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Mass and heat transfer behavior of a rough vertical vibrating cylinder in relation to annular electrochemical and catalytic reactor design

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ABSTRACT

Rates of mass transfer were measured at a vibrating rough (V threaded) vertical cylinder by the electrochemical technique. Variables studied were frequency and amplitude of oscillation, and degree of surface roughness. The rate of mass transfer at the rough vibrating cylinder was found to increase by a factor ranging from 2.75 to 6.1 compared to the smooth vibrating cylinder depending on the operating conditions. In general the enhancement ratio increases with increasing Re_V especially at high amplitudes; for low amplitudes it passes through a maximum and then decreases with further increase in Re_V. The data for oscillating rough cylinder were correlated by the equation:

$$Sh_L = 0.535\ Sc^{0.33} Re_{V.L}^{0.5} \left(\frac{e}{P}\right)^{0.67}$$

A mathematical model based on the surface renewal theory was found to correlate the present data with a standard deviation of 7.29%. Implications of the present study for the design and operation of high space time yield annular catalytic and electrochemical reactors used to conduct diffusion controlled reactions was noted. Also the importance of the present results to the design and operation of annular dialyzers using corrugated vibrating cylindrical membrane was highlighted.

1. Introduction

The annular geometry owes its attraction in building electrochemical and catalytic reactors to two attributes, namely: (i) the current and potential distribution are uniform on the inner cylinder [1,2], this is a highly desirable property especially in electroorganic synthesis where a high degree of selectivity is needed to avoid producing byproducts along with the main product thus obviating the need for costly purification processes, and (ii) cooling water can be passed through the inner surface of the inner tube and through a cooling jacket surrounding the outer surface of the outer tube to absorb excess heat generated during the reaction, this feature is highly needed in case of producing heat sensitive products or using heat sensitive catalysts such as immobilized enzymes. Despite the above merits the annular reactor suffers from limited active area which decreases its space time yield in case of diffusion controlled liquid–solid catalytic and electrochemical reactions. This shortcoming can be remedied by increasing the rate of mass transfer. The use of turbulent flow to increase the rate of mass transfer controlled reactions not only increases the pumping power but also reduces the residence time and the degree of conversion per pass. Other methods of enhancing the rate of mass transfer in the annular reactor which allow low feed rate and high residence time have been studied such as gas stirring [3,4], swirl flow [5], cylinder rotation along with axial flow [6], pulsating flow superimposed on steady flow [7,8] and particulate turbulence promoters [9]. In line with this trend the aim of the present work was to study the combined effect of surface roughness and electrode vibration on the rate of mass transfer at the inner cylinder of an annular electrochemical reactor. To this end an electrochemical technique which involves measuring the limiting current of the cathodic reduction of $K_3Fe(CN)_6$ in a large excess of supporting NaOH was used [10]. Although much work has been done on the effect of active surface roughness on the rate of heat and mass transfer in steady flow [11–19], no study has been reported on the combined effect of active surface roughness and vibration on the rate of heat or mass transfer, only the combined effect of inert turbulence promoters in the form of transverse plastic ribs (baffles) and oscillating flow has been studied [20–28]. Nishimura et al. [29,30] studied the effect of pulsatile flow on the rate of mass

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Nomenclature

A	geometrical cathode area (πdL)
a	amplitude of oscillation
C_o	bulk concentration of reactant
C_i	interfacial concentration of reactant
D	diffusivity of ferricyanide ions
d	cylinder diameter
e	peak to valley height of the roughness element, cm
F	Faraday's constant (96,500 Coulomb per equivalent)
f	frequency of oscillation
I_L	limiting current
k	mass transfer coefficient
$\acute{k}$	mass transfer coefficient based on the true area
L	active cylinder height
P	pitch (distance between successive roughness peaks)
V	average solution velocity
V_V	vibration velocity ($2\pi af$)
V_x, V_y	solution velocity in the x and y directions respectively
x	distance in the direction of flow
y	distance perpendicular to the direction of flow
z	number of electrons involved in the reaction
$Re_{V,e}$	vibrational Reynolds number $\left(\frac{\rho V_V e}{\mu}\right)$
$Re_{V,L}$	vibrational Reynolds number $\left(\frac{\rho V_V L}{\mu}\right)$
Sc	Schmidt number $\left(\frac{\mu}{\rho D}\right)$
Sh_e	Sherwood number $\left(\frac{Ke}{D}\right)$
Sh_L	Sherwood number $\left(\frac{KL}{D}\right)$
μ	solution viscosity
v	kinematic viscosity
ρ	solution density
δ	diffusion layer thickness
δ_h	oscillating hydrodynamic boundary layer thickness

transfer in grooved channels and wavy-walled channels using the electrochemical technique. Active macroscopic surface roughness machined in the electrode surface has the advantage over inert turbulence promoting plastic ribs that they increase the effective electrode area besides enhancing the rate of mass transfer.

