International Journal of Heat and Mass Transfer 126 (2018) 1129–1137

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Liquid – Solid mass transfer behaviour of heterogeneous reactor made of a rotating tubular packed bed of spheres

M.H. Abdel-Aziz [a,b,*], I. Nirdosh [a], G.H. Sedahmed [b]

[a] Chemical Engineering Department, Lakehead University, Thunder Bay, Ontario, Canada
[b] Chemical Engineering Department, Faculty of Engineering, Alexandria University, Alexandria, Egypt

ARTICLE INFO

Article history:
Received 9 January 2018
Received in revised form 29 March 2018
Accepted 9 May 2018

Keywords:
Packed bed
Electrochemical reactor
Catalytic reactor
Mass transfer
Rotating reactors

ABSTRACT

The mass transfer behaviour of a rotating tubular packed bed of spheres 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, physical properties of the solution, and bed thickness (L). The mass transfer coefficient was found to increase with increasing bed rotation speed and decreases with increasing bed thickness. The mass transfer data were correlated by the equation:

$$Sh = 0.126\, Sc^{0.33} Re^{0.52} \left(\frac{L}{d_P}\right)^{-0.8}$$

Importance of the present study in the design and operation of high space – time yield heterogeneous reactors such as electrochemical reactors, catalytic reactors, photocatalytic reactors and immobilized enzyme biochemical reactors suitable for conducting diffusion controlled liquid – solid reactions was highlighted. Advantages of the present reactor in conducting small scale production compared to other reactors were pointed out.

1. Introduction

Recently there has been notable progress in developing new catalytic reactors suitable for small scale production of fine chemicals, pharmaceuticals and waste water treatment. In developing theses reactors authors are trying to avoid the drawbacks of the conventional stirred slurry reactor which is the work horse of small scale production of chemicals via catalytic, photocatalytic and immobilized enzyme biocatalytic reactions. The drawbacks of stirred slurry reactors include catalyst particle attrition, low rate of mass transfer between the catalyst particle and the solution, the costly separation of the final product from the catalyst particles and the low rate of heat transfer between the solution bulk and the outer cooling jacket especially in large diameter reactors which handle heat sensitive catalysts or products [1,2]. Recently developed reactors include the spinning disc reactor [3–5], heat exchanger/reactor where the surface acts simultaneously as a heat exchanger and a catalyst support [6–11] and the stirred fixed bed reactor where an agitated vessel fitted with a fixed bed at its wall or bottom was used [12,13]. Other reactors such as the rotating cylindrical screen bed reactor [14,15], the rotating foam reactor [16,17] and the rotating tube reactor [18,19] have been recently developed to overcome the limitations of the stirred slurry reactor. Table 1 shows the mass transfer equations obtained for some of these reactors. In line with this trend the aim of the present work is to examine the performance of a rotating tubular packed bed of spheres in conducting diffusion controlled liquid solid reactions to benefit from the mass transfer intensifying effect of the centrifugal force [20]. The suggested reactor would potentially serve the following fields:

(i) The rotating annular bed can be used in conducting photocatalytic reactions which usually use a slurry of TiO_2 catalyst, in this case TiO_2 particles can be supported on the sphere packing (glass or ceramic) using the sol-gel technique [21], the UV lamps required to activate the reaction can be placed in the inner duct of the rotating tubular bed and around it.
(ii) Rotating tubular packed bed can be used to conduct diffusion controlled catalytic reactions such as immobilized enzyme catalyzed biochemical reactions, in this case a

* Corresponding author at: Chemical Engineering Department, Faculty of Engineering, Alexandria University, Alexandria, Egypt.
E-mail addresses: mhmousa@alexu.edu.eg, mhmousa@lakeheadu.ca (M.H. Abdel-Aziz).

https://doi.org/10.1016/j.ijheatmasstransfer.2018.05.050
0017-9310/

Nomenclature

A	cathode (rotating packed bed) area, cm^2
A_i	area of the inner cylindrical surface of the bed
A_o	area of the outer cylindrical surface of the bed
A_m	mean flow area of the rotating bed through which induced radial flow passes
a, a_1, a_2, a_3, a_4, a_5, a_6	constant
C	bulk concentration of ferricyanide ions, $mol\cdot cm^{-3}$
D	diffusivity of transferring ions, $cm^2\cdot s^{-1}$
d	mean bed diameter $\left(d = \frac{d_i+d_o}{2}\right)$, cm
d_p	sphere diameter
F	Faraday's constant (96,500 $C\cdot mol^{-1}$)
$(F_c)_i$	force acting on the inner cylindrical surface of the bed
$(F_c)_o$	force acting on the outer cylindrical surface of the bed
f	friction factor
I	limiting current, A
k	mass transfer coefficient, cm s^{-1}
L	bed height, cm
N	bed rotation speed, r.p.s
P	power consumption, W
$(P_c)_i$	power dissipated at the inner cylindrical surface
$(P_c)_o$	power dissipated at the outer cylindrical surface
P_b	power dissipated in the rotating bed
Q	radial volumetric flow rate of the solution in the bed, $cm^3\cdot s^{-1}$
r	average radius of the bed $\left(r = \frac{r_i+r_o}{2}\right)$, cm
r_i	inner bed radius, cm
r_o	outer bed radius, cm
t	contact time, s
V	average linear velocity ($v = \omega r$), $cm\cdot s^{-1}$
V_b	radial velocity through the rotating bed
V_i	tangential linear velocity at the inner cylindrical surface of the rotating bed
V_o	tangential linear velocity at the outer cylindrical surface of the rotating bed
x	distance perpendicular to the surface, cm
Re	Reynolds number $\left(\frac{\rho v d_p}{\mu}\right)$
Sc	Schmidt number $\left(\frac{\mu}{\rho D}\right)$
Sh	Sherwood number $\left(\frac{k d_p}{D}\right)$
Δp	pressure drop across the bed
α	constant
β	constant
$\in$	specific energy dissipation, $cm^2\cdot s^{-3}$
μ	solution viscosity, $g\cdot cm^{-1}\cdot s^{-1}$
v	kinematic viscosity, $cm^2\cdot s^{-1}$
ρ	solution density, $g\cdot cm^{-3}$
ω	rotation speed, $\omega = 2\pi N$

