Electrochemical removal of chromium from aqueous solutions using electrodes of stainless steel nets coated with single wall carbon nanotubes

Yao-Xing Liu, Dong-Xing Yuan*, Jun-Mei Yan, Quan-Long Li, Tong Ouyang

State Key Laboratory of Marine Environmental Science, Environmental Science Research Center, Xiamen University, 421 Siming, Xiamen 361005, China

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ABSTRACT

An electrochemical technique was adopted to investigate the removal of Cr(VI) species and total chromium (TCr) from aqueous solution at a laboratory scale. The electrodes of stainless steel nets (SSNE) coated with single wall carbon nanotubes (SWCNTs@SSNE) were used as both anode and cathode. Three parameters, including solution pH, voltage and electrolyte concentration, were studied to explore the optimal condition of chromium removal. The optimal parameters were found to be pH 4, voltage 2.5 V and electrolyte concentration 10 mg/L. Under these conditions, the Cr(VI) and TCr removal had a high correlation with the amount of SWCNTs coated on the electrodes, with coefficients of the regression equations 0.953 and 0.928, respectively. The mechanism of Cr(VI) removal was also investigated. X-ray photoelectron spectroscopy (XPS) study and scanning electron microscope (SEM) picture showed that the process of chromium removal involved the reduction of Cr(VI) to Cr(III) on the cathode, and then the adsorption of Cr(III) by SWCNTs on the cathode. The study results indicated that the proposed method provided an interesting means to remove chromium species from aqueous solution, especially Cr(VI) in acidic condition.

1. Introduction

Chromium is widely used in the industries of electroplating, metal finishing, magnetic tapes, pigments, leather tanning, wood protection, chemical manufacturing, brass, electrical and electronic equipment and catalysis [1]. Large amount of wastewater containing chromium has been discharged into the environment from various industry processes. Chromium compounds mainly exit in the environment as forms of Cr(VI) and Cr(III), and threaten natural life and public health for their non-degradable, mutagenic and carcinogenic properties [2]. Cr(VI) has a significant mobility in water body for its high solubility, and is generally considered 500–1000 times more toxic than Cr(III) [3]. Exposure to Cr(VI) may cause health problems of epigastria, nausea, vomiting, severe diarrhea, internal hemorrhage, dermatitis, liver and kidney damage [4]. Long time contamination with Cr(VI) can result in digestive tract and lung cancers [2]. On the other hand, Cr(III) has a lower solubility in water and is readily to precipitates as $Cr(OH)_3$ under alkaline to slightly acidic conditions [5]. As an essential trace element form in mammalian metabolism, Cr(III) has effective function for reducing blood glucose levels, and is often offered to diabetes sufferers [1]. However, long time exposure to excessive doses of Cr(III) may also cause some adverse health effects [6]. Thus environmental regulations usually define limitation values for both total chromium TCr (Cr(VI), Cr(III) and other forms of chromium) and Cr(VI) concentrations in waters. According to the United States Environmental Protection Agency (USEPA), the permitted concentration of Cr(VI) and TCr discharged to surface water should be less than 0.05 mg/L and 0.1 mg/L [7]. Based on this criterion, almost all the wastewater produced by the plants that use chromium during industrial process needs to be treated before being discharged into the environment.

Up to now, numerous treatment methods have been studied to remove chromium from wastewater, such as reduction [8], chemical precipitation [9], ion exchange [10,11], membrane separations [12,13], electrochemical precipitation [14], ultrafiltration [15], flotation [16], electrocoagulation [17], solvent extraction [18], sedimentation [19], reverse osmosis [20] and adsorption [21,22]. Chemical precipitation is traditionally the most used method, including hydroxide precipitation, sulfide precipitation, carbonate precipitation and phosphate precipitation. Although these methods are quite satisfactory in terms of removing chromium from water, the rising problem is the production of solid residue, e.g. sludge. Generally the final disposal of the sludge is land filling with relative high costs and a possibility of polluting ground water.

Electrosorption with different carbon material electrodes is a novel technique for removing dissolved inorganic contaminants such as radionuclides, metal ions, and anions from aqueous solutions [23–25]. It is generally regarded as potentially induced

* Corresponding author. Tel.: +86 0592 2184820; fax: +86 0592 2184820.
E-mail addresses: yxliu19830218@xmu.edu.cn (Y.-X. Liu), yuandx@xmu.edu.cn (D.-X. Yuan).

adsorption on the surface of charged electrodes. After voltage supplied on both electrodes, ions in the water solution can move towards the oppositely charged electrode under the imposed electric field. And once the electric field is removed, the ions will quickly withdraw back to the solution. The electrosorption capacity of electrodes have close relation with two factors [26]. The first one is the electrical double-layer capacity due to the electrostatic attraction force between the ions and the electrode. This capacity is mainly affected by the ion concentration in the solution and the applied voltage on the electrodes. The second factor is pseudocapacity induced by faradic reactions, which depend on the chemical characteristic of the solute and the functional groups on the electrode surface.

In the past a few years, various researchers have used different materials as electrodes in the electrochemical reactors. Conductive materials such as carbon aerogel [27], graphite and stainless steel [28], vitreous carbon [29] have been used for heavy metal removal. The conventional activated carbon and carbon aerogel electrodes often use some polymeric binders to hold the carbon particles together, however, the polymeric binders can occlude fractions of the activated carbon surface and increase the electrical transfer resistance [30,31].

