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Flow pattern and model development for coaxially placed entry region coil-disc assembly as turbulence promoter in circular conduits

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ABSTRACT

Flow pattern and model development for coaxially placed entry region coil-disc as turbulence promoter in circular conduit have been presented in this paper. The electrolyte was equimolal potassium ferricyanide, potassium ferrocyanide and excess sodium hydroxide. The mass transfer correlation is based on law of the wall similarity. The variables covered in this study are the flow rate of the electrolyte, the geometric parameters of the promoter – pitch of the coil from 0.015 m to 0.035 m, length of the coil 0.01 m to 0.125 m, disc diameter from 0.02 m to 0.04 m, height of the disc from 0 m to 0.50 m, velocity of the fluid from 0.0591 m/s to 0.2751 m/s. The correlation may be extended to a wider range of parameters by virtue of the law of the wall. Experimental mass transfer function in terms of geometric parameters have been developed and presented.

$$\bar{g} = 5.76[Re_{\rm m}^{+}]^{-0.003}\left(\frac{P_{\rm c}}{d}\right)^{0.003}\left(\frac{L_{\rm c}}{d}\right)^{0.001}\left(\frac{d_{\rm d}}{d}\right)^{0.616}\left(\frac{H_{\rm d}}{d}\right)^{-0.00001}$$

1. Introduction

Flow of electrolyte through circular conduit with axially placed insert promoter generates a variety of flow fields. The turbulence promoters have good potential in electro chemical reactors namely electro winning, refining, electro organic synthesis, etc. Lin et al. [1] studied mass transfer rates of ions and other reacting species in diffusion controlled reactions in order to obtain design information for electrochemical processes. The flow devices form an important group of passive augmentation methods which coaxially placed entry region coil-disc assembly as turbulent promoter. In pursuit of this, several strategies have been devised and adopted. Chiou [2] made experimental investigation for the augmentation of heat transfer coefficient in forced convection heat transfer. He employed spiral spring coil as an insert promoter in circular tube. Changal Raju [3] obtained data for mass transfer at wall electrodes using limiting current technique. Coils of different sizes wound on central annular rod were used as promoter. Naphon [4] investigated the heat transfer characteristics and the pressure drop of the horizontal double pipe with coil-wire insert. Alberto García et al. [5] studied wire coil inserts offer their best performance within the transition region. Rajendra Prasad [6,7] studied ionic mass and momentum transfer with coaxially placed spiral coils as turbulent promoter in homogeneous flow and in fluidized beds and did experiments using ferri–ferro cyanide system by limiting current technique. Discs placed across the flow of circular conduits generate wakes and internal circulation within the column. The effectiveness of a disc varies with the length of the column. Venkateswarlu and Raju [8,9] obtained mass and momentum transfer data with coaxially placed discs on a central rod. The augmentation was about 12-fold over the data in conduits in the absence of disc promoter elements. Ravi et al. [10] obtained mass transfer data on the walls of the fluidized beds using an electrochemical technique with disc as promoter. Sherwood and Stone [11] determine the flow of fluid around a disc in a pipe and the added mass of the accelerating disc and flow profiles are also presented. Ziókowska and Dolata [12] investigated the intensification of the heat transfer between a gas stream and the wall of a tube provided with a set of perforated discs used as turbulence promoters and the accompanying pressure drop. Mass transfer with entry region coil-disc assembly as turbulence promoter was selected for the present study.

2. Experimentation

The schematic diagram of the experimental unit was shown in Fig. 1. The equipment essentially consisted of a re-circulating tank, a centrifugal pump, rotameter and an entrance calming section, a test section, and an exit calming section. The test section was made with Perspex material and was provided with a number of point

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Nomenclature

A	area of electrode, m^2
C	concentration of electrolyte, kg-mole/m^3
c_l	length of the conduit, m
d	diameter of the conduit, m
d_d	diameter of the disc, m
D	diffusion coefficient, m^2/s
D_e	eddy diffusivity, m^2/s
F	faraday's constant = 96,500 coulombs/g-mole
H_d	height of the disc, m
I_L	limiting current density, amps
k_L	mass transfer coefficient, m/s
L_c	Length of the coil, m
N	mass flux
P_c	Pitch of the coil, m/turn
R	radius of the conduit, m
u_i	velocity at the interface, m/s
u_b	average velocity, m/s
u^*	friction velocity, $\sqrt{\tau_0/\rho}$
u_i^+	dimensionless velocity, u/u^*
u_b^+	dimensionless bulk velocity
u_m^+	average fluid velocity, m/s,
V	superficial velocity, m/s
y	coordinate distance normal to wall, m
y_1	distance from wall at which $u = u_b$
y_1^+	dimensionless distance, yu^*/ν