central tube (or helical tube) along with an external cooling jacket surrounding the bed can be used to cool the reactor in case of exothermic reactions in order to save heat sensitive materials from degradation.

(iii) The rotating tubular bed can be used as an electrochemical reactor for conducting diffusion controlled electroorganic synthesis and wastewater treatment, to improve the current distribution on the rotating bed working electrode, two counter electrodes can be used, a central one and an outer one surrounding the rotating bed electrode. The use of two counter electrodes would improve potential and current distribution at the bed and improve reaction selectivity and yield [22–25].

The rate of liquid – solid mass transfer behaviour of the rotating bed was studied by the electrochemical technique [26] which involves measuring the limiting current of the cathodic reduction of potassium ferricyanide in a large excess of NaOH as a supporting electrolyte.

Although some work has been done on the gas – liquid and the liquid – liquid mass transfer behaviour of rotating packed beds [27–33] few studies have been done on the liquid – solid mass transfer behaviour of rotating beds of woven screens [14,15]. In view of the fact that the geometry of the packing particles has a profound effect on the rate of mass transfer in flow through fixed beds [23], the present study on rotating beds of spherical packing is worthwhile.

2. Experimental technique

The apparatus (Fig. 1a) consists of the cell and the electrical circuit, the cell was 4 L Plexiglas cylindrical container of 15 cm diameter and 25 cm height with a rotating tubular packed bed of nickel plated steel spheres 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 screen anode surrounding the cathode. Three bed cathodes of thickness one layer, two layers and three layers of packed spheres were used. The spheres were packed in a tubular stainless steel wire mesh basket of square opening of 0.4 cm, mesh wire diameter was 0.071 cm, and sphere diameter was fixed at 0.5 cm (Fig. 1b). The inner diameter of the tubular

Table 1
Liquid – solid mass transfer correlations obtained by previous studies on some rotating reactors.

Reactor	Mass transfer correlation
(1) Stirred tank reactor with a packed bed at the wall [12]. ($Re = \frac{\rho N d_i}{\mu}$; $Sh = \frac{k d_p}{D}$; d_i is the impeller diameter; T is the container diameter; L is the bed thickness)	$Sh = 0.043Sc^{0.33}Re^{0.59}\left(\frac{T}{L}\right)^{0.335}$
(2) Stirred tank reactor with a packed bed at its bottom [13]. (*Sh*, *Re* and L are defined as in case (1).	$Sh = 0.046Sc^{0.33}Re^{0.78}\left(\frac{d_p}{L}\right)^{0.45}$
(3) Tubular rotating bed of woven screens [14]. ($Re = \frac{\rho N d}{\mu}$; $Sh = \frac{kd}{D}$; d is the mean bed diameter; d_h is the screen hydraulic diameter)	$Sh = 4.85Sc^{0.33}Re^{0.32}\left(\frac{d_h}{d}\right)^{-0.25}$
(4) Rotating horizontal mesh disc in a limited space [5]. ($Re = \frac{\rho\omega r^2}{\mu}$; $Sh = \frac{kr}{D}$; r is the disc radius; ω is the angular velocity)	$Sh = 0.892Sc^{0.33}Re^{0.57}$
(5) Rotating cylindrical packed bed made of woven wire mesh [15]. ($Re = \frac{\rho\omega r_2 d}{\mu}$; $Sh = \frac{kd}{D}$, d is the outer bed diameter; r_2 is the external radius; $\bar{r}$= mean radius; d_h is the hydraulic diameter of the screen; H is the distance between wires)	$Sh = 0.967Sc^{0.33}Re^{0.58}\left(\frac{d_h}{2\bar{r}}\right)^{0.58}\left(\frac{d}{d_h}\right)\left(\frac{H}{\bar{r}}\right)^{0.47}$
(6) Rotating horizontal single screen disc and closely packed screen discs [20]. ($Re = \frac{\rho\omega r^2}{\mu}$; $Sh = \frac{kr}{D}$; r is the disc radius; ω is the angular velocity; d_w = screen wire diameter)	$Sh = 0.26Sc^{0.33}Re^{0.58}\left(\frac{r}{2d_w}\right)^{0.58}$