In this research, stainless steel net (SSN) electrodes coated with single wall carbon nanotubes (SWCNTs) were used to study the feasibility of chromium removal from aqueous solution. The SSN were used because of its unique thermal, mechanical and electrical properties. SWCNTs are an excellent electrode material for electrosorption because of their low electrical resistively, high specific surface area. Bonders were not necessary for preparing the SSN electrodes (SSNE) coated with SWCNTs (SWCNTs@SSNE), and thus the problems that encountered in conventional activated carbon and carbon aerogel electrodes could be avoided.

2. Materials and methods

2.1. Reagent and materials

Na_2SO_4, H_2SO_4, NaOH, $KMnO_4$ and N,N-dimethylformamide of analytical grade were supplied by Sinopharm Chemical Reagent Co. (Shanghai, China). $K_2Cr_2O_7$, $NaNO_2$ and urea of analytical grade were supplied by Xilong Chemical Co. (Shantou, China). Ultra pure water (18.2 MΩ/cm) was obtained from an ultra-pure water system (Unique-R30, Research Scientific Instruments Co., China). SWCNTs were purchased from Institute of Solid State Physics of Chinese Sciences Academy (Hefei, China). The SSN of 40 meshes with wire diameter of 0.2 mm was purchased from the local store.

2.2. The electrolysis cell

The experiment was carried out in a laboratory scale in a lab-made Plexiglas cell, with 8.0 cm in length, 6.5 cm in height and 4.0 cm in width. The sketch diagram of the experimental set up is shown in Fig. 1. An electrochemical analytical instrument (CHI630B, Shanghai Chenhua Instrument Co., China) was used to supply voltage and record signal. SWCNTs@SSNE was used as both cathode and anode, and a saturated calomel electrode (SCE) was used as a reference electrode to keep the stability of the applied voltage. The solution was stirred constantly with a magnetic stirrer (JBZ-14, Shanghai Kang-Yi Instruments Co., China) to maintain the electrolyte in the solution homogenously. The experiments were performed at room temperature. Each sample of 1 mL for chromium analysis was obtained from the electrolysis cell at regular time intervals.
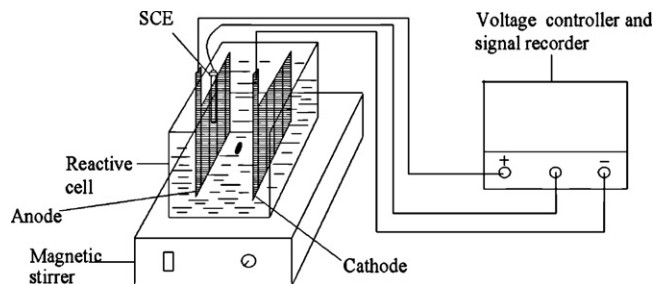

Fig. 1. The sketch of experimental setup.

2.3. Preparation of SWCNTs and SWCNTs@SSNE

The SSN was cut into 4.5 cm × 6.5 cm (Fig. 2A) and rinsed with sulfuric acid solution (1:10, v/v) to wash the dirt on the surface. Electrophoretic deposition method based on the work of Li et al. [32] was adopted for preparing SWCNTs@SSNE. SWCNTs of 1.0 g were refluxed in 60 mL nitric and sulfuric mixture acid solution (1:3, v/v) at 130 °C for 45 min. The mixture was washed to pH 7 with ultra pure water. After centrifuging, the SWCNTs were dried in a constant temperature blast airer (DHG-9146A, Shanghai Jing-hong Instrument Co., China). Then 500 mg treated SWCNTs in 200 mL dimethylformamide were ultrasonically dispersed at 300 W and 40 kHz. A suspended solution containing 2.5 mg/mL of SWCNTs was obtained after 48 h. Two pieces of clean SSN, one used as cathode and the other as anode, were parallel immersed into the suspension of SWCNTs. The distance between the two SSNs was kept at 2.5 cm. A direct current voltage of 40 V was applied and a SWCNTs deposit began to appear on the SSN anode. Then the SSN anode was taken from the suspension and dried at 120 °C to remove the solvent, and
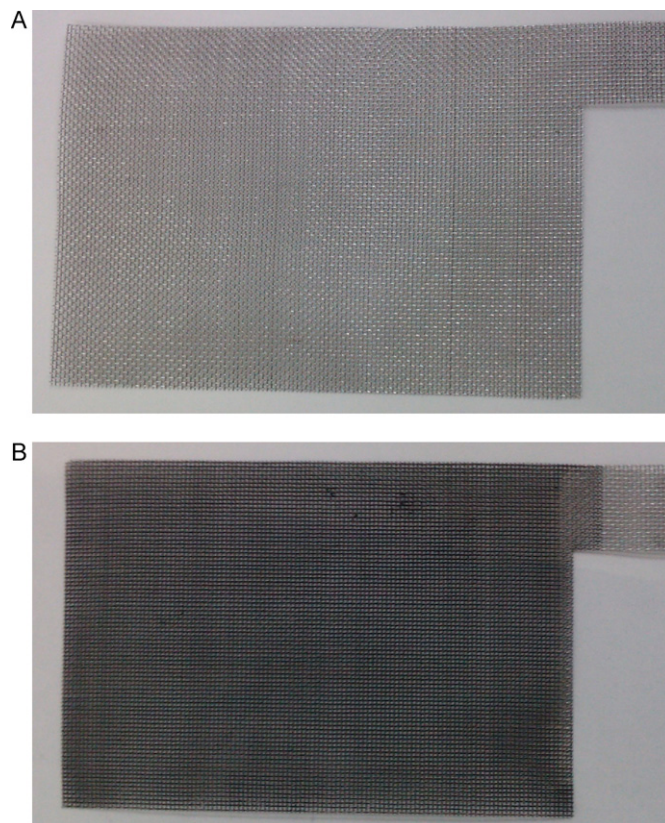