Dimensionless

$\bar{g}$	modified mass transfer function
Re_m^+	modified Reynolds number
St	Stanton number, k/u_b or k_L/V
Sc	Schmidt number, ν/D
Φ	Ratio between molecular viscosity and eddy viscosity, $(\nu_e/D_e)_t$
Φ_1	P_c/d
Φ_2	L_c/d
Φ_3	d_d/d
Φ_4	H_d/d
n	number of ions transferred

Greek symbols

τ	shear stress, kg/ms^2
μ	viscosity of the fluid, poise
ρ	density of the fluid, kg/m^3
τ_0	wall shear stress, kg/m s^2, $f/2 \cdot \rho \cdot u_b^2$
υ	kinematics viscosity
υ_e	eddy kinematics viscosity

Subscripts

b	buffer
i	interface
t	turbulent
o	wall
v	viscous
v–b	viscous buffer region

electrodes fixed flush with its surface longitudinally at equal spacing (0.03 m). The wall of the entrance calming section acted as wall electrode in much larger surface area. The promoter was mounted in the test section coaxially by means of gland nuts and positioned by supporting grid. Entry region coil-disc assembly as turbulence promoter was made of copper wire with provision to fix it rigidly within test section. The details of the coil-disc promoter were shown in Fig. 2. After inserting the promoter in the column, one-hundred liter of the electrolyte consisting of equimolal 0.01 M potassium ferricyanide and potassium ferrocyanide together with 0.5 N sodium hydroxide was prepared in the storage tank. The concentration of the electrolyte is maintained constant throughout the experiment, small changes of temperature of electrolyte offers changes in Schmidt number in the range from 902.5 to 1089. The solution is kept in the dark and closed recirculation tank. The electrolyte was pumped through the test section. The flow rate of the electrolyte was adjusting by operating the control and by pass valves. Limiting current data were measured at point copper electrodes for the reduction of potassium ferricyanide ion. The procedure followed similar to the works of Lin et al. [1] and several others [3,6,7]. Room temperature is around 30 °C. Temperature is recorded for every reading of limiting current using the thermometer with 0.1 °C accuracy. This ensures the accuracy of physical properties such as μ, D, ρ. Thermometers are attached at both ends of the column. The electrochemical reaction involved is given below

$$Fe[(CN)_6]^{-3} + e^- \rightarrow Fe[(CN)_6]^{-4} \quad \text{(a)}$$

The limiting current was indicated by a small increase in current for a sharp increase in voltage. The experiments were repeated by varying the pitch of the spiral coil (P_c), Length of the coil (L_c), Diameter of the disc (d_d) and Height of the disc (H_d). The range of variables covered is given in Table 1. Mass transfer coefficients are calculated by the following expression:

$$K_L = \frac{I_l}{nAFc_i} \quad \text{(b)}$$

3. Theory

Flow of electrolyte through tubular flow reactor with entry region coil insert promoters will establish momentum and concentration profiles and was shown in Fig. 3. The profile is divided into two regions, the inner region and outer region. The inner region again divided into laminar sub layer and viscous–buffer zone. The outer region is turbulent core region and is fully turbulent. The turbulent core separated by an interface. A model is developed with the following assumptions:

1. The fluid is Newtonian, incompressible, and has constant transport properties and independent of time.
2. Flow through smooth tube is fully developed with no entrance effects. The effect of body forces is small in comparison to that of viscous and inertial forces.
3. The axial velocity profile is independent of axial coordinate, similarly the concentration gradients.
4. The mass flux varies in the radial direction. The mass flux varies linearly with y, and is represented by

$$\frac{N}{N_w} = 1 - \frac{y}{R} \quad (1)$$

The radial variation of mass flux is taken into account by dividing into viscous–buffer zone and turbulent core. The flux at the interface is considered radially opposite directions, Flux at the interface towards the wall,

$$N_{i(v-b)} = -k_{(v-b)}(c_i - 0) \quad (2)$$