

STUDIES ON MASS TRANSFER IN ELECTROCHEMICAL CELLS WITH COAXIALLY PLACED ENTRY REGION COIL AS TURBULENCE PROMOTER IN ANNULAR CONDUIT IN HOMOGENEOUS FLOW

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Abstract: Mass transfer data were obtained in annular conduit using an electrochemical technique with a potassium ferri-ferro cyanide redox system was chosen as system of the study. In annular conduit coaxially placed entry region spiral coil was used as turbulence promoters presented in this paper. Mass transfer coefficients were evaluated from measuring limiting currents. The study covered wide range of parameters like Effect of Pitch of the coil, Effect of Length of the coil, Diameter of the coil, Diameter of the coil wire, Diameter of the annular rod on mass transfer were studied. A model was developed for mass transfer data. A study is also made on the energy efficiency of the promoter. The Experimental mass transfer function in terms of geometric parameters have been developed and presented here under.

$$\bar{g}(h^+) = 5369.5 \text{Re}_m^{+0.19} \left(\frac{P_c}{d_e}\right)^{-0.19} \left(\frac{L_c}{d_e}\right)^{-0.30} \left(\frac{d_c}{d_e}\right)^{1.19} \left(\frac{d_w}{d_e}\right)^{0.21}$$

Keywords: Mass transfer, annular conduit, entry region spiral coil, turbulence promoter, modeling, augmentation.

I. INTRODUCTION

Augmentation of heat and mass transfer processes are never ending quest for an engineer or technologist. Augmentation of a transfer processes offer the following advantages. The other advantages are less floor area, ease in handling of raw material and utilities. These factors leads to the reduction unit product cost. Hence the augmentation technique found attractive for researchers. To arrive at this above objective, several strategies have been followed. The earliest augmentative technique is surface roughness [1] several works were reported in literature. Use of baffles [2] and surface alternations also come under this section. Works like spheres [3], fins [4], bluff bodies [5] and stream lined bodies [6] placed across the flow were also extensively found in literature. Flow through ducts and arched channels [7], jets [8] were also encountered. Investigations on insert promoters in heat and mass transfer operations were reported extensively. The work reported was on concentric rod placed in the circular conduit, since then heat and mass transfer studies with coaxially placed turbulence promoters were reported extensively. The investigation on co-axially placed promoters like twisted tapes[9], tapes wound on a rod[10], spiral coils[11], string of spheres[12] and cones[13], discs[14], orifices[15], circular rings places on a rod[16] were also studied. But works found in literature seemed to increase friction there by higher operating costs. This is particularly true for string of spheres, string of cone, string of discs [17], and flow past cylindrical rod (18), across stream lined bodies [19], and many devices like axially displaced promoters, and surface modifiers. In the present study an effort is made in acquiring higher augmentation rate with lower frictional losses. It will lead to the construction of energy efficient transfer operation. Several researchers

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employed swirl flow for the augmentation of their process. Therefore an attempt is made to employ swirl motion in achieving this objective swirl flow devices were incorporated in circular conduits and found their effectiveness on heat and mass transfer processes. Among the swirl generating devices twisted tapes [20], tapes wound on a rod [21], spiral coils [11], spiral coils placed on central rod of an annular conduits [22] and tangential entry of fluid are prominent. Among the coaxially placed promoters, Entry region swirl generating promoters received the attention of several researchers. Nageswara Rao V., and Rajendra Prasad P., [23] employed tape, tape-disc assembly as turbulence promoters in their study. Murali Mohan et al [24] used entry region coil and coil-disc assembly as turbulence promoters in circular conduits generated useful data for the augmentation. Present investigation is directed towards achieving energy efficient transfer process. To that effect, it envisaged to obtain mass transfer data at the inner wall of annular conduits along the length of the column. Subsequently, local mass transfer data were obtained and the results were reported. These results could be adopted for enhancing mass transfer processes like electro dialysis [25], ultra filtration [26], reverse osmosis [27] and several other processes and reported increased transfer rates. The electrochemical processes like electro winning [28], electro refining [29], electro milling [30] and electro organic synthesis [31] could employ swirl generating promoters to obtain higher transfer rates. Swirl flows have wide range of applications in various engineering areas such as chemical processes like mechanical mixing and separation devices, combustion chambers, turbo machinery, rocketry, etc. It can be effectively used in heat and mass transfer enhancements. Mass transfer with entry region spiral coil as turbulence promoter was selected for the present study. The parameters covered in the study are presented in Table: 1

Table: I Range of variables covered in the present study.

