic field on the arsenic removal efficiency vs. contact time based on iron filings dosage of 0 g/L.

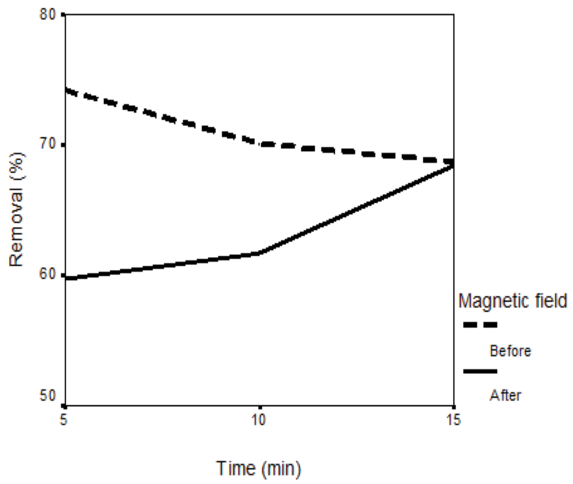

Fig. 3. Effects of the magnetic field on the arsenic removal efficiency vs. contact time based on iron filings dosage of 2.5 g/L.

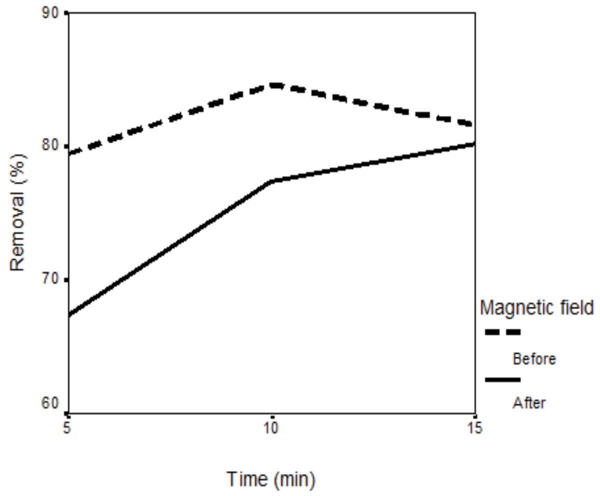

Fig. 4. Effects of the magnetic field on the arsenic removal efficiency vs. contact time based on iron filings dosage of 5 g/L.

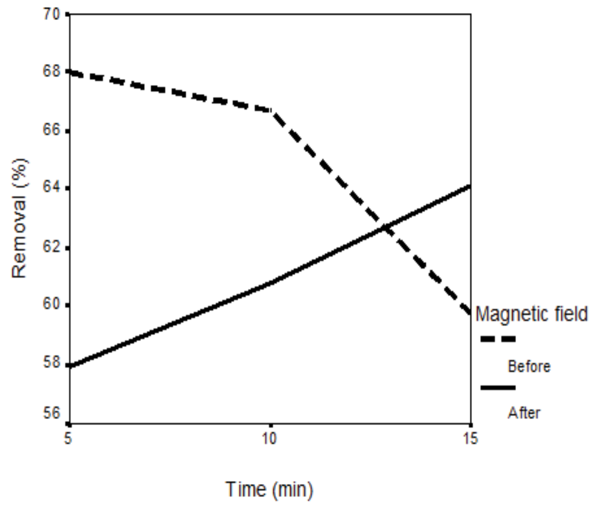

Fig. 5. Effects of the magnetic field on the arsenic removal efficiency vs. contact time based on the initial arsenic concentration of 0.5 mg/L.

