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Liquid–solid mass transfer to a rotating mesh electrode in a rotor–stator spinning disc configuration

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ABSTRACT

Here we present the mass transfer coefficient for liquid–solid mass transfer to a rotating mesh electrode and a smooth flat disc electrode in a rotor–stator spinning disc reactor. The mass transfer coefficients are measured with the limiting current density technique. Additionally, the torque is measured and the energy dissipation rate in the system is calculated. The volumetric mass transfer coefficient of the mesh electrode increases a factor 5 compared to that of the flat disc electrode at virtually equal energy dissipation rates. Due to the characteristics of the mesh, the mesh electrode offers 2.77 times higher electrode area than the flat disc. The mass transfer coefficients measured for the rotating mesh electrode are a factor 1.74 higher compared to the flat disc. Average Sherwood numbers are reported and a correlation is presented that predicts mass transfer rates of rotating meshes in rotor–stator spinning disc reactor configurations.

1. Introduction

Electrochemical processes play an important role in the chemical industry, for instance in the production of important chemicals such as chlorine, sodium hydroxide, sodium chlorate, hydrogen, oxygen, and aluminium among others [1,2]. Due to the intrinsic characteristic of being an energy-intensive industry, there is a continuous drive for process improvement in order to increase the production rate with minimal power consumption. By increasing the current density of an electrochemical process, the rate of production proportionally increases. One of the challenges of operating at high current densities is that the rate at which reactants and/or products are transported to/from the electrode becomes the limiting step. When the limiting current density is reached, the rate of reaction can no longer be compensated with the rate of mass transport to/from the electrode and the process becomes mass transfer controlled. A further increase in the current density leads to undesired reactions at the electrodes and higher power consumption due to a steep increase in the cell potential. It is therefore desired to increase the mass transfer rate in electrochemical reactors. An option for this intensification is the use of high shear forces that promote a rapid mixing of fluids and a high surface renewal rate. A type of rotating equipment that uses these principles is the rotor–stator spinning disc reactor (RS-SDR) [3]. This reactor consists of a rotating disc in a cylindrical housing, with a typical gap distance between the rotor and the stator in the order of 1 mm. The high velocity gradient between the rotor and the stator and high shear forces cause high turbulence that intensify the gas–liquid [4–6], liquid–liquid [7] and liquid–solid [8] mass transfer, as well as heat transfer [9,10]. Moreover, due to the small reactor volume, the RS-SDR offers a fast start-up and shut down which is beneficial when intermittent production is required, e.g. at peak electricity production by wind or solar energy.

Mesh electrodes are used in industrial cells, for instance in zero gap cell configurations [11,12], where the electrode and membrane are in close contact and the mesh electrodes allow the contact with the electrolyte. Furthermore mesh electrodes offer the advantage of promoting turbulence, higher surface area and facilitating gas removal [13]. Rotating mesh electrodes have been previously studied by Sedahmed et al. [14]. These authors reported higher mass transfer coefficients for the rotating mesh than the predictions for the free disc in laminar regime. The flow pattern for the configuration used by Sedahmed et al. resembles that of a free disc, where the gap between the rotating disc and the bottom stator is very large. Alternatively, the reactor volume can be significantly reduced by using the RS-SDR configuration previously described, where the rotating disc electrode is placed at a small distance from

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Nomenclature

Symbols

a	fitting parameter (–)
A	area (m^2)
a_{LS}	liquid–solid interfacial area (m_i^2/m_R^3 s)
b	fitting parameter (–)
C^*	concentration of the electroactive species at the bulk (mol/m^3)
D	diffusion coefficient (m^2/s)
d_o	opening size of the mesh (mm)
d_w	wire diameter (mm)
E_{dr}	rotational energy dissipation rate (W)
F	Faraday constant (s A/mol)
i_L	limiting current density (A/m^2)
k_{LS}	liquid–solid mass transfer coefficient (m_L^3/m_i^2 s)
$k_{LS}a_{LS}$	volumetric liquid–solid mass transfer coefficient (m_L^3/m_R^3 s)
n	number of electrons transferred (–)
n_m	mesh size (mesh units/in^2)
R	radius (m)
Re	Reynolds number (Re = $\omega R^2/\nu$)
Sc	Schmidt number (Sc = ν/D)
Sh	Sherwood number, Sh = $k_{LS}R/D$

Greek letters

δ	thickness of the diffusion layer (m)
ω	rotational speed (rad/s)
ν	kinematic viscosity (m^2/s)
τ	torque (Nm)

Abbreviations

CE	counter electrode
WE	working electrode
RDE	rotating disc electrode
RS-SDR	rotor–stator spinning disc reactor

the stator which is then used as counter electrode. In practical applications the RS-SDR configuration exhibits a lower ohmic drop and therefore lower cell voltage due to the small gap distance between electrodes. This configuration resembles that of the pump cell electrolyzer that has been studied extensively by Jansson et al. for processes like metal deposition [15] and electroorganic synthesis [16]. However the use of mesh or other structured electrodes in the RS-SDR configuration has not been investigated yet.

