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Mass transfer characteristics of reciprocating screen stack electrochemical reactor in relation to heavy metal removal from dilute solutions

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Abstract

Rates of mass transfer were measured for copper deposition from dilute acidified copper sulphate solution on reciprocating arrays of separated and closely packed screens by the limiting current technique under different conditions of amplitude, frequency of oscillation and copper ion concentration. The mass transfer data for the diffusion controlled copper deposition at the limiting current from a solution of constant concentration were correlated by the equations:

$$j_D = 0.732 Re_v^{-0.35}$$

for the closely packed screen array, and

$$j_D = 0.98 Re_v^{-0.38}$$

for the separated screen array.

A mathematical model based on the surface renewal theory was found to agree fairly with the above equations. Study of the removal of copper by constant current electrolysis at the limiting current using an insoluble lead anode has shown that the reactor is capable of reducing copper ion concentration below the maximum permissible value in a time which depends on the operating conditions.

The potential of using the present reactor for processing sparingly soluble reactants such as immiscible organic liquids, organic solids and gases which need to be dispersed prior to reacting at the electrode was highlighted. Also the possibility of using oscillating screen array as a catalytic reactor suitable for conducting liquid–solid diffusion controlled catalytic reactions such as removal of organic pollutants from industrial effluents by wet oxidation was noted.

Keywords: Mass transfer; Copper deposition; Electrochemical reactor; Vibration; Water pollution

1. Introduction

Increasing awareness of the risks associated with hazardous chemical waste disposal is causing governments to implement stricter environmental legislation to prevent pollution and environmental damage by industrial waste. Industrial waste water containing toxic ions represents a challenging case owing to the difficulty of removing these ions by biodegradation. Furthermore, some heavy metals such as Pb, Cu, Hg and Cr inhibit or prevent the oxidation of organic waste by bacteria [1]. Pollution by toxic metals including Cd, Cu, Cr, Pb, Hg and Zn is generated by a wide range of manufacturing industries such as mining, metal finishing, printed circuit fabrication and metallurgical industries. Recently, with the advent of high space-time yield electrochemical reactors, the electrochemical technique has proved to be a very powerful tool for removing heavy metals from waste solutions. In many cases the technique was found to be superior to other techniques such as chemical precipitation, ion exchange and cementation [2–4]. The technique is gaining a growing acceptance by industry in view of the fact that it does not only diminish the toxic ion concentration to the safe level but also it allows recovery of precious

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Nomenclature

a	amplitude of oscillation
$á$	constant
A	cathode area
C	concentration of Cu^{2+}
C_b	bulk concentration of Cu^{2+}
C_i	interfacial concentration of Cu^{2+}
C_0	initial concentration of Cu^{2+}
d	cylinder diameter
d_h	hydraulic diameter of the screen
d_w	screen wire diameter
D	diffusivity of Cu^{2+}
f	frequency of oscillation
F	Faraday's constant
i_L	limiting current density
I_L	limiting current
j_D	mass transfer factor ($St{\cdot}Sc^{0.67}$)
K	mass transfer coefficient
K_0	mass transfer coefficient without vibrationt
K_c	mass transfer coefficient obtained from the constant current electrolysis
L	vertical plate height
N	rate of copper deposition
Q	volume of the solution in the reactor
t	time
t_r	contact time
u	velocity component parallel to the mass transfer surface
V	solution velocity past a stationary cylinder or screen
V_r	instantaneous relative velocity between a sinusoidal vibrating plate and solution
V_v	vibrational velocity ($V_v = 2\pi fa$)
x	distance parallel to the mass transfer surface
y	distance perpendicular to the mass transfer surface
Re	Reynolds number for stationary cylinders and screens in cross flow ($\rho Vd/\mu$)
Re_v	vibrational Reynolds number ($\rho V_v d_h/\mu$)
$Re_{v,w}$	vibrational Reynolds number based on wire diameter ($\rho V_v d_w/\mu$)
Sc	Schmidt number ($\mu/\rho D$)
Sh	Sherwood number (Kd_w/D)
St	Stanton number (K/V_v)

Greek letters

α, β	proportionality constants
μ	solution absolute viscosity
ρ	solution density
ω	angular velocity ($2\pi f$)

metals such as Ag, Au and Cu. For the usually small concentrations of metal ions in waste waters, cathodic deposition of metals such as Cu, Ag, Zn, Pb and Cd is diffusion controlled [2–6], and hence, the rate of metal deposition, N, is given by [7,8]:

$$N = \frac{I_L}{ZF} = KAC \quad (1)$$

The above equation shows that to obtain a high rate of metal removal from such a dilute solution the electrochemical reactor should have a high mass transfer coefficient or a high surface area or both. Some electrochemical reactors satisfying the above criteria have been developed and used successfully in industry for waste water treatment. These reactors include three-dimensional electrodes such as the fluidized bed electrode and the fixed bed electrode, and two-dimensional electrodes such as the rotating cylinder electrode [2–6].

In view of the high specific area and the high turbulence promoting ability of woven screens, the present work aims at exploring the possibility of using oscillating horizontal arrays of separated and closely packed screens electrochemical reactors in removing and recovering heavy metals from dilute solutions such as industrial effluents and leach liquors resulting from leaching low grade ores. The present study was carried out using copper deposition in view of its industrial importance. The performance of the suggested reactor was evaluated by determining (i) the reactor mass transfer behaviour using the well-known limiting current technique [7], and (ii) the extent to which the reactor can reduce Cu^{2+} concentration by constant current electrolysis under different operating conditions. In earlier reports [9,10], the mass transfer behaviour of oscillating horizontal single screen and array of screens was studied by measuring the limiting current of the cathodic reduction of $K_3Fe(CN)_6$. The authors correlated their data for single screen by an equation which shows that the mass transfer coefficient increases with the 0.33 power of the vibrational velocity. For vibrating screen array, the deviation from the single screen behaviour was presented without data correlation. The authors used an amplitude ranging from 0.25 to 1.5 cm while the frequency range was limited to 0.75–5 Hz. The results of the present study are expected to differ from the early study on vibrating horizontal screens [9,10] not only because of the difference in the range of experimental conditions but also because the metal depositing system used in the present work may induce surface roughness and significant natural convection compared to the ferri-ferrocyanide system used in the earlier study.

Apart from metal deposition, the present reactor is also suitable for processing systems involving sparingly soluble reactants such as electro-organic synthesis using immiscible liquid organic reactants or sparingly soluble solid particle reactants. In this case the oscillating screen array would efficiently disperse the reactant in the aqueous phase beside acting as an electrode [11,12]. The reactor is also suitable for electrochemical processing of gaseous reactants, e.g., flue gas desulphurisation where SO_2 is first absorbed in aqueous solution and then anodically oxidized to H_2SO_4 [13]. In this case the oscillating screen array would enhance the gas–liquid mass transfer [14] and the liquid–solid mass transfer simultaneously.

Previous studies on the use of screens in building electrochemical reactors of high space-time yield include gas sparged screens [15,16], rotating horizontal single and array of circular