Chemical Engineering Journal 260 (2015) 749–756

Contents lists available at ScienceDirect

Chemical Engineering Journal

journal homepage: www.elsevier.com/locate/cej

Heavy metal ions removal from metal plating wastewater using electrocoagulation: Kinetic study and process performance

Mohammad Al-Shannag [a], Zakaria Al-Qodah [b,*], Khalid Bani-Melhem [c], Mohammed Rasool Qtaishat [a], Malek Alkasrawi [d]

[a] Chemical Engineering Department, Faculty of Engineering and Technology, The University of Jordan, 11942 Amman, Jordan
[b] Chemical Engineering Department, Taibah University, Saudi Arabia
[c] Department of Water Management and Environment, Faculty of Natural Resources and Environment, Hashemite University, Al-Zarqa, Jordan
[d] Department of Paper Science and Engineering, Faculty of Natural Resources, University of Wisconsin Stevens Point, Stevens Point, WI 54481, USA

HIGHLIGHTS

- High removal of heavy metal ions from metal plating wastewater using EC treatment.
- Pseudo first-order kinetic model describes heavy metal ions removal adequately.
- Electrocoagulation time and DC current density are the key parameters in EC process.
- Metal plating wastewater treatment by electrocoagulation is economically rewarding.

ARTICLE INFO

Article history:
Received 15 July 2014
Received in revised form 8 September 2014
Accepted 9 September 2014
Available online 21 September 2014

Keywords:
Electrocoagulation
Heavy metal ions
Metal plating wastewater
Iron electrodes

ABSTRACT

The main objective of the present study was the removal of heavy metal ions, namely Cu^{2+}, Cr^{3+}, Ni^{2+} and Zn^{2+}, from metal plating wastewater using electrocoagulation technique. An electro-reactor was used with six carbon steel electrodes of monopolar configurations. Three of the electrodes were designated as cathodes meanwhile the other three as anodes. The results showed that the removal efficiency of heavy metal ions increases with increasing both electrocoagulation (EC) residence time and direct current (DC) density. Over 97% of heavy metal ions were removed efficiently by conducting the EC treatment at current density (CD) of 4 mA/cm^2, pH of 9.56 and EC time of 45 min. These operating conditions led to specific energy consumption and specific amount of dissolved electrodes of around 6.25 kWh/m^3 and 1.31 kg/m^3, respectively. The process of metal plating removal using EC consumes low amount of energy, making the process economically feasible and possible to scale up. Moreover, the kinetic study demonstrated that the removal of such heavy metal ions follows pseudo first-order model with current-dependent parameters.

1. Introduction

Metal plating industry is one of the major chemical processes that discard large amounts of wastewaters. These industrial wastewaters contain various types of harmful heavy metals and toxic substances such as chromium, nickel, copper, zinc, cyanide and degreasing solvents [1]. Numerous approaches such as physical, chemical and biological processes including adsorption, biosorption, precipitation, ion-exchange, reverse osmosis, filtration and other membrane separations are employed to treat wastewaters [2]. Precipitation of heavy metals in an insoluble form of hydroxides is the most effective and economical method to treat heavy metals wastewater. The main idea of precipitation method is to adjust the pH of wastewater and to add chemical coagulants like aluminum or iron salts to remove pollutants as colloidal matter [3]. The precipitation typically occurs according to the following reaction:

$$M^{+n}_{(aq)} + nOH^{-}_{(aq)} \leftrightarrow M(OH)_{n(s)} \quad (1)$$

Although the chemical coagulation technique is considered to be effective in treating industrial wastewater effluents, it has quite high cost. On the other hand, the addition of chemical coagulants to the wastewater may produce side-products that are considered as secondary pollutants [4]. Alternatively, electrocoagulation (EC)

* Corresponding author. Tel.: +966 560948161.
E-mail addresses: z_alqodah@hotmail.com, zqudah@taibahu.edu.sa (Z. Al-Qodah).

http://dx.doi.org/10.1016/j.cej.2014.09.035
1385-8947/

was found to be an effective technique for precipitating industrial wastewater pollutants [5,6]. The simplicity of EC operation, low energy consumption, high quality effluent, low sludge formation and low dissolved solids made electrocoagulation a desirable treatment method [5,7,8].

In electrocoagulation process, no chemicals are added to form coagulant agents. Basically, wastewater solution is subjected to a direct electrical (DC) current field through sacrificial electrodes (cathodes and anodes) that are generally made of iron or aluminum [1,5,6]. Though it is traditional to use solid flat electrodes, cylindrical perforated ones are adopted in some previous studies to have better distribution of the applied DC field onto the wastewater treated [9,10]. Due to electrical potential difference between cathodic and anodic electrodes in electrocoagulation, water is oxidized to produce hydrogen ions (H^+) and oxygen gas and the metal oxidation will generate its cations. Simultaneously, water reduction occurs at the cathode to generate hydroxyl ions (OH^-) and hydrogen gas. For iron-iron electrodes, as in the present study, two ferric hydroxides, $Fe(OH)_2$ and $Fe(OH)_3$ are produced according to the following electrolytic reactions [11,12]:

$$Fe_{(s)} \leftrightarrow Fe^{2+}_{(aq)} + 2e^- \quad (2)$$

$$2H_2O_{(1)} + 2e^- \leftrightarrow H_{2(g)} + 2OH^-_{(aq)} \quad (3)$$

$$Fe^{2+}_{(aq)} + 2HO^-_{(aq)} \leftrightarrow Fe(OH)_{2(s)} \quad (4)$$

$$\underline{\text{Overall :}}\ Fe_{(s)} + 2H_2O_{(1)} \leftrightarrow Fe(OH)_{2(s)} + H_{2(g)} \quad (5)$$

$$4Fe_{(s)} \leftrightarrow 4Fe^{2+}_{(aq)} + 8e^- \quad (6)$$

$$8H^+_{(aq)} + 8e^- \leftrightarrow 4H_{2(s)} \quad (7)$$

$$4Fe^{2+}_{(aq)} + 10H_2O_{(1)} + O_{2(s)} \leftrightarrow 4Fe(OH)_{3(s)} + 8H^+_{(aq)} \quad (8)$$

$$\underline{\text{Overall :}}\ 4Fe_{(s)} + 10H_2O_{(1)} + O_{2(s)} \leftrightarrow 4Fe(OH)_{3(g)} + 4H_{2(s)} \quad (9)$$

