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Mass and heat transfer behavior of a rotating disc with parallel rectangular grooves

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ABSTRACT

Rates of liquid-solid mass transfer at a rotating disc with parallel rectangular grooves were measured by the electrochemical technique. Variables studied were disc rotation speed, groove depth (e) and physical properties of the solution. Grooves were found to enhance the rate of mass transfer by a factor ranging from 1.23 to 2.24 depending on groove depth and disc rotation speed. The data were correlated by the dimensionless equation:

$Sh_r = 0.928\ Sc^{0.33}\ Re^{0.54}\ (e/w)^{0.276}$

Implication of the present study for the design and operation of equipments which use the rotating disc such as pump electrochemical reactor and high space time yield of multirotating disc electrochemical and catalytic reactors was highlighted. Also the importance of the present work for the design and operation of high efficiency membrane processes such as ultrafiltration and dialysis was noted.

1. Introduction

Recently there have been a growing interest to use the rotating disc in building electrochemical and catalytic reactors used to conduct liquid–solid diffusion controlled reactions [1–5] in view of the fact that this geometry offers the following advantages:

(i) The reactor capacity can be increased by extending the reactor vertically via increasing the number of rotating discs mounted on a vertical rotating shaft, this would reduce the floor space and the capital costs of the reactor. (ii) the radial flow induced by the rotating disc would assist in the rapid heat transfer from the disc surface to a cooling jacket surrounding the reactor, this is a highly desirable property in case of exothermic reactions involving heat sensitive products or catalysts as in the case of biological reactions catalyzed by immobilized enzymes. The following examples show the wide range of technical processes which use the rotating disc reactor. The pump cell is a continuous electrochemical reactor which consists of a rotating disc electrode placed at a small distance from a stationary disc counter electrode, the reactor is used in the electrolytic production of metal powders, electroorganic synthesis and wastewater treatment [6]. The rotating disc reactor has been used widely to recover precious and toxic heavy metals from industrial waste solution by cementation on a less noble metal [7–10]. Recently rotating disc rector has been used to conduct photochemical reactions [11]. Rotating discs have been used to intensify the rate of diffusion controlled membrane processes such as ultrafiltration and dialysis [12] by placing a rotating metallic disc ata distance from a stationary membrane, the flow induced by the rotating disc enhances the rate of mass transfer and reduce concentration polarization at the membrane surface. Rotating disc membranes have also been used [13]. As mentioned above, the rotating disc has the potential of being used to conduct diffusion controlled immobilized enzyme catalyzed biochemical reactions where the catalyst is supported on the rotating disc. Previous attempts to increase the space time yield of the rotating disc reactor have concentrated on increasing its area via using multirotating discs mounted on a vertical rotating shaft [1–5]. In order to improve the performance of the reactor furthermore, Sedahmed et al. [14] used an array of rotating screen discs. The authors reported a substantial increase in the volumetric mass transfer coefficient over that of solid rotating disc. The superior performance of rotating screen discs over solid discs was attributed to the high specific area and the high turbulence promoting ability of screens.

The aim of the present work is to improve the mass transfer behavior of single rotating disc by machining parallel rectangular

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Nomenclature

A Cathode area
a Constant
b Constant
C Ferricyanide concentration
d Disc diameter
D Diffusivity of ferrocyanide
e Groove depth
F Faraday's constant (96,500 C mol^{-1})
I_L Limiting current
k Mass transfer coefficient
r Disc radius
V Disc linear velocity ($V = \omega r$)
w Groove width
Z Number of electrons involved in the reaction
Re Reynolds number ($\rho \omega r^2/\mu$)
Sc Schmidt number ($\mu/\rho D$)
Sh_r Sherwood number (kr/D)
δ_h Hydrodynamic boundary layer thickness
ε Specific energy dissipation
μ Solution viscosity
ν Kinematic viscosity (μ/ρ)
ρ Solution density
ω Radial velocity [$\omega = 2\pi(r.p.s)$]