Fig. 2. Pictures of SSN before and after SWCNTs deposition: (A) before deposition and (B) after deposition.
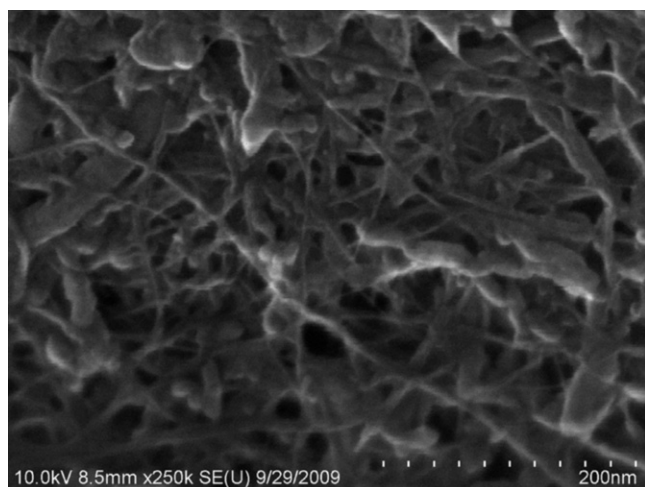
Fig. 3. SEM picture of the SWCNTs@SSNE surface.

a SWCNTs@SSNE was thus prepared (Fig. 2B). As shown in Fig. 2B, it was found that SWCNTs had an even distribution on the surface of SSN.

2.4. Characteristic of the electrode SWCNTs@SSN

Scanning electron microscope (SEM, S4800, Hitachi Co., Japan, operated at 10.0 kV) picture of SWCNTs@SSNE surface is shown in Fig. 3, from which threadlike SWCNTs are clearly observed. The pole size, length and specific surface area of SWCNTs were 1–2 nm, 5–30 μm and higher than 380 m^2/g, respectively. It was reported [33] that the pore size of CNTs was mainly micropores and mesopores. The micropores were important for adsorption of ion, and the mescopores could been regarded as the ions transportation route [33].

Oxygen-contained functional groups such as carboxyl and hydroxyl were introduced onto the surface of SWCNTs during the acid treatment [32]. In addition, the SWCNTs@SSNE was negatively charged due to the occurrence of carboxylic groups.

2.5. Analytical methods

The Cr(VI) and TCr were determined with a spectrophotometer (723PC, Shanghai Spectrum Instruments Co., China) according to the standard method [34]. The concentration of Cr(III) in solution was calculated as the difference between TCr and Cr(VI) concentrations. The amount of SWCNTs deposited on the electrode was calculated by the weight different of the electrode before and after electrophoretic deposition. The X-ray photoelectron spectroscopy (XPS) of the electrodes was analyzed on a PHI Quantum 2000 Scanning Electron Spectroscopy for Chemical Analysis Microprobe (Physical Electronic Co., USA) equipped with an Al K$_a$ radiation. The enlarged spectra in the Cr$_{2p3/2}$ regions were measured with the pass energy of 20 eV and the step-width of 0.125 eV. The binding energies were referred to C$_{1S}$ peak from the adventitious contamination layer during the testing process.

2.6. Electrosorption process

A stock solution of Cr(VI) (1000 mg/L) was prepared by dissolving a certain amount of K$_2$Cr$_2$O$_7$ in ultra pure water. The Cr(VI) solution of desired concentration for the experiment was obtained by diluting the stock solution with ultra pure water. Na$_2$SO$_4$ was used as supporting electrolytes. The pH of the solution was adjusted with a pH meter (UB-7, Denver Instrument, USA) using NaOH or

H$_2$SO$_4$ solution. The experiments were carried out on the condition of pH 4, voltage 2.5 V, solution volume 200 mL, electrode distance 3 cm, electrolyte concentration 10 g/L, unless elsewhere indicated.

3. Results and discussion

The electrosorption process can be affected by several operating parameters, such as solution initial pH, applied voltage, concentration of supporting electrolytes and amount of SWCNTs coated on the electrode. In the study these parameters were, respectively, investigated for optimization of the electrosorption performance. Samples were obtained after voltage being applied for 0, 10, 20, 30, 45, 60, 90, 120, 180, 240 min, respectively. A new generated SWCNTs@SSNE would be used in every set of electrosorption experiment to avoid the error due to the carryover from the used electrode.

3.1. Mechanism of Cr(VI) removal

Cr(VI) solution was prepared by dissolving K$_2$Cr$_2$O$_7$ in water, thus in the solution there were three types of Cr(VI) anionic species, Cr$_2$O$_7^{2-}$, HCrO$_4^-$ and CrO$_4^{2-}$, and their proportion depended on pH. Three forces, convection, electromigration and diffusion, led the ions in the electrolytic cell move onto the electrode surfaces.

