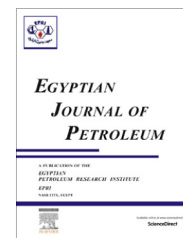




Egyptian Petroleum Research Institute  
Egyptian Journal of Petroleum

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FULL LENGTH ARTICLE

# Electrodeposition of copper from a copper sulfate solution using a packed-bed continuous-recirculation flow reactor at high applied electric current



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Received 26 March 2014; accepted 22 June 2014

Available online 23 July 2015

## KEYWORDS

Copper removal;  
Packed-bed;  
Flow reactor;  
Current efficiency;  
Energy consumption

**Abstract** The purpose of this study is mainly to investigate the performance of a packed-bed continuous-recirculation flow reactor at high applied electric current in removing copper, Cu(II), from simulated electrolyte by electrodeposition. The effects of pH<sub>0</sub>, circulation rate of flow, initial copper concentration, intensity of the applied current and the method of application of electric current, as to have a constant value during all the time of electrolysis or to be decreased with time, on copper electrodeposition and current efficiency are revealed. The results showed that the increase in pH (provided not lead to the deposition of Cu(OH)<sub>2</sub>), initial concentration of the copper and flow rate increased the electrodeposition of copper as well as improved current efficiency. However, increasing intensity of the applied electric current led to an increase in the electrodeposition of copper and decreased electrical efficiency. It was also observed that reducing the intensity of applied electric current with time during the electrolysis process while maintaining other operating variables constant led to a significant reduction in the consumption of electrical energy used in the process of copper removal by electrodeposition; a reduction of 41.6% could be achieved.

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## 1. Introduction

Wastewaters containing heavy metal ions arise during some industrial activities. Unlike organic contaminants, heavy

metals are not biodegradable and tend to accumulate in living organisms, and many heavy metal ions are known to be toxic or carcinogenic. The effects of such chemical pollutants in the environment are not limited to ourselves, but may be passed on to future generations by way of genetic mutations, birth defects, inherited diseases and so on [1]. Heavy metals of particular concern include copper nickel, mercury, cadmium, lead, and chromium.

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Peer review under responsibility of Egyptian Petroleum Research Institute.

<http://dx.doi.org/10.1016/j.ejpe.2015.07.009>

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The metal ions are effectively removed from dilute solution using different techniques; Fenglian and Wang [2] reviewed the methods that have been used to treat heavy metal wastewater and evaluated these techniques. Electrochemical techniques are uniquely capable of recovering pure metal for recycle and can be considered a relatively simple and clean method. These techniques were reviewed by Walsh and Reade [3]; they focused on how to select an appropriate cell design. Also, Guohua Chen [4] reviewed the development, design and applications of electrochemical technologies in water and wastewater treatment with a special focus on electrodeposition, electrocoagulation, electroflotation and electrooxidation.

Copper is a valuable metal and an essential element used by man; it is unique in its use as electrical conductor. The price of copper is getting higher, and the production cost is increasing. Waste streams from some industrial processes such as copper electroplating industries and textile industries are contaminated with copper to the level of 500 ppm (mg/L) or more. Substantial savings of copper can be obtained by recovering copper from waste streams.

Researchers with various cell designs have attempted removal of copper from solutions with varying degrees of achievements and improvements [5–18]. All of these researches were done keeping either the applied potential or the applied current constant during an experimental run and none of them used sodium chloride as supporting electrolyte. The effect of initial pH of treated electrolyte on removal of copper, via electrodeposition, and current efficiency, unfortunately, in these researches has not received the attention that it deserves. Few investigators considered the effect of initial pH. Chin [18] reported that during electrolysis the pH decreased from an initial value of 6–7 to a final value around 3. Issabayeva et al. [10], used two initial values of pH (3 and 5), observed that the initial pH value affected both the removal and current efficiencies during electrodeposition of copper and they reported that the pH significantly increased for a short time and decreased thereafter to around a value of 3. Basha et al. [1] studied the electrodeposition of copper at different initial pH values but they did not follow how the pH changed during electrolysis. Yaqub et al. [11] investigated the electrolytic removal of Cu and Pb at different pH conditions and reported that the optimum pH range was 3–3.5 in the presence of ultrasound enhancement.

