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Mass transfer at a rotating tubular packed bed of woven screens in relation to electrochemical and catalytic reactor design

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ABSTRACT

The mass transfer behavior of a rotating tubular packed bed of woven screens was studied using an electrochemical technique which involved measuring the limiting current of the cathodic reduction of potassium ferricyanide in a large excess of supporting electrolyte. Variables studied were bed rotation speed, bed thickness and mesh number of the woven screen. The mass transfer coefficient was found to increase with increasing bed rotation speed and mesh number but decreases with increasing bed thickness. The data for rotating screen bed were correlated by the dimensionless equation:

$$Sh = 4.85Sc^{0.33}Re^{0.32}\left(\frac{d_h}{d}\right)^{-0.25}$$

The mass transfer coefficient at single rotating screen cylinder was found to be higher than that of rotating packed bed of screens. Both rotating single and packed bed of screens gave higher volumetric mass transfer coefficient than smooth rotating cylinder. Implication of the present results for the design and operation of electrochemical and catalytic reactors suitable for conducting liquid–solid diffusion controlled reactions such as photocatalytic reactions and immobilized enzyme catalyzed biochemical reactions was highlighted.

1. Introduction

The rotating cylinder electrochemical reactor is one of the most important reactors which has been used widely in practice for processing dilute solutions such as those encountered in waste water treatment and electroorganic synthesis where diffusion controlled reactions are involved [1–11]. The widespread use of the reactor is attributed to merits such as the high mass transfer coefficient, the uniform current and potential distribution, the low floor space occupied by the reactor and the possibility of continuous operation at low feed rate in order to increase the residence time, the high rate of mass transfer and the high residence time would increase the degree of conversion per pass. However the reactor suffers from a limited active area which limits its productivity. Some attempts have been carried out to improve the reactor volumetric mass transfer coefficients (kA) by increasing its mass transfer coefficient and its active area via using finned [1] and rough rotating cylinders [2–7]. To benefit from the high turbulence promoting ability and the high specific area of woven screens Grau and Bisang [12–14] and Bazan and Bisang [15] used 3 dimensional rotating cylinder made of packed bed of screens and expanded metal to increase the space time yield of the reactor, the authors used a counter electrode wire coil surrounding the rotating packed bed. The authors examined the performance of the rotating packed bed in heavy metal removal [14,15] and found out that their reactor gave mass transfer coefficient three times higher than that of smooth rotating cylinder under the same conditions. The disadvantage of the 3 dimensional electrodes is the high potential drop inside the porous matrix [16], this gives rise to nonuniform current and potential distribution inside the rotating porous bed. The lack of potential and current distribution leads to loss of yield and selectivity especially in case of electroorganic synthesis [16].

The aim of the present work is to study the mass transfer behavior of a rotating tubular packed bed of closely spaced screens with two counter electrodes to improve current and potential distribution in the bed, a cylindrical counter electrode was placed in the center of the bed and another cylindrical screen counter electrode surrounds the bed (Fig. 1). The two counter electrodes can be made in the form of a helical coils to serve as a cooler in case of highly

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Nomenclature

A	cathode (rotating cylinder screen) area, cm^2
a	constant
b	constant
C	concentration of Cu^{++} at time t, mol cm^{-3}
C_b	bulk concentration of ferricyanide ions, mol cm^{-3}
C_o	initial concentration of Cu^{++}, mol cm^{-3}
D	diffusivity of transferring ions, $cm^2\ s^{-1}$
d	mean bed diameter ($d = \frac{d_i + d_o}{2}$), cm
d_i	inner bed diameter, cm
d_o	outer bed diameter, cm
d_h	screen hydraulic diameter ($d_h = \frac{\in}{\emptyset}$), cm
d_e	Equivalent diameter, cm
F	Faraday's constant (96500 Coulomb mol^{-1})
I_L	limiting current, A
I	current, A
k	mass transfer coefficient, cm s^{-1}
k_c	mass transfer coefficient at constant current electrolysis, cm s^{-1}
L	cylinder length, cm
n	Rotation speed, (r p s)
Q	Volume of the solution in the reactor, cm^3
V	average linear velocity, cm s^{-1}
Re	Reynolds number $\frac{\rho n d^2}{\mu}$
Sc	Schmidt number ($\frac{\mu}{\rho D}$)
Sh	Sherwood number ($\frac{Kd}{D}$)
μ	solution viscosity, g $cm^{-1}\ s^{-1}$
ρ	solution density, g cm^{-3}
$\in$	screen volumetric porosity
$\emptyset$	screen specific surface area

exothermic electrochemical or catalytic reactions which need temperature control. The present reactor can be used for conducting liquid- solid diffusion controlled catalytic reactions such as photocatalytic reactions where TiO_2 catalyst can be fixed on the surface of the woven screens forming the rotating bed, biochemical reactions catalyzed by immobilized enzymes and other catalytic reactions involving organic compounds such as organic synthesis and wet oxidation to remove organic pollutants from waste solutions. The mass transfer behavior of rotating tubular packed bed of screens was studied by measuring the limiting current of the cathodic reduction of $K_3Fe(CN)_6$ [17]. In order to test the applicability of the mass transfer correlation obtained from the ferricyanide data to reactions such as heavy metal removal from dilute solutions where complications such as surface roughness and gas evolution may arise, the mass transfer behavior of the present reactor during the galvanostatic (constant current) deposition of copper from dilute $CuSO_4$ solution was also studied.