Variable	Minimum	Maximum
Pitch of the coil (P_c), m/turn	0.016	0.046
Length of the coil (L_c), m	0.05	0.16
Diameter of the coil (D_c), m	0.031	0.038
Diameter of the coil wire (D_w), m	0.006	0.008
Diameter of the annular rod (D_i), m	0.0127	0.0254
Reynolds number, Re	1200	14,500
Schmidt number, Sc	789	1132

A. The study is carried out to obtain the following information.

1. To obtain limiting currents data on the outer wall of an annular conduits with entry region spiral coil as turbulence promoters.
2. To study the effect of geometric parameters on mass transfer namely - pitch of the coil (P_c), length of the coil (L_c), diameter of the coil (D_c), diameter of the coil wire (D_w), and diameter of the annular rod (D_i) on the outer wall mass transfer coefficients.

B. The following information is derived out of the study.

1. Mass transfer coefficient is increases with increasing in velocity.
2. As the pitch of the coil increases mass transfer coefficient increases up to pitch of 3.6 followed by a marginal decrease. The pitches 1.6, 2.6 have shown a marginal change.
3. Mass transfer is increasing monotonously with increase in length of the coil.
4. The effect of mass transfer coefficient on the diameter of the coil is marginal because marginal variation is only possible.
5. The present study shows maximum augmentation of 10 fold over Lin et al and 1.58 folds over entry region coil without solids.
6. Correlations were developed based on semi theoretical considerations. Wall similarity concept is used in the development of correlations. The following Correlation developed for mass transfer is presented as

C. Mass Transfer:

$$\text{Homogeneous flow } \bar{g}(h^+) = 5369.5 \text{Re}_m^{+0.19} \left(\frac{P_C}{d_e}\right)^{-0.19} \left(\frac{L_C}{d_e}\right)^{-0.30} \left(\frac{d_c}{d_e}\right)^{1.19} \left(\frac{d_w}{d_e}\right)^{0.21}$$

1

This equation is useful for the design and development of energy efficient transfer processes.

II. EXPERIMENTATION

The experimental setup used for the study was similar to those used in earlier studies [1, 2, 3, 4 and 5]. Schematic diagram of experimental set up is shown in figure: 1. It was essentially consisted of a recirculation tank, an entrance calming section (A), a test section(B), and an exit calming section (C), thermo wells (E₁, E₂), flanges (F₁,F₂), gland nuts (G₁ to G₄), coiled copper tube (H), pump (P), rotameter (R), recirculation tank (T), U-tube manometer (UM) and valves (V₁ to V₅).

The recirculation tank was a cylindrical copper vessel of 100 liter capacity with a drain pipe and a gate valve (V₁) for periodical cleaning of the tank. A copper coiled tube (H) provided with perforations. The perforations were meant for bubble of nitrogen through the electrolyte. The bubbling of nitrogen through the electrolyte expels the dissolved oxygen present if any. The tank was connected to the pump with a 0.025 m diameter copper pipe on the suction line of the centrifugal pump. The suction line was also provided with a gate valve (V₂). The discharge line from the pump divided into two lines. One line served as a bypass and a controlled by valve (V₃) is incorporated in it. The other line was connected to the entrance calming section (A). A control valve (V₄) and a rotameter were also incorporated in the line. The control valve was used to regulate the flow of electrolyte. The rotameter served as flow measuring device. The rotameter has a range of 0 to 347x10⁻⁶ m³/s. The entrance calming section was circular copper pipe of 0.046 m ID provided with a flange and closed at the bottom with a gland nut (G₁). To an extent of 0.1m of entrance calming was filled with capillary tube to damp the flow fluctuations and to facilitate steady flow of the electrolyte through the test section.