When the electrolytic cell had only SSNEs, it was found that Cr(VI) concentration was kept almost the same as the original after the electrosorption process. The Cr(VI) anionic species, drawn by the electromigration force, moved onto the anode but could not undergo any further oxidation process. However, by convection and diffusion forces Cr(VI) species might also move towards the cathode, where they were reduced to Cr(III) especially in acidic solution. As to Cr(III) species, according to chromium pe-pH relationship diagram [35], Cr^{3+}, Cr(OH)$^{2+}$, Cr(OH)$_2^+$, Cr(OH)$_4^-$ and CrO$_2^-$ are the main forms of Cr(III), depending on pH. Cr(III) cations may move towards the cathode, where only few can be reduced to metallic chromium with critical condition. Anionic Cr(III) species would easily reach the anode under the force of electromigration, and should be oxidized to Cr(VI). Therefore, an equilibrium was built between the reduction and oxidation, resulting in equilibrium between Cr(VI) and Cr(III) concentrations with Cr(VI) as the dominating species.

Once the electrolytic cell was equipped with SWCNTs@SSNEs, SWCNTs would adsorb some ions thus shift the equilibrium mentioned above. Two different adsorption phenomena, electrical double-layer and chemical adsorption, can be observed during the electrosorption. Acid treated SWCNTs, with large amount of surface area and carboxyl and hydroxyl functional groups [32], have great tendency to bond cations. With the application of voltage an electrical double-layer can be formed on the SWCNTs@SSNEs, and the attraction due to both electromigration and chemical absorption on the different electrodes towards the corresponding ions is different. On SWCNTs@SSN anode the anionic Cr(VI) species would be partly repelled by the carboxyl and hydroxyl groups on the SWCNTs, while on SWCNTs@SSN cathode the cationic Cr(III) species will be adsorbed. If pH is between 4 and 6, Cr(OH)$^{2+}$ and Cr(OH)$_2^+$ are formed according to the chromium pe-pH relationship diagram [35]. Those cationic species would move onto the cathode under the electrical attraction, where they react with carboxyl and hydroxyl functional groups on the SWCNTs thus deposit on the SWCNTs@SSN cathode. Therefore, as the electrolysis time increases, the concentration of chromium in the cell solution should be decreased. The chromium redox reaction on the SWCNTs@SSNEs is illustrated in Fig. 4.

In this study, when the electrolytic cell was equipped with SSN anode and SWCNTs@SSNE cathode, the electrosorption of
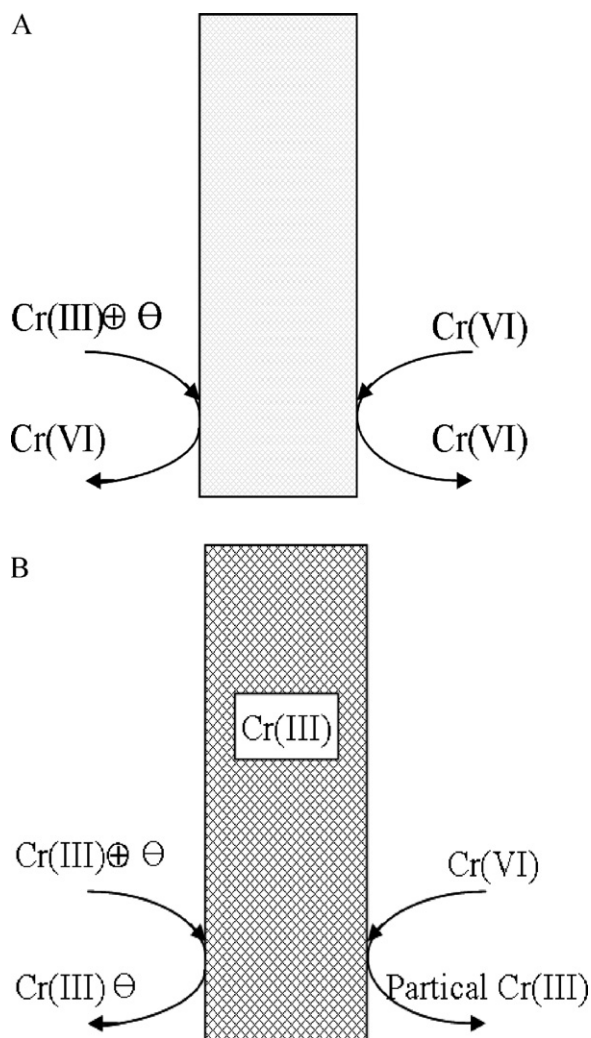
Fig. 4. The sketch diagram of chormium redox reaction on the SWCNTs@SSNEs: (A) anode and (B) cathode.

Fig. 5. SEM pictures of the SWCNTs@SSNEs after electrosorption: (A) anode and (B) cathode.

chromium could also be observed on the cathode. Moreover, the chromium removal efficiency from the solution in this setup was the same as with both SWCNTs@SSNE.

The SEM pictures of anode and cathode electrodes are shown in Fig. 5. From the pictures, it can be found that the surface of SWC-NTs@SSN anode (Fig. 5A) is nearly the same as that shown in Fig. 3, indicating that there was no either Cr(VI) or Cr(III) on the anode. On the other hand, on the surface of SWCNTs@SSN cathode (Fig. 5B), large amount of deposition could be observed.