No doubt that rate of flow of electrolyte has an effect on the electrolytic removal of copper. This effect depends on the mode of operation, i.e. single-pass or multiple-pass. For single-pass mode [6,7,12], the removal was reported to decrease with increasing flow rate as long as the bed height was held constant; this means that less residence or retention time. For multiple-pass, keeping constant bed height [5,16,17], the removal increased with increasing flow rate; which is interpreted by increasing the residence time. For current efficiency, some authors [7] reported that the current efficiency decreased with an increase in hydraulic retention time.

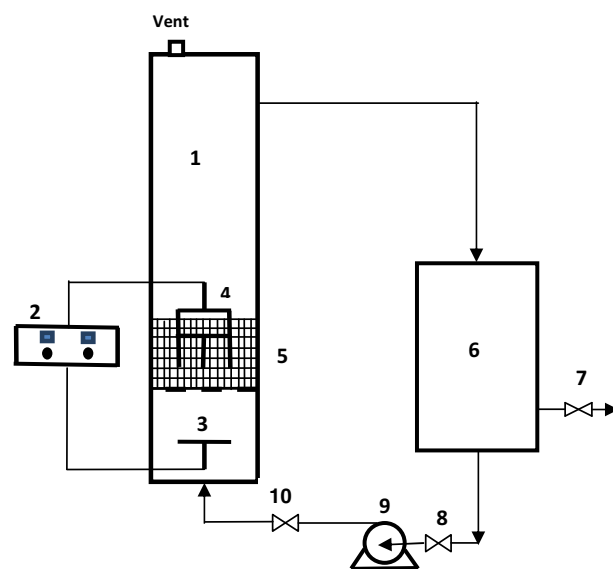
The work herein investigated the cathodic reduction of copper ions on a fixed bed of carbon particles in a continuous-recirculation flow reactor at high applied electric current. The effects of initial pH value, electrolysis time, flow rate and applied current on copper electrodeposition and current efficiency were carefully investigated.

## 2. Experimental

Fig. 1 is a schematic representation of the experimental setup. The cylindrical column was made from acrylic, to enable better visualization of the process. The inside diameter and the height were 10 cm and 70 cm, respectively. A height of 70 cm was enough to give a sufficient disengagement height to allow for any entrained carbon particles to separate from the treated solution leaving the column so that the mass of the bed was kept constant. The column is separated by a flow distributor into upper and lower parts. The distributor, perforated acrylic plate, had holes of 1 mm diameter arranged in equilateral triangular configuration of 5 mm pitch. The upper surface of the distributor was covered with a porous polyethylene membrane to enhance better flow distribution.

The counter electrode, had a disk shape of 5 cm diameter, was fixed in the lower part of the column while the working electrode (carbon bed) was in the upper part. The current feeder to the packed bed was cup-shaped opened from the lower side and the upper side is covered with a perforated disk; the holes had 1 cm diameter and arranged in equilateral triangular configuration of 1.5 cm pitch; this is to facilitate the upward flow of the treated solution and to permit the escape of generated gases on the bed surface. The cup was supplied with 6 additional legs, of 5 cm length and 1 cm width, to give good contact with the particulate-bed. Both current feeder and counter electrode were made of 316 Stainless Steel.

The packed bed material was prepared by grinding carbon pieces of high purity (as analyzed by XRD), and collecting the sieved fractions of 1–4 mm diameter particles; the average particle size was 2.5 mm. The particles were washed with nitric acid and distilled water and packed to an initial dry height of 6 cm.



**Figure 1** Schematic representation of the experimental setup (1) Column, (2) Power supply, (3) Counter electrode (anode), (4) Current feeder, (5) Carbon bed, (6) electrolyte reservoir; (7) Sampling valve, (8) Flow regulating valve, (9) Centrifugal pump (10) Flow regulating valve.

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