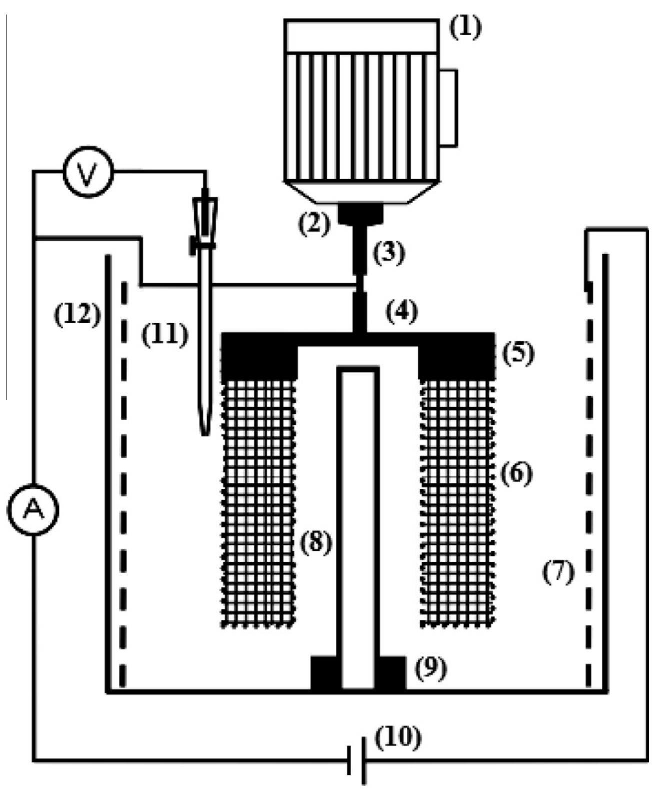

Fig. 1. Apparatus. (1) Motor, (2) Plastic sleeve, (3) Isolated steel shaft, (4) Strip of metal (stainless steel) welded to the screen, (5) Isolated part, (6) Rotating tubular fixed bed of closely rolled woven screens, (7) Stainless steel screen anode, (8) Stainless steel cylinder anode, (9) Plastic cavity, (10) d.c power supply, (11) Luggin tube, (12) Plexiglass tank.

2. Experimental technique

The apparatus (Fig. 1) consists of the cell and the electrical circuit, the cell was a 4 L plexiglass cylindrical container of 15 cm diameter and 25 cm height with a rotating tubular packed bed of woven screens cathode and two anodes, a central stainless steel rod anode of 2.5 cm diameter and 15 cm height and a cylindrical woven stainless steel anode surrounding the cathode. The cathode was built of a number of coaxial closely packed layers of vertical screen cylinders which ranged from 1 to 7. The tubular cathode has an inner diameter of 5 cm and a height of 10 cm, screens were made of Ni plated stainless steel. The geometric characteristics of the screens used are shown in Table 1. The cathode was connected to the shaft of a variable speed motor by means of a stainless steel holder which consisted of a horizontal rectangular strip of stainless steel of the dimensions 3 × 7 cm (3 mm thickness) with a vertical stainless steel shaft welded at its center. The two ends of the strip were welded to the upper edge of the tubular cathode wall while the shaft of the holder was connected to the shaft of the variable speed motor through a plastic sleeve. The stainless steel strip cathode holder and the upper part of the cathode were insulated by epoxy. The lower part of the inner rod anode was connected to the outer anode by an insulated electrical wire resting on the cell bottom (not shown in the figure). The inner rod anode was fixed in position by fitting its lower end in a plastic circular cavity in the cell bottom.

The electrical circuit consisted of 12 volt d.c power supply with a built-in voltage regulator, a multirange ammeter connected in series with the cell, a voltmeter was connected in parallel with the cell to measure its voltage in case of galvanostatic copper

Table 1
Geometric parameters of the screens used in the present work.

Mesh number	Wire diameter, cm	Aperture, cm	Volumetric porosity	Hydraulic diameter, cm
20	0.0356	0.084	0.767	0.117
10	0.05	0.2	0.823	0.236
5	0.01	0.25	0.9	0.32