In order to confirm that no chromium species were on SWC-NTs@SSNE anode but the cationic Cr(III) species were adsorbed on SWCNTs@SSNE cathode, XPS, a powerful instrument for identification of element and its valent state, was adopted to characterize the surfaces of the electrodes. The results showed that there was no $Cr_{2p3/2}$ peak on the cathode. However, as illustrated in Fig. 6, an obvious $Cr_{2p3/2}$ peak was found on the cathode.

Comparing the binding energy of the $Cr_{2p3/2}$ peak (577 eV) with the standard binding energy in $Cr_{2p3/2}$ regions (Fig. 7 [36]), it can be concluded that the chromium on the cathode was trivalent. This result further confirmed that the Cr(VI) in the solution was reduced to Cr(III) during the electrosorption process. No atomic $Cr_{2p3/2}$ peak is shown in Fig. 6, revealing that Cr(III) on the cathode was not further reduced to elemental chromium.
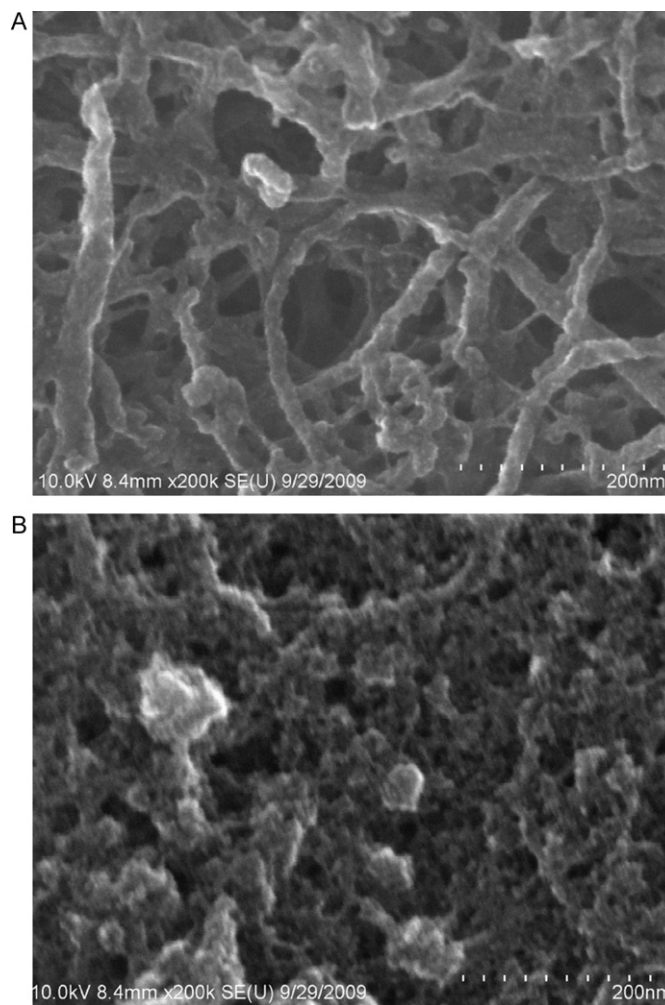
3.2. Effect of pH on chromium removal

From the equilibrium shown in (1) and (2), it is well known that the redox reaction of Cr(VI)/Cr(III) is pH dependent. The higher the
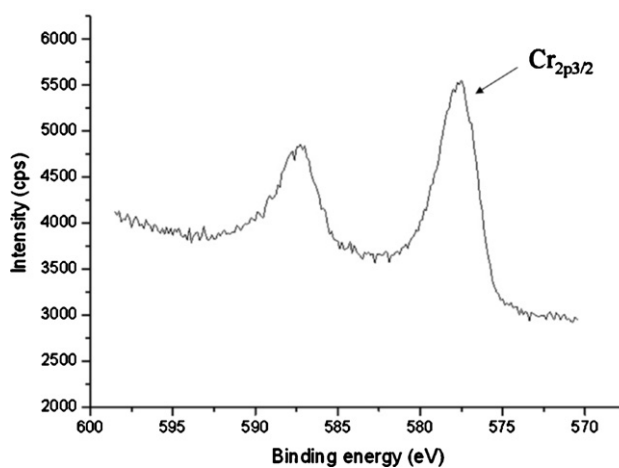

Fig. 6. XPS spectrum of chromium on the cathode SWCNTs@SSNEs after electrosorption.
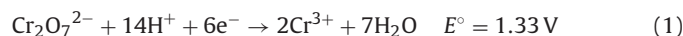
Fig. 7. Chromium element standard binding energy image in $Cr_{2p3/2}$ regions.

Table 1
Cr(III) concentration in solution before and after electrosorption at pH less 4 (mg/L).

pH	Raw solution	After electrosorption
3.50	0.18	0.71
3.00	0.51	2.00
2.50	0.51	8.29
2.25	0.44	9.23
2.00	0.61	9.85

acidity is, the stronger the oxidative ability will be.

$$Cr_2O_7^{2-} + 14H^+ + 6e^- \rightarrow 2Cr^{3+} + 7H_2O \quad E^\circ = 1.33\,V \quad (1)$$

$$HCrO_4^- + 7H^+ + 3e^- \rightarrow Cr^{3+} + 4H_2O \quad E^\circ = 1.35\,V \quad (2)$$

The effect of solution pH on chromium removal was studied with different solution pH adjusted to 5.00, 4.50, 4.00, 3.50, 3.00, 2.50, 2.25, and 2.00, with a separated electrode for each solution, respectively. The results about Cr(VI) and Cr(III) removal are shown in Fig. 8A and B, respectively.