2. Experimental technique

Fig. 1 shows the apparatus used in the present work it consists of the cell, the vibrator and the electrical circuit. The cell consisted of a 4 L cylindrical plastic container of 15 cm diameter and 25 cm height. The cathode was a nickel-plated copper cylinder of 2.5 cm diameter and 15 cm height located at the center of the container, the bottom of the cylinder and its upper part were isolated with epoxy resin. The active cylinder height was 10 cm. The anode was a cylindrical stainless steel screen lining the wall of the container. The cylinder cathode was connected to the shaft of the vibrator through a plastic sleeve. Rough cylinder cathodes were prepared by cutting V-threads in the cylinders, peak to valley heights were 1, 1.5 and 2 mm, thread pitch was fixed at 2 mm. The vibrator consisted of a variable speed motor and an eccentric. The eccentric was driven by the motor at a frequency which ranged from 3 to 33 Hz. The vibrator's shaft which connected the eccentric and the cathode had different connecting locations with the cathode to allow different amplitudes of vibration. The motor of the vibrating system was fixed firmly against a brick wall in order to eliminate radial vibration as far as possible. Three values of amplitude were used in the present work namely; 0.2, 0.4 and 0.6 cm.

The electrical circuit consisted of 10 V d.c power supply with a voltage regulator, a multirange ammeter and the cell, a voltmeter was connected in parallel with the cell to measure its voltage. Before each run the cell was filled with 3 L of fresh solution containing 0.01 M $K_3Fe(CN)_6$, 0.1 M $K_4Fe(CN)_6$ and 2 M NaOH as supporting electrolyte. The limiting current was determined under different conditions from polarization curves which were constructed by increasing the current stepwise and measuring the cell voltage. Fig. 2 shows typical polarization curves with a well-defined limiting current plateau for different vibration frequencies. In view of the high ferrocyanide concentration compared to the ferricyanide and the high anode area compared to the cathode area, the anode was taken as a reference electrode against which the cathode potential was measured thus obviating the use of an external reference electrode and the Luggin tube which may interfere with the flow pattern in the cell. Polarization curves with a well defined limiting current plateau were obtained under different conditions. All solutions were prepared using distilled water and A.R chemicals, temperature was 25 ± 1 °C. The mass transfer coefficient was determined from the limiting current using the equation [10]:

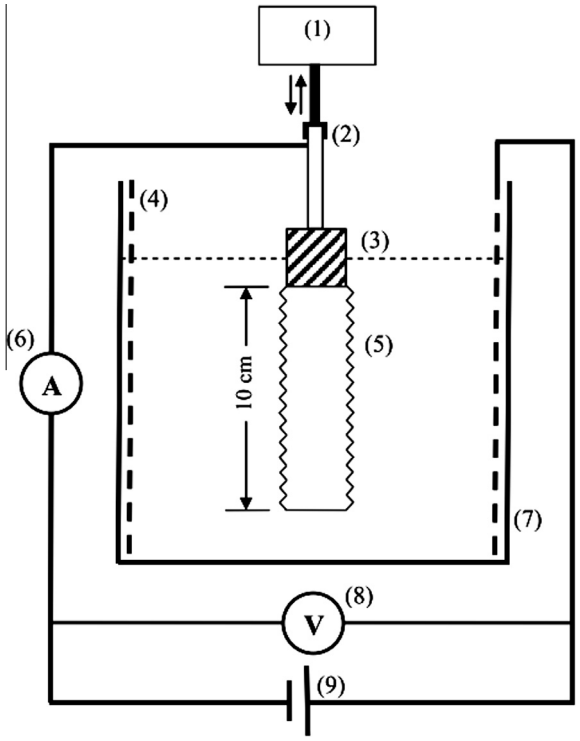

Fig. 1. Apparatus, (1) vibrator, (2) plastic sleeve, (3) electrolyte level, (4) stainless steel screen anode, (5) rough cylinder, (6) ammeter, (7) Plexiglas tank, (8) voltmeter, (9) D.C power supply.

$$\frac{I_L}{ZF} = kAC_o \tag{1}$$

Following previous studies on heat and mass transfer at rough surfaces [11–19] the projected (geometrical) area A of the rough cylinder (πdL) rather than the true area was used in calculating the mass transfer coefficient at rough cylinders. Solution viscosity and density needed for data correlation were determined experimentally using an Ostwald viscometer and density bottle respectively [31]. Diffusivity of the ferricyanide ion was obtained from the literature [10].