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Mass and heat transfer at an array of horizontal cylinders placed at the bottom of a square agitated vessel

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ABSTRACT

Rates of liquid–solid mass transfer at horizontal array of cylinders resting on the base of a square agitated vessel were studied. An electrochemical technique which involves measuring the limiting current of the cathodic reduction of $K_3Fe(CN)_6$ in a large excess of NaOH supporting electrolyte was used. The mass transfer data were correlated by dimensionless mass transfer equations. Drag reducing polymers were found to reduce the rate of mass transfer at the tube array by an amount ranging from 2.4 to 21.8% depending on the operating conditions. The volumetric mass transfer coefficient (*kA*) at the tube array was found to be higher than that of the flat tank bottom cathode by a factor ranging from 4.24 to 9.33. The importance of the present study in the design and operation of stirred square tank reactor with a cooling system at the bottom was noted. Also the importance of the present results in designing semi-continuous tubular dialyzers was highlighted. The possibility of using the outer tube surface as a catalyst support and the inner surface as a cooler for conducting diffusion controlled reactions which need critical temperature control such as immobilized enzyme catalyzed biochemical reactions was discussed.

Keywords: Agitated vessel; Biochemical reactors; Dialysis; Diffusion controlled reactions; Heat transfer; Mass transfer

1. Introduction

Although much work has been done on the heat and mass transfer behavior of cylindrical agitated vessels, little has been done on rectangular and square agitated vessels despite their importance in practice (Kresta et al., 2006; El-Shazly et al., 1997; Sedahmed et al., 2004; Clark et al., 1994), for instance they are used in electroplating industry, wastewater treatment and textile finishing industry, they also have the potential of being used as stirred tank chemical reactors in view of their simple design and the fact that they do not need baffles to improve their mixing efficiency (Abdel-Aziz et al., 2013; Oldshue, 1983). Temperature control of rectangular agitated vessels is usually carried out by serpentine coils which may be located parallel to the wall of the vessel or at its bottom (Durney, 1987; Richards, 1950). The aim of the present work is to study the rate of mass and heat (by analogy) transfer behavior of an array of horizontal tubes placed at the bottom of a square agitated vessel by the electrochemical technique which is used widely for heat and mass transfer studies. Beside assisting in the design of a built in heat transfer facility in square agitated vessels the present study can also serve the following purposes: (i) the outer surface of the tube array can be used as a catalyst support for conducting diffusion controlled exothermic reactions which uses heat sensitive catalysts or produce heat sensitive products such as immobilized enzyme catalyzed biochemical reactions, in this case excess heat can be removed quickly by passing cold water through the inner side of the tubes. The presence of the shear sensitive catalyst in the low shear zone of the container bottom away from the high shear zone of the impeller is an asset (Baily and Ollis, 1987). (ii) the present mass

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Nomenclature

A	cathode area
a_1, a_2	constants
C	bulk concentration of reactant
D	diffusivity of ferricyanide ions
d	cylinder diameter
d_i	impeller diameter
F	Faraday's constant (96,500 Coulomb per equivalent)
I_L	limiting current
k	mass transfer coefficient
k_o	mass transfer coefficient at the flat tank bottom
L	cylinder length
n	number of horizontally oriented cylinders
S	distance between cylinders
T	tank equivalent diameter (4 × C.S.A/wetted perimeter)
z	number of electrons involved in the reaction
Re	Reynolds number ($\rho\omega d_i^2/(60 \times \mu)$)
Sc	Schmidt number ($\mu/\rho D$)
Sh	Sherwood number (Kd/D)
μ	solution viscosity
ρ	solution density
δ	diffusion layer thickness
ω	rotation speed, rpm

transfer study at an array of horizontal tubes placed at the bottom of a square agitated vessel can form the basis of a semi-continuous dialyzer where the solution passes through the inner surface of the horizontal tube while the solute accumulates in the agitated vessel. Despite the much work that has been done on mass and heat transfer in rotary system (Hajmohammad and Nourazar, 2014a, 2014b; Triveni et al., 2010) and the work done on different aspects of agitated vessels (Abdel-Aziz, 2013; Takahashi and Motoda, 2009; Hiraoka et al., 2001; Mavros et al., 1998) no work has been reported on the present arrangement despite its potential industrial importance.