From Fig. 8A, it is found that Cr(VI) was well removed under all the tested pH conditions except for pH 5.00. The removal efficiencies of Cr(VI) were all over 99.9%, within pH 2.00–4.50. Removal speed of Cr(VI) increased with the decreasing of pH. As shown in Fig. 8B, the maximum TCr removal rate of 96.9% was attained at pH 4.00. According to chromium pe-pH relationship diagram [35], at pH 4.00, and pe between −4 and 14, Cr(III) exists mostly as $Cr(OH)^{2+}$, while with the increasing pH, Cr(III) can be further hydrolyzed to $Cr(OH)_2^+$ and $Cr(OH)_3$. Therefore at a higher pH less positive charged $Cr(OH)_2^+$ species could be less remained on the cathode to react with carboxyl and hydroxyl anionic groups. Moreover, since Cr(VI) is less likely to be reduced to Cr(III) at higher pH (Eqs. (1) and (2)), thus lower TCr removal was obtained at pH 5.00 compared with that at pH 4.00.

With pH less than 4.00, Cr(III) can form a hydrated complex $Cr(H_2O)_6^{3+}$ through the reaction with H_2O in aqueous solution [37]. The larger $Cr(H_2O)_6^{3+}$ species may block its own way to be adsorbed on the cathode, resulting in its higher concentration in the solution. Table 1 shows the Cr(III) concentration of solution before and after electrosorption with pH less than 4.00. From Table 1, it can be seen that the Cr(III) concentration in solution after electrosorption was higher than that in the raw solution.

In Fig. 8B, it is interesting to see that TCr concentration exceeded the original TCr in untreated solution when pH ≤ 2.5. The stainless steel net inside the SWCNTs@SSNs could be the source of chromium. When voltage was applied on the electrolysis cell, as an important composing element chromium in the stainless steel net of the electrode was oxidized under the strong acidic condition, causing higher concentration of TCr in the solution.
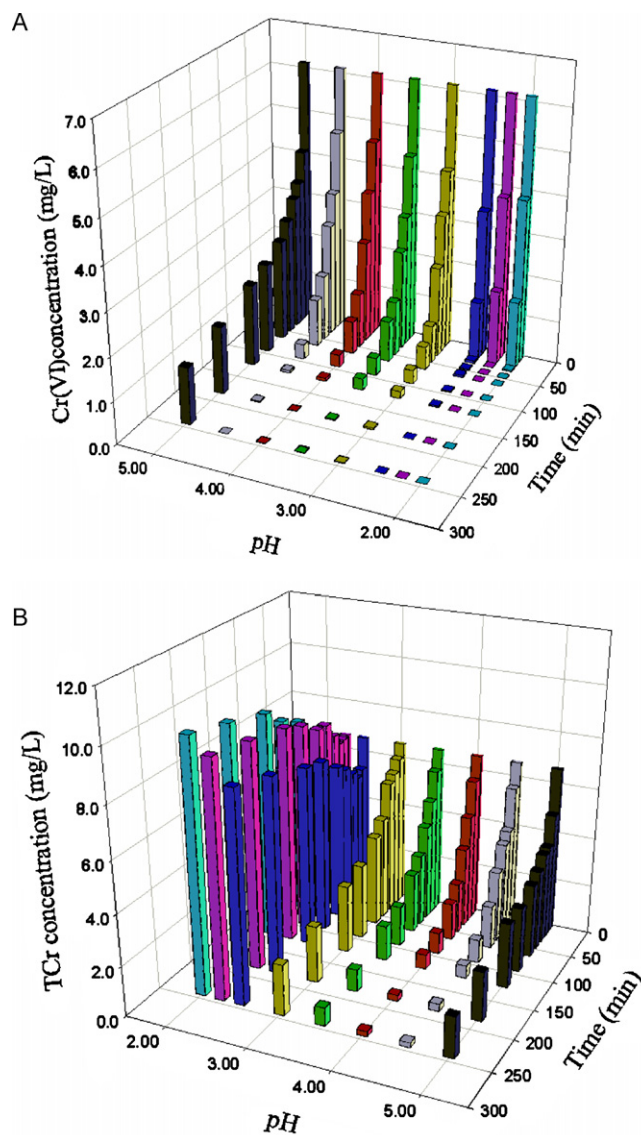

Fig. 8. Effect of pH on chromium removal: (A) Cr(VI) and (B) TCr. Electrosorption conditions: voltage 2 V, electrolyte concentration 6.7 g/L, the SWC-NTs weight on the SWCNTs-SSNE 6.02 ± 0.08 mg ($n = 8$), original Cr(VI) concentration 6.13 ± 0.19 mg/L ($n = 8$), and original TCr concentration 6.59 ± 0.13 mg/L ($n = 8$).

3.3. Effect of applied voltage on chromium removal

The effect of applied voltage on the chromium removal was investigated. The results are plotted in Fig. 9. The two figures clearly show that the maximum Cr(VI) and TCr removal efficiency were achieved at higher voltage, e.g. the concentration of Cr(VI) and TCr decreased from 6.35 mg/L to 0.03 mg/L (removal efficiency 99.6%) and from 6.41 mg/L to 0.17 mg/L (removal efficiency 97.4%), respectively, at voltage 2.5 V. However, only 7.8% Cr(VI) and 6.5% TCr were removed at voltage 1 V.

