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Research Paper

Effect of free swirl flow on the rate of mass and heat transfer at the bottom of a vertical cylindrical container and possible applications

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HIGHLIGHTS

- Mass transfer at the bottom of a cylindrical container was studied under decaying swirl flow.
- Parameters studied are swirl flow velocity, diameter of the inlet nozzle and solution properties.
- A dimensionless equation was obtained using the significant parameters.
- The present results were compared with the results obtained using perpendicular inlet nozzle.
- Relevance of study to the design of membrane processes was highlighted.

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ABSTRACT

Rates of mass transfer at the base of a vertical cylindrical container were determined under decaying swirl flow by the electrochemical technique. Variables studied were swirl flow solution velocity, diameter of the tangential inlet nozzle and physical properties of the solution. The data were correlated by a dimensionless mass transfer equation. The equation can be used to predict the rate of heat loss from the bottom of swirl flow equipment as well as the rate of diffusion controlled corrosion of the bottom. The importance of the derived equation in the design and scale up of a cylindrical batch recirculating catalytic or electrochemical reactor with a catalyst layer or electrode at the bottom and a cooling jacket around the vertical wall suitable for conducting exothermic liquid – solid diffusion controlled reactions which need rapid temperature control to avoid the loss of heat sensitive catalysts or heat sensitive products was pointed out. Comparison of the present results with the results obtained using perpendicular inlet nozzle which generates parallel flow at the bottom and axial flow along the cylindrical container revealed the fact that although swirl flow produces higher rates of heat and mass transfer at the cylindrical wall than axial flow and the reverse is true at the container base. Relevance of the present study to the design and operation of membrane processes and heat recovery from hot pools of liquid metals and low melting alloys in the production stage was highlighted.

1. Introduction

Decaying swirl flow induced by tangential feed nozzle has been used to enhance the rate of heat and liquid – solid mass transfer at the walls of the tubes and annuli in many engineering applications in order to improve the performance of equipment such as heat exchangers [1,2], membrane processes such as dialysis, reverse osmosis and ultrafiltration [3], and electrochemical reactors used to conduct diffusion controlled reactions [4]. Cylindrical catalytic reactors where the catalyst is supported on the container wall such as photocatalytic reactors, immobilized enzyme catalytic reactors and other catalytic reactors can benefit from the swirl flow in enhancing the rate of mass transfer in case of diffusion controlled liquid – solid reactions. All previous studies on heat and mass transfer under swirl flow were concerned with the wall of the tube or the annulus along which swirl flow is advancing, no work has been reported on the effect of swirl flow on the rate of heat or mass transfer at a surface perpendicular to the direction of swirl flow e.g. the bottom of the cylindrical container in the inlet zone despite the technical importance of the subject. So the aim of the present work is to study the rate of mass and heat transfer (by analogy) at the

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Nomenclature

A	cathode area, cm^2
a, a_1	constant
C	ferricyanide concentration, $mol \cdot cm^{-3}$
D	diffusivity of ferricyanide, $cm^2 \cdot s^{-1}$
d	reactor diameter, cm
d_i	impeller diameter, cm
d_n	feed nozzle diameter, cm
d_e	equivalent diameter of annulus, cm
F	Faraday's constant (96,500 C mol^{-1})
h	solution height, cm
I	limiting current, mA
k	mass transfer coefficient, $cm \cdot s^{-1}$
L	height of annuls or tube, cm
N	impeller rotation speed, (rps)
P	dissipated power, $dyn \cdot cm \cdot s^{-1}$
r	radius of the reactor, cm
$\bar{r}$	radial distance from the reactor center, cm sp
V	solution velocity in the reactor, $cm \cdot s^{-1}$
V_n	nozzle solution velo ρ city, $cm \cdot s^{-1}$
Z	number of electrons involved in the reaction

Dimensionless groups

f	friction factor ($f = 0.146Re^{-0.2}$)
Re	solution Reynolds number in the reactor $\left(\frac{\rho V d}{\mu}\right)$
Re_i	impeller Reynolds number $\left(\frac{\rho N d_i^2}{\mu}\right)$
Re_n	nozzle Reynolds number $\left(\frac{\rho V_n d_n}{\mu}\right)$
Sc	Schmidt number $\left(\frac{\mu}{\rho D}\right)$
Sh	Sherwood number $\left(\frac{kd}{D}\right)$