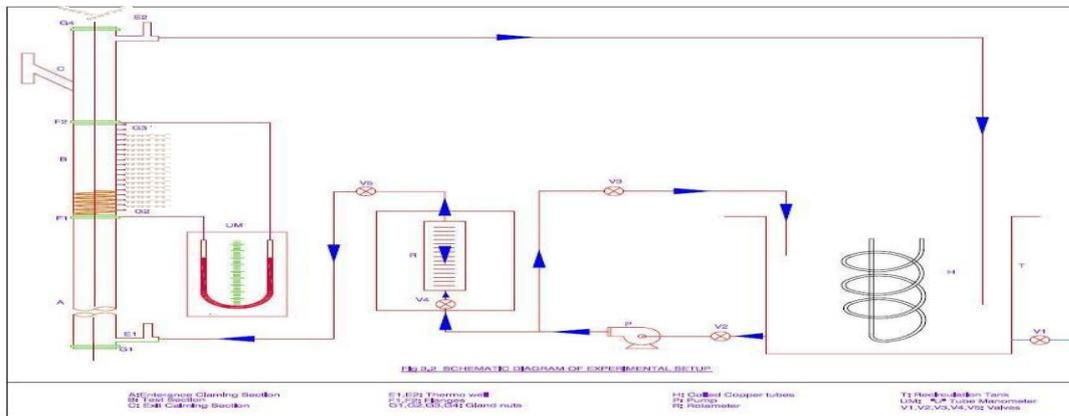


Fig. 1 Schematic Diagram of Experimental Set Up

A: Entrance calming section, B: Test section, C: Exit calming section, E₁, E₂: Thermo wells, G₁ to G₄: Gland nuts, F₁, F₂: Flanges, H: Coiled copper tube, P: Pump, R: Rota meter, T: Recirculation tank, UM: U tube manometer, V₁ to V₅: Valves.

The details of the test section are shown in figure: 2. it was made of a graduated perspex tube of 0.68 m length with point electrodes fixed flush with the inner surface of an outer wall of the test section. The point electrodes were made out of a copper rod and machined to the size. The electrodes were fixed flush with the inner surface of the outer wall of the test section at an equal spacing of 0.0254m. The diameter of the exit calming section was also of the same diameter. The entrance calming section made of copper tube of 1.8m long, and it was provided with a flange on the upstream side for assembling with the test section. The exit calming is also made of copper tube of length 0.7m and diameter of 0.046m. The exit and entrance calming sections were provided with gland nuts (G₂, G₃) at the top and bottom ends. The column comprised of three sections namely the entrance calming section, the test section and the exit calming section. These sections were assembled by means of flanges F₁, F₂. Two thermo wells (E₁, E₂) were provided,

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one at upstream side of the entrance calming section and the other at the downstream side of exit calming section to measure the temperature of the electrolyte.

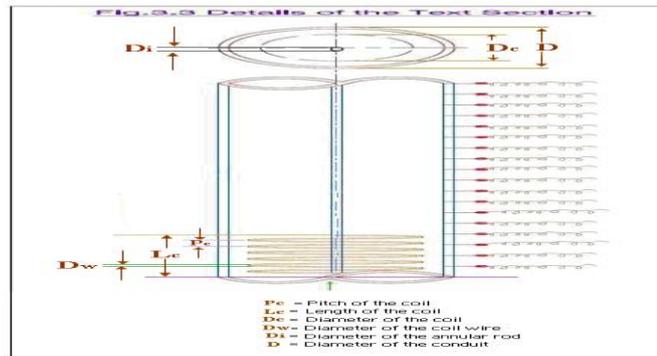


Fig. 2 Details of Test Section

The coil is fixed at the entrance of the test section with the help of flanges. And the central rod is placed inside the column from top to bottom. The entry region coil was a spiral coil made from a copper wire of 0.006, 0.007, 0.008m diameters. The copper wire was coiled to obtain coil diameters of 0.031m, 0.034 and 0.038m. The pitches of the coils were varied as 1.6, 2.6, 3.6, 4.6cm. The spiral coil was welded to a flange. The flange has a matching perforation with that of test section. It is placed concentrically in the test section and fixed via flanged joints.