Therefore, this paper presents liquid–solid mass transfer coefficients (k_{LS}) of a rotating mesh electrode in a RS-SDR configuration determined by measuring the limiting current density [17,18]. Furthermore, mass transfer coefficients for a flat smooth disc in the RS-SDR configuration are also reported. The values of mass transfer coefficients presented here correspond to the average values over the entire surface of the rotating mesh or rotating disc. The system investigated here corresponds to Schmidt numbers much larger than unity, for which several empirical and semi-empirical mass transfer equations have been reported. In Table 1 we present some examples of correlations reported in literature, though the list is not exhaustive. For free discs, an overview of the available equations can be found in [19].

The results obtained in this study are also reported in the form of a Sherwood correlation as a function of the Reynolds number of the type:

$$\mathrm{Sh} = a\,\mathrm{Re}^{b}\,\mathrm{Sc}^{0.33} \tag{1}$$

where Sh = $k_{LS}R/D$ is the Sherwood number, Re = $\omega R^2/\nu$ is the rotational Reynolds number and Sc = ν/D is the Schmidt number with k_{LS} being the mass transfer coefficient, R the disc radius, D the diffusion coefficient, ω the rotational speed, ν the kinematic viscosity, a and b are fitting parameters.

2. Methodology

2.1. Limiting current density method

The mass transfer coefficient was measured using the limiting current density method. When the rate of reaction is so high that the concentration at the electrode becomes zero, the limiting current density i_L is reached and the rate of reaction can be expressed by:

Table 1
Compilation of previously reported mass transfer data in the form of Sherwood correlations as functions of Reynolds and Schmidt for free discs and rotor–stator configurations and the correlations proposed in the present study.

Correlation and range of validity		Authors	Notes
Free disc in infinite liquid			
$\mathrm{Sh} = 0.62\mathrm{Re}^{0.5}\mathrm{Sc}^{0.33}$	(6)	Levich [23]	a, d
$\mathrm{Re} < 2.7 \times 10^5$			
$\mathrm{Sh} = (0.89 \times 10^5\mathrm{Re}^{-0.5} + 9.7 \times 10^{-15}\mathrm{Re}^3)\mathrm{Sc}^{0.33}$	(7)	Mohr et al. [28]	a, d
$2 \times 10^5 < \mathrm{Re} < 4 \times 10^5$			
$\mathrm{Sh} = 0.007\mathrm{Re}^{0.9}\mathrm{Sc}^{0.33}$	(8)	Daguenet [26]	b, d
$\mathrm{Re} > 2.7 \times 10^5$			
Disc in rotor–stator configuration			
$\mathrm{Sh} = 0.85\mathrm{Re}^{0.5}\mathrm{Sc}^{0.33}$	(9)	Cavalcanti et al. [27]	a, d
$87 < \mathrm{Re} < 9.7 \times 10^3, 0.1 < G < 2.26$			
$\mathrm{Sh} = 2 \times 10^{-8}\mathrm{Re}^2 + 9 \times 10^2$	(10)	Meeuwse et al. [8]	c, e
$1 \times 10^5 < \mathrm{Re} < 7 \times 10^5$			
$\mathrm{Sh} = 0.799\mathrm{Re}^{0.492}\mathrm{Sc}^{0.33}$	(11)	Present work	
$5.89 \times 10^3 < \mathrm{Re} < 2.24 \times 10^5$			
$\mathrm{Sh} = 7.27 \times 10^{-4}\mathrm{Re}^{1.055}\mathrm{Sc}^{0.33}$	(12)		
$2.24 \times 10^5 < \mathrm{Re} < 6.72 \times 10^5$			
Rotating mesh in free disc configuration			
$\mathrm{Sh} = 0.26Re^{0.5}Sc^{0.33}(R/d_w)^{0.5}$	(13)	Sedahmed et al. [14]	a, f
$5.2 \times 10^4 < Re < 3.4 \times 10^5, 35.7 < R/d_w < 92.6$			
Rotating mesh in rotor–stator configuration			
$\mathrm{Sh} = 0.892\mathrm{Re}^{0.57}\mathrm{Sc}^{0.33}$	(14)	Present work	
$5.89 \times 10^3 < \mathrm{Re} < 6.72 \times 10^5$			

Notes:
[a] Empirical correlation based on measurements of limiting current density of the reduction of ferricyanide.
[b] Empirical correlation based on measurements of limiting current density of the reduction of triiodide.
[c] Empirical correlation based on mass transfer measurements of heterogeneously catalyzed glucose oxidation.
[d] Without superposed flow.
[e] With radially inwards superposed flow.
[f] The electrode gap although not specified it was estimated to be large and therefore it was considered to be a free disc configuration with electrolyte recirculation, i.e. superposed axial flow.

$$\frac{i_L}{nF} = \frac{D}{\delta}C^* = k_{LS}C^* \tag{2}$$

where i_L is the limiting current density, n is the number of electrons transferred, F is the Faraday constant, D is the diffusion coefficient, δ