the Hall effect, the sodium and arsenite ions were dissociated, and also according to Laplace–Lorentz force, AsO_2^- ions were moved and reacted with the ferric hydroxide formed on the surface of the spiral iron (Fig. 1). Accordingly, the arsenic level of the samples without iron fillings was reduced, because the AsO_2^- ions were reacted and captured by spiral iron (Fig. 2). Mixing the samples containing $NaAsO_2$ with iron filings at different contact times reduced the dissolved arsenic and consequently increased the removal efficiency. The arsenic-iron complexes were not detectable by ICP. Passing the samples through the magnetic column caused the separation of AsO_2^- ions from arsenic-iron complexes and the soluble arsenic was increased. The effect of magnetic fields on $NaAsO_2$ bonds by Laplace–Lorentz force is similar to an increase in temperature, which is the increase of the thermal motion of water constituents. According to the dynamic magnetic susceptibility of polyatomic molecules based on the deviation of the electron clouds from spherical symmetry, covalent bonding in $NaAsO_2$ molecule is considered to contribute to the paramagnetic term [15]. The thermal motion of the partially charged atoms of $NaAsO_2$ under the magnetic field gives rise to the Laplace–Lorentz force. The force will be exerted on the center of the polar molecule, and the direction of the force on the positive charge center is the opposite of the negative center, which results in the rotational motion of the charge center [16]. As a result, the positive and negative charge centers will be relocated, and the distance between them will become larger [17]. It must be pointed out that the energy of the covalent bond is very sensitive to the distance between the bonds between molecules. In other words, the interaction can weaken or partially break the covalent bonds of the $NaAsO_2$ molecules in aqueous solutions. Furthermore, the Laplace–Lorentz force causes the positive and negative ions to rotate oppositely, which

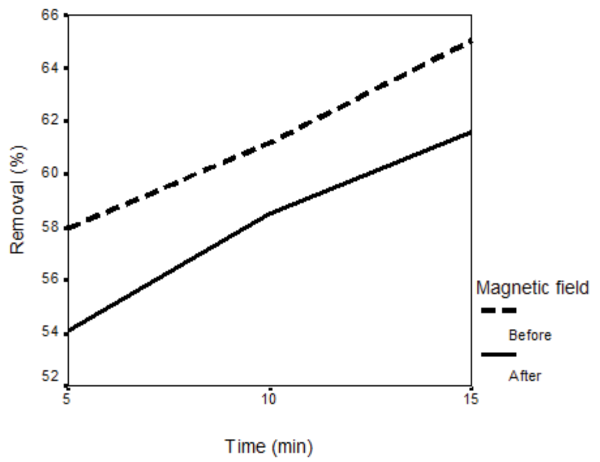

Fig. 6. Effects of the magnetic field on the arsenic removal efficiency vs. contact time based on the initial arsenic concentration of 2 mg/L.

increases the chances of collision between them [18]. Then, the movement of molecules becomes intense, and its thermal motion enhances. When the thermal motions of the contained molecules increase, covalent bonding becomes weaker. Also, the thermal motion is in equilibrium after sufficient magnetized time. Coey and Cass [10] explained that the magnetic fields might modify the local ionic concentrations via Lorentz force and Hall effect. Their study ionic concentration was increased [10]. Ma et al. [12] reported that the magnetic field can weaken the bond between the ions. In their study, fluid velocity was considered as 2 mm/s and the intensity of the magnetic field was considered as 0.4 T. In another study, Silva et al. [19] examined the effect of the magnetic field on ion hydration and sulfate deposit formation. The magnetic flux density was considered to be 1 T in their study. The results of their study showed that divalent cations are affected by the magnetic field more than monovalent and mono/divalent anions. It has not been definitively proven that magnetic water treatment can completely replace chemical treatment methods to prevent sediment formation, but this can substantially reduce the number of chemicals used in chemical water treatment. Furthermore, the mechanisms of magnetic water treatment that has been used practically for over a century are still not completely understood.

5. Conclusion

Magnetic water treatment helps avoid the use of chemicals, which can be detrimental to human life or distractive to the environment. The present study showed that magnetic forces can affect water impurities through mechanical trajectories and chemical interactions. The dissociation and dissolution of the ions in the process were due to the mechanisms of the Laplace–Lorentz force and the Hall effect. The results can be very encouraging and we can successfully use physical phenomena such as magnetic forces in the treatment of high-mineral waters in the future.

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