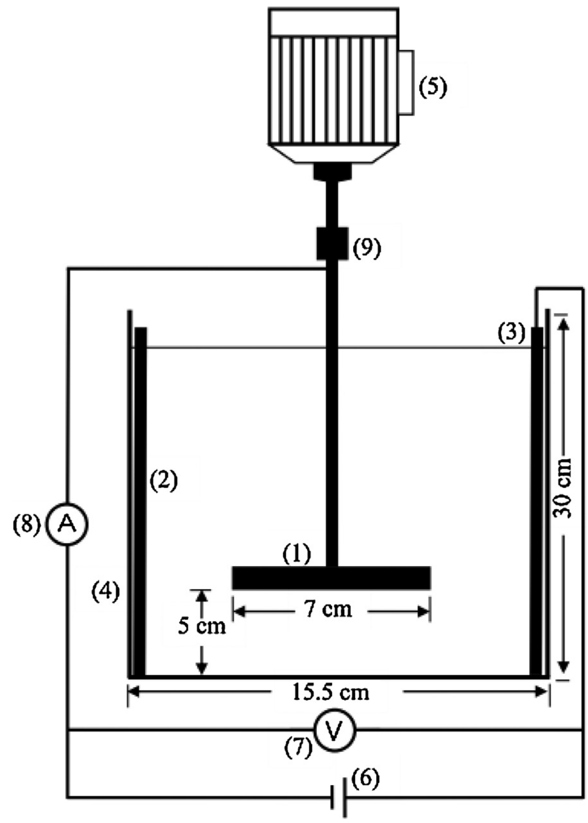

Fig. 1. Apparatus.
(1) rotating disc cathode (2) stainless steel cylindrical sheet anode (3) electrolyte level (4) plexiglass cylindrical container (5) variable speed motor (6) 10 volt d.c power supply (7) voltmeter (8) multirange ammeter (9) plastic sleeve.

grooves in the disc in order to rate of mass transfer in disc reactors used to conduct liquid-solid diffusion controlled reactions. The use of turbulence promoters such as the present grooves under laminar flow conditions to increase the space-time yield of the reactor is more economic than operating the disc under turbulent flow conditions where mechanical energy consumption is high [15]. Parallel rectangular grooves have proved to be an effective type of turbulence promoters which enhanced the rate of mass transfer at rotating cylinders [16]. Previous studies to enhance the rate of mass transfer at rotating discs have used a fluidized bed of solid particles as turbulence promoter [17–20]. Such technique has drawbacks such as the need to separate the particles from the products and the possibility of particle overflow in case of continuous operation. The rate of mass transfer was measured by 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 [21]. In view of the analogy between heat and mass transfer [15,21] the present study is of relevance to many engineering applications of the rotating disc where the rate of heat transfer at the rotating disc needs to be enhanced [22].

2. Experimental technique

The apparatus (Fig. 1) consisted of the cell and electrical circuit. The cell consisted of a Plexiglas cylindrical container of 15.5 cm diameter and 30 cm height, the cathode which was mounted in the center of the cell consisted of a nickel plated horizontal copper disc of 7 cm diameter and 0.5 cm thickness, the disc was fixed in position by a 1 cm diameter copper shaft connected to the disc at its center, the copper shaft was connected to the shaft of a variable speed motor through a plastic sleeve. The variable speed motor was fixed firmly against a brick wall to a void vibration. The copper shaft acted a disc holder and a current feeder. The anode was a stainless steel cylindrical sheet lining the wall of the container. The copper holder and the back and sides of the disc cathode were insulated with epoxy resin. In addition to the smooth disc cathode four nickel plated grooved discs were used, each grooved disc contains a number of parallel rectangular grooves machined in the disc. Groove depth was 0.5, 1, 1.5 and 2 mm, groove width was 3 mm, the distance between grooves was fixed at 3 mm. The number of grooves per disc were 11.

The circuit consisted of 10 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 cathode was fed with electrical current via a copper brush pressed against the rotating shaft.

Before each run the cell was filled with the solution, the rotation speed of the cathode was adjusted at the required value by means of a variac, speed of rotation was measured by an optical tachometer. Three solutions of different composition were used, each solution contained 0.1 M $K_4Fe(CN)_6$ and 0.025 M $K_3Fe(CN)_6$ dissolved in a large excess of NaOH as a supporting electrolyte, NaOH concentrations were 1, 2 and 3 M. All solutions were prepared using A.R. chemicals and distilled water. The limiting current was determined under different conditions by increasing the current stepwise and measuring the corresponding total cell voltage until the limiting current plateau is obtained. The high cathode/anode area and the high concentration of ferro to ferricyanide ratio used in the present work made it possible to use the cell anode as a reference electrode thus obviating the need for a Luggin tube with an external reference electrode which may interfere with the flow pattern of the rotating disc. Cell temperature was fixed at 30 ± 1 °C by placing the cell in a thermostated water bath. Solution viscosity and density needed for data correlation were determined by an Ostwald viscometer and