With the increase of voltage, the flow velocity of electrons is increased and the electrostatic attraction becomes greater. Moreover, at higher voltage the functional groups of carboxyl and hydroxyl on the SWCNTs@SSNE become more active to possess higher sorption ability, resulting in an increase of the chromium removal.

3.4. Effect of electrolyte concentration on chromium removal

The effect of electrolyte concentration on the chromium removal was studied with Na_2SO_4. The results shown in Fig. 10
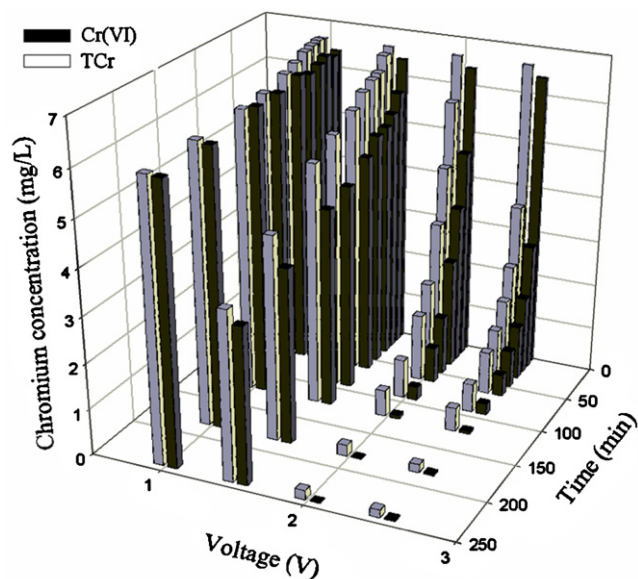
Fig. 9. Effect of applied voltage on Cr removal.
Electrosorption conditions: electrolyte concentration 6.7 g/L, SWCNTs weight coated on the electrodes 6.04 ± 0.11 mg ($n = 8$), original Cr(VI) concentration 6.39 ± 0.10 mg/L ($n = 4$), and original TCr concentration 6.63 ± 0.14 mg/L ($n = 4$).
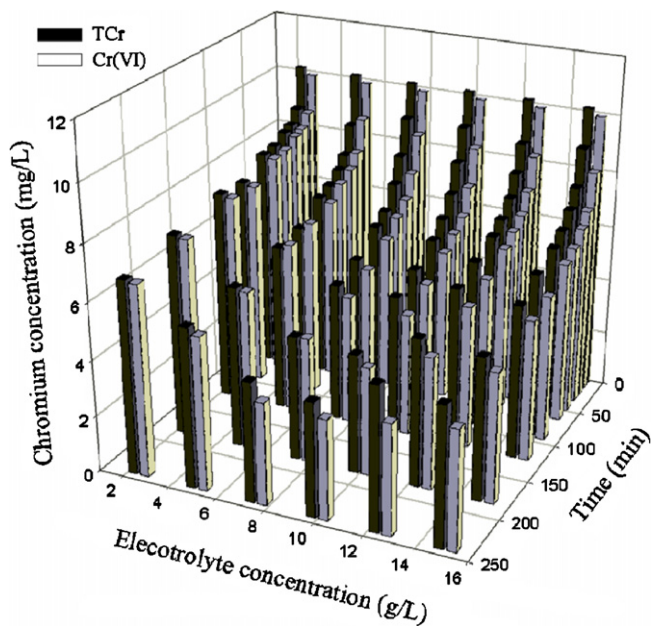

Fig. 10. Effect of electrolyte concentration on Cr removal.
Electrosorption conditions: original Cr(VI) concentration 9.90 ± 0.31 mg/L ($n = 6$), original TCr concentration 10.13 ± 0.17 mg/L ($n = 6$), and SWCNTs weight on electrodes 5.5 ± 0.12 mg ($n = 6$).

indicate that Cr(VI) and TCr had the highest removal efficiency at the electrolyte concentration 10.0 g/L. When the electrolyte concentration less than 10.0 g/L, the removal efficiency of Cr(VI) and TCr enhanced as the electrolyte concentration increased. When the electrolyte concentration was higher than 10.0 g/L, the tendency of removal efficiency was opposite.

Under the applied pH and voltage, the removal efficiency of Cr(VI) was closely relative to two factors, i.e., electron flow velocity and the rate of Cr(VI) species reaching the cathode surface. The electron flow velocity has a positive correlation with the electrolyte concentration in a certain range. The cathode had higher ability to reduce Cr(VI) with higher electrons flow velocity. On the other
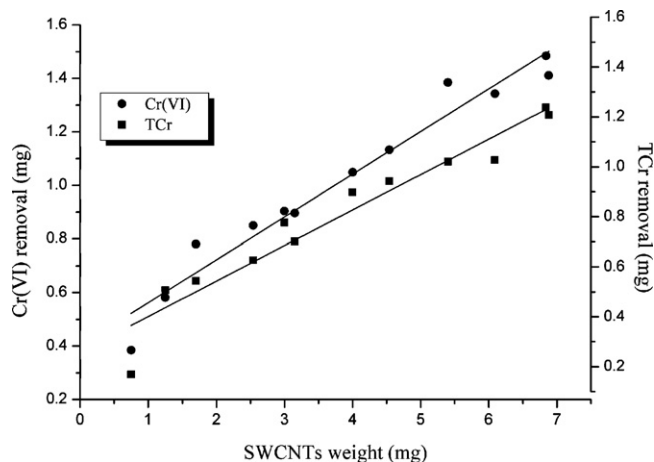