Multimeter of Motwane make with accuracy of 0.01mA was used as an ammeter and another multimeter was acted as voltmeter and has an accuracy of 0.01V. They were used for measuring the limiting currents and potentials respectively. The other equipment used in circuit was rheostat, key, commutator, selector switch and a lead acid battery. The battery served as the power source. The commutator facilitated to reverse the polarity. The measurement of limiting currents for reduction process was taken. The selector switch facilitated the measurements of limiting currents at any desired electrode.

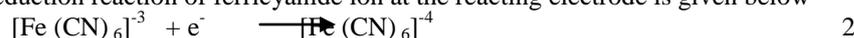
Table: II Details of the coil assembly promoter covered in the present study:

Pitch of the Coil (P_c), m	: 0.016, 0.026, 0.036, 0.046
Length of the Coil (L_c), m	: 0.05, 0.09, 0.12, 0.16
Diameter of the Coil (D_c), m	: 0.031, 0.034, 0.038
Diameter of the coil wire (D_w), m	: 0.006, 0.007, 0.008

D. Experimental Procedure:

The limiting current data were obtained for the case of reduction of ferricyanide ion in annular conduit in the presence of entry region spiral coil as insert promoters in homogeneous flow.

The cathodic reduction reaction of ferricyanide ion at the reacting electrode is given below



Eighty liters of equimolar solution of 0.01 N Potassium ferricyanide and 0.01N Potassium ferrocyanide with 0.5N NaOH as electrolyte was prepared used as the system. The electrolyte was analyzed for ferrocyanide ion concentration by volumetric titration method using standard potassium permanganate solution [1] and for ferricyanide ion using idometric method [2]. The viscosity of the solutions at different temperatures were measured with Ostwald Viscometer and densities were measured using specific gravity bottle. The point electrodes in the test section were polished using four zero emery to get a smooth surface followed by degreasing with trichloroethylene solution. The size of the electrode was measured with a traveling microscope. After fixing the promoter in position, blank runs i.e were conducted with sodium hydroxide electrolyte alone to ensure that the limiting currents obtained were due to diffusion of reacting ions (Ferricyanide ion) only. Subsequently, known quantities of potassium ferricyanide and potassium ferrocyanide were added to get the concentration of electrolyte was maintained at equimolar 0.01M Ferri-ferro Cyanide couple was maintained. The coils of known geometry were fitted at the entrance of the test section by means of flanged joint and the annular rods were fixed by means of gland nuts. The experiments were

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repeated by replacing the coil and /or annular rod. The electrolyte was pumped at a desired flow rate (through the test section) by operating the control and by-pass valves. After the steady state was attained, potential was applied across the test electrode and wall electrode in small increments of potential (100mV) and the corresponding current values were measured for each increment. As the area of the wall electrode was relatively large in relation to the area of the test electrode, nearly constant potential was obtained at the test electrode. Since the potential values are not of criteria in the present study, the limiting currents only were obtained from the current and potential data. The experiment was repeated by changing the flow rate of the electrolyte and the limiting currents measurements were taken for each flow rate. The experiment was repeated by changing the flow rate of the electrolyte and the limiting currents measurements were taken for each flow rate. Measurement of limiting current: The plots of current versus potential data yields limiting currents. Increase in potential increases the current up to certain value and further increase in potential would be maintained nearly constant current values, which is taken as the limiting current. Mass transfer coefficients were computed from the measured limiting currents by the following equation:

$$k_L = \frac{i_L}{n F A C_o} \tag{3}$$

Pressure drop measurements for each flow rate were made simultaneously by using a U – tube manometer with Carbon tetrachloride as manometer liquid.