The generated ferric hydroxide flocs serve as coagulant agents that can precipitate various wastewater pollutants. It is reported that Fe(III) hydroxide coagulants are more effective than Fe(II) hydroxide due to the higher stability of $Fe(OH)_3$ [13]. There are many physiochemical phenomena involved in electrocoagulation that can be summarized as [6]: (i) anodic oxidation and cathodic reduction, (ii) generation and migration of flocculating agents in the aqueous phase (iii) coagulation and adsorption of pollutants on flocculating agents and (iv) electroflotation or sedimentation of coagulated aggregates. In order to achieve optimal treatment effectiveness, the chemical/physical properties of wastewater must be monitored during the EC operation.

Electrocoagulation has been successfully applied for the treatment of different types of wastewater generated from municipal wastewater [4,10], pulp and paper mill industries [12,14], olive mills [15], textile processing [16], potato chips manufacturing [17], baker's yeast production [18] and pigments industries [13,19]. Several studies have proved the high efficiency of electrocoagulation in the removal of heavy metal ions from industrial/synthesis wastewater [1,20–22]. Unlike these studies, the present work investigated simultaneous removal of chromium (Cr^{3+}), copper (Cu^{2+}), nickel (Ni^{2+}) and zinc (Zn^{2+}) ions from metal plating wastewater using electrocoagulation (EC) technique. In addition, a kinetic study was conducted for the first time to describe the removal rates of heavy metal ions. The impact of EC time, direct current density, pH and electrical conductivity (σ) on the heavy metal ions removal by electrocoagulation was investigated. Finally, the consumption levels of both electrical energy and electrode material were assessed at different operating conditions to demonstrate qualitatively the cost-effective features.

2. Materials and methods

2.1. Experimental setup

Fig. 1 shows the schematic diagram of the electrocoagulation (EC) laboratory scale setup. The EC reactor was constructed from Pyrex glass with dimensions of 120 mm × 112 mm × 89 mm. Iron (carbon steel) plates were used as sacrificial electrodes, arranged in monopolar configurations. Six electrodes were positioned vertically with spaces of 15 mm. Three plates were connected as cathodes and the other three as anodes. The plates have rectangular geometry with the dimensions of 45 mm × 53 mm × 3 mm. The total effective surface area of electrodes immersed in wastewater solution was around 247.5 cm^2. The electrodes were connected to a direct current (DC) power supply providing voltage in the range of 0–30 V and electrical current in the range of 0–6 A. During electrocoagulation experiments, the solution was agitated continuously using mechanical mixer (Stuart Scientific, UK) with rotational speed of about 1000 rpm.

2.2. Experimental procedure

The metal plating wastewater samples were collected from the Union Locks Company/Sayegh Group located in the region of Abu-Alanda, Amman, Jordan. The physical and chemical characteristics of the metal plating wastewater used in this study are listed in Table 1. The EC reactor shown in Fig. 1 was filled with nearly 600 ml of the wastewater solution to run out the electrocoagulation experiments. The DC was adjusted to give the desired current density (CD) which is defined as the ratio of the applied direct current to the total effective surface area of electrodes. After each experiment, the EC reactor was rinsed with diluted HCl, followed by frequent distilled water washes. Before analyzing the concentrations of the heavy metal ions, the original and treated

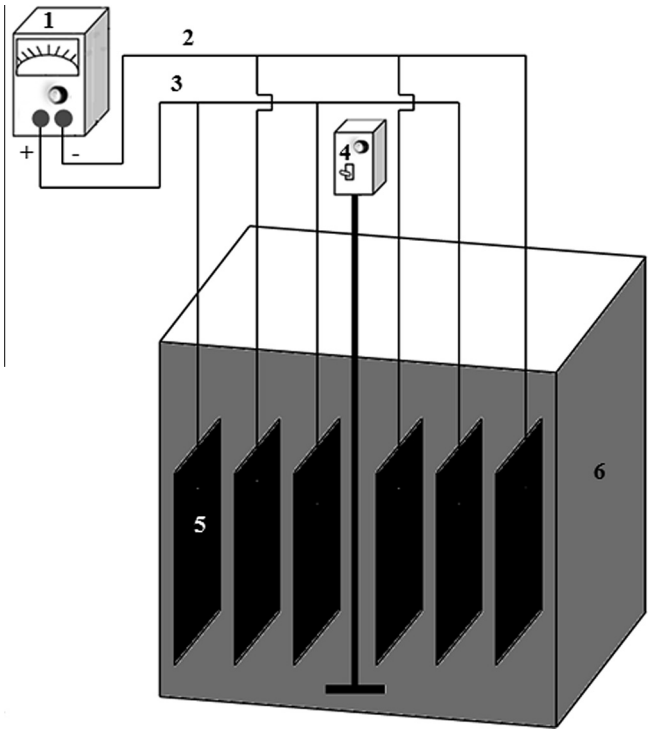

Fig. 1. Schematic diagram of experimental setup: (1) DC power supply; (2) cathode; (3) anode; (4) mechanical stirrer; (5) carbon steel electrodes; (6) EC reactor.