Greek symbols

δ	diffusion layer thickness, cm
μ	solution viscosity, $g \cdot cm^{-1} \cdot s^{-1}$
ν	kinematic viscosity, $cm^2 \cdot s^{-1}$
ρ	solution density, $g \cdot cm^{-3}$
$\in$	specific energy dissipation, $cm^2 \cdot s^{-3}$
τ	shear stress, $dyn \cdot cm^{-2}$

interface between the horizontal bottom of a cylindrical container and a solution admitted continuously at the container bottom through a tangential inlet nozzle. The second object of the present work is to compare between the effect of tangential inlet nozzle and perpendicular inlet nozzle [5] on the rate of mass and heat transfer at the interface between the bottom of a cylindrical container and the upward flowing solution. To this end the electrochemical technique which involves measuring the limiting current of the cathodic reduction of potassium ferricyanide in a large excess of sodium hydroxide was used to conduct the present study in view of its accuracy [6]. The use of sodium hydroxide as a supporting electrolyte eliminates mass transfer of ferricyanide ion to the cathode surface by electrical migration i.e. under this condition mass is transferred by convection and diffusion only and therefore analogy with heat transfer becomes valid [6].

Among other possible applications the present study would assist in the design and operation of batch recirculating catalytic and electrochemical reactors with horizontal reaction surface [7] which use swirl flow to enhance the rate of heat and mass transfer. In such reactors an exothermic mass transfer controlled liquid – solid reaction would take place on a horizontal electrode or a horizontal catalyst surface placed at the bottom of the cylindrical container. In this case swirl flow of the reacting solution performs two functions, namely (i) it enhances the rate of diffusion controlled reaction taking place at the horizontal electrode or catalyst (ii) as the flow progresses vertically it removes the excess heat from the reaction zone and transfer it to a cooling jacket surrounding the cylindrical reactor, rapid heat removal from the sphere of the reaction is essential in case of exothermic reactions involving heat sensitive reactants, products or catalysts such as immobilized enzyme biochemical reactions [8]. Besides, temperature control improves the selectivity and the yield of other catalytic and electrochemical reactions especially in electroorganic synthesis [7].

Diffusion controlled membrane processes employing horizontal membranes such as dialysis, ultrafiltration and reverse osmosis [3] can benefit from the present study by using swirl flow to decrease concentration polarization and membrane fouling and increase the production rate at lower energy consumption. The present study would also assist in predicting the rate of heat recovery and the rate of cooling of pools of hot liquid metals such as mercury and gallium (melting point = 29 °C) and low melting alloys (68–230 °C) in the production stage where direct contact cooling with a stream of water is used [9].

2. Experimental technique

The apparatus (Fig. 1) consisted of the cell and the electrical circuit. The cell consisted of a plexiglass cylindrical container of 11 cm diameter and 30 cm height fitted with an overflow weir at its top. A layer of mercury of 1 cm height placed at the cell bottom formed the cathode, the use of mercury as a cathode offers the advantages that it is free from surface roughness which may interfere with the rate of mass transfer beside its high H_2 overpotential [10] which delays early H_2 evolution at the limiting current with a consequent production of a well-defined limiting current plateau under the present conditions. The anode was a cylindrical stainless steel screen of 25 cm height lining the container wall, and the lower edge of the anode was 2 cm above the level of the mercury cathode. The container was fitted with a tangential inlet plexiglass feed nozzle at the level of the mercury cathode (Fig. 1b). The large anode area compared to the cathode area allowed the use of the anode as a reference electrode, thus obviating the need to use an external reference electrode to construct polarization curves. The cell electrodes were fed with current using nickel plated copper wires. The electrical circuit consisted of 12 V d.c power supply with a voltage regulator and a multirange ammeter connected in series with the cell. A voltmeter was connected in parallel with the cell to measure its voltage. A 0.2 horse power plastic centrifugal pump was used to circulate the electrolyte between 30 L plexiglass storage tank and the cell. A bypass with two plastic ball valves was used to control the solution velocity. Solution velocity was measured by determining the volume of the solution collected in a certain time in a graduated cylinder. The limiting current of the cathodic reduction of ferricyanide ion was determined under different conditions by increasing the current stepwise and measuring the corresponding cell voltage until the limiting current plateau was reached.

Solution used had the composition 0.01 M $K_3Fe(CN)_6$ and 0.01 M $K_4Fe(CN)_6$ with a large excess of NaOH as a supporting electrolyte, physical properties of the solution were changed by changing NaOH concentration, three different NaOH concentrations were used namely, 1, 2 and 4 M. All solutions were prepared using distilled water and analytical grade chemicals. Solutions were freed from dissolved O_2 by bubbling N_2 gas in the storage tank before and during experiments. Solution density and viscosity required for data correlation were determined by a density bottle and an Ostwald viscometer respectively [11]. Diffusivity of ferricyanide