Since drag-reducing polymers have the potential of being used in agitated vessels to reduce the mechanical power required for rotating the impeller (Al-Ameeri, 1987; Quraishi et al., 1976, 1977; Mashelkar et al., 1975; Montantea et al., 2011) by the virtue of their ability to damp the energy dissipating small scale high frequency eddies (White and Mungal, 2008; Sellin et al., 1982), the present work also aims to study the extent to which drag reducing polymers reduce the rate of mass transfer at the cylinder array. To this end polyethylene oxide (Polyox WSR-301) a product of Union Carbide was used. Apart from the potential intentional use of water soluble polymers to reduce mechanical power consumption in agitated vessels, studying of the effect of dag reducing agents on the rate of mass transfer is of relevance to industries which use water soluble polymers and surface active agents to perform functions different from drag reduction, for instance, carboxy methylcellulose polymer is used in the preparation of some pharmaceutical and food formulations (Anon, 1971) in agitated vessels, surface active agents are used in the pharmaceutical industry as solublizers to dissolve sparingly soluble solutes. Also polyelectrolyte polymers are used as flocculants in wastewater treatment in agitated vessels (Sellin et al., 1982). In all these cases the polymer and the surface active agents (Sellin et al., 1982) would exercise a drag reducing effect on the rotating impeller and reduce mechanical power consumptions beside the intended function.

The rate of mass transfer was determined by an electrochemical technique involving the measurement of the limiting current of the cathodic reduction of $k_3Fe(CN)_6$ in a large excess of NaOH as a supporting electrolyte. The large excess of NaOH eliminates the transfer of $Fe(CN)_6$ by electrical migration, under such conditions the analogy between heat and mass transfer becomes valid and the mass transfer results can be transposed to heat transfer (Selman and Tobias, 1978; Mizushina, 1971).

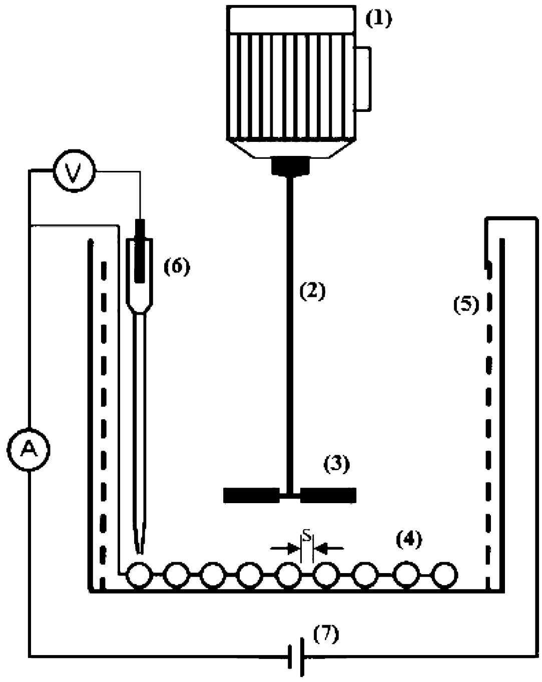

Fig. 1 – Experimental apparatus. (1) Motor, (2) isolated steel shaft, (3) impeller, (4) array of horizontally oriented cylinders cathode, (5) stainless steel screen anode, (6) Luggin tube, (7) dc power supply.

2. Experimental technique

2.1. *Apparatus*

Fig. 1 shows the apparatus used in the present study, it consisted of a Plexiglas tank, variable speed digital electric motor, impeller, and electrical circuit. The tank had a square cross sectional area of 15 cm × 15 cm and 25 cm height. The height of fluid in the tank was 15 cm. Two types of impellers were used namely; four blade 90° turbine impeller (radial flow type) and four blade 45° pitched turbine impeller (axial flow type). Each impeller had a 5 cm diameter and 1 cm blade height. The impeller was mounted on a steel shaft connected to the variable speed motor. The shaft and the impeller were isolated by epoxy resin. The impeller was placed in the tank center at 5 cm distance from the tank bottom (McCabe et al., 1993). Impeller rotational speed was varied within the range of 200–550 rpm. The electrical circuit consisted of 12 V d.c power supply with a voltage regulator, a multirange ammeter connected in series with the cell. A voltmeter was connected in parallel with the cell to measure its voltage. The cell anode was a 20 mesh stainless steel screen lining the inner walls of the tank. The cathode was an array of eight horizontally oriented Ni plated copper cylinders placed on the tank bottom. Three different cylinder diameters were used namely; 0.5, 1 and 2 cm. Six cylinder separation within the array were used namely; 0.25, 0.5, 0.75, 1, 1.25 and 1.5 cm.

2.2. *Procedure*

Before each run 3 L of a solution composed of 0.01 M $K_3Fe(CN)_6$, 0.1 M $K_4Fe(CN)_6$ in a large excess of NaOH supporting