Fig. 11. The relationship between chromium removal and SWCNTs weight on the electrode.
Electrosorption conditions: original Cr(VI) concentration 9.56 ± 0.24 mg/L ($n = 12$), original TCr concentration 9.64 ± 0.36 mg/L ($n = 12$), and volume of solution 180 mL.

hand, however, more electrolyte cations would be attracted to the cathode with the increasing of the electrolyte concentration, resulting in a difficulty for Cr(VI) species to reach the cathode. Hence, the Cr(VI) removal efficiency should be a combined result of the electron flow velocity and the ability of Cr(VI) species reaching the cathode. When the electrolyte concentration was less than 10.0 g/L, the dominating factor to control the Cr(VI) removal was electron flow velocity; Cr(VI) removal was increased as the electrolyte concentration increased. If the electrolyte concentration was higher than 10.0 g/L, Cr(VI) removal decreased with the increasing of the electrolyte concentration, because less Cr(VI) species to reach the cathode became the dominating factor, which was due to more electrolyte cations around the cathode.

3.5. The relationship between chromium removal and amount of SWCNTs coated on the electrode

Twelve electrodes on which different amount of SWCNTs coated were used to remove chromium from a set of solutions with same concentration of Cr(VI) and TCr, respectively, in order to investigate the effect of amount of SWCNTs on the removal efficiency. The SWCNTs weight on the electrodes varied from 0.75 mg to 6.88 mg. The relationships between the amounts of SWCNTs coated on the electrodes and the removals of Cr(VI) and TCr are shown in Fig. 11. As the amounts of SWCNTs on the electrodes increased, the amount of Cr(VI) removal increased from 0.335 mg to 1.412 mg (removal efficiency 33.8–86.3%), and the TCr removal varied from 0.169 mg to 1.208 mg (removal efficiency 9.71–71.3%).

The regression equations between Cr(VI)/TCr removal and the amount of SWCNTs on the electrode are as the follows:

$$Y_1 = 0.160X + 0.403, \quad R^2 = 0.953 \tag{3}$$

$$Y_2 = 0.142X + 0.259, \quad R^2 = 0.928 \tag{4}$$

where Y_1 and Y_2 are the amount of Cr(VI) and TCr removal (mg), respectively. And X is the SWCNTs weight (mg) on the electrode. From Eqs. (3) and (4), it can be seen that both Cr(VI) and TCr removal had high correlation with the amounts of SWCNTs on the electrodes. The reason for chromium removal increasing with the amount of SWCNTs increasing could be that more SWCNTs on the cathode can provide more active sites for adsorption of Cr(III) species. Cr(VI) species removal was slightly higher than TCr removal, because not every Cr(III) pieces reduced could be adsorbed by SWCNTs on the electrodes.

Table 2
The comparison of electrodes features.

Electrode	Polymer binder	Regeneration	Capacity (mg/L)	References
Carbon aerogel	Yes	Yes	Ca: 1.16	[39]
CNTs-CNFs film	Yes	Yes	Cu: 10.24	[40]
CNTs-CNFs film	Yes	–	Na: 22.0	[41]
Carbon cloth	–	Yes	Mo: 5.67 Cr: no removal	[42]
Carbon cloth	–	Yes	SCN⁻: 127.0	[43]
SWCNTs-SSN	No	Yes	Cr: 180.8	This study

3.6. Electrode desorption and regeneration

Desorption helps to regenerate the electrode, as well as to recover deposited chromium from the electrodes. A reverse voltage was applied on the SWCNTs@SSN cathode to desorb the Cr(III). With the conditions of voltage −2.5 V, pH 4, electrode distance 3 cm and original Cr(VI) concentration 10 mg/L, the desorption rates of Cr(VI) 92.3% and TCr 94.9% were obtained. The electrosorption process had been carried out in a new Cr(VI) solution of concentration 10 mg/L with the regenerated electrode, and the result indicated that the chromium removal was about the same as that with a new electrode. This electrical desorption method provides several advantages among which the most important ones are no secondary waste generated and no additional reagent needed. On the other hand, in other conventional technologies, some strict methods are needed to recover the adsorbents. For example, in ion exchange the regeneration of used resin requires concentrated solutions of salt, acid or base [38].

3.7. Comparison with other electrodes

The characteristics of the SWCNTs@SSNE and some other electrodes were compared. The features, including with/without polymer binder in electrode preparing, possible regeneration, and adsorption capacity, are summarized in Table 2.

4. Conclusion

The proposed electrolysis cell equipped with SWCNTs@SSNE has a high efficiency to remove chromium from aqueous solution. It can be regarded as a potential technique to treat chromium wastewater. Some preliminary conclusions from this study are provided as follows:

1. The parameters of pH, voltage and electrolyte concentration have significant effects on chromium removal.
2. The mechanism of chromium removal is deduced as that Cr(VI) is reduced to Cr(III), and afterwards some Cr(III) cations are adsorbed onto the cathode coated with SWCNTs.
3. Chromium removal efficiency is highly correlated with the weight of SWCNTs on the cathode.

Acknowledgement

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