III. RESULTS AND DISCUSSION

This chapter deals with 7500 local limiting current data obtained at the outer wall of an annular conduit fitted with an entry region spiral coil as a turbulence promoter. Local limiting currents at the outer wall of an annulus were measured along the length of the column. Cathodic reduction of ferricyanide ion was chosen as the system for the present study.

E. Studies on homogeneous flow with entry region coil in annular conduits:

Mass transfer

The experimental measurements consists of the flow rate of an electrolyte (Q), limiting current (i_L). From the measured current potential data, limiting currents were identified. The concentration of reacting ion (C_o) was estimated by idometry. Physical properties of the solution namely density (ρ), viscosity (μ) were measured by suitable method. The values of Diffusivities (D_L) were estimated by the method mentioned in experimental procedure. Diameter of the test section (d) and dimensions of the promoter assembly viz., pitch of the coil (P_C), length of the coil (L_C), diameter of the coil (D_c), diameter of the wire of the coil (D_w), diameter of the annular rod (d_i) and temperature (T), were measured with suitable instruments.

The limiting currents obtained from the study were transformed into mass transfer coefficients using the following expression.

$$k_L = \frac{i_L}{AnFC_o} \tag{4}$$

The velocity of the fluid flow was computed from the following expression.

$$V = \frac{Q}{\frac{\pi}{4} (d_e^2)} \tag{5}$$

F. Local Variation of Mass Transfer along the Length of the Column:

Local limiting currents are plotted against distance from the start of the coil which was fixed at the entrance of test section and could be seen in figure: 3. The limiting current value are found to fluctuating little extent with distance indicating oscillatory behavior, but the oscillating tendency is dampened with the length of the test section. It reveals the following information.

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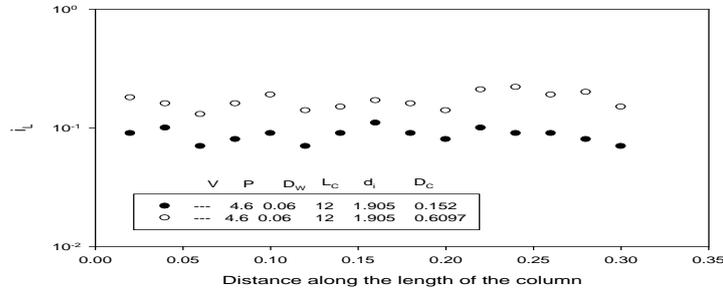


Fig: 3. variation of k_L with distance along the length of the column

The enhancements in limiting currents are largely uniform along the length of the test section. The augmentation is continuous and nearly uniform with small fluctuations when observed along the length of the column. For much longer distances, the limiting current values would have been decreased if the study continues further along the length of the column and it is supposed to reach that of the conduits with no promoter and no solids. The local i_L values were arithmetically averaged and are nearly coinciding with the values computed with integral averaging method and used in the further analysis. Limiting currents are increasing with increase in the velocity. At higher velocities a marginal declining tendency in oscillating behavior was seen from the figure. The data was analyzed in terms of dynamic and geometric parameters of the study. Range of variables covered in this study is given in the table 1. and table 2.

Range of variables covered in homogeneous flow of fluid is presented in the table 2.

Table: 2		
Variable	Minimum	Maximum
Pitch of the coil (P_c), m/turn	0.016	0.046
Length of the coil (L_c), m	0.05	0.016
Diameter of the coil (D_c), m	0.031	0.038
Diameter of the coil wire (D_w), m	0.006	0.008
Diameter of the annular rod (d_i), m	0.0127	0.0191

G. Augmentation Capacity of the Promoter

The entire data that forms bound for the study are identified and shown in figure: 4 as plot A is the best augmenting set it mean the promoter geometry with which maximum augmentation is obtainable while plot B is the least augmenting one which mean the promoter with geometric configuration produces minimum augmentation obtainable within the range of variables covered in the present study. The plot C is the data obtained from Lin et al for tube without any promoter. These promoters augment mass transfer rate from 2 folds to 4 folds at a velocity of 10 cm/s while that tapered off 1.67 to 2.5 for the best augmenting one at a velocity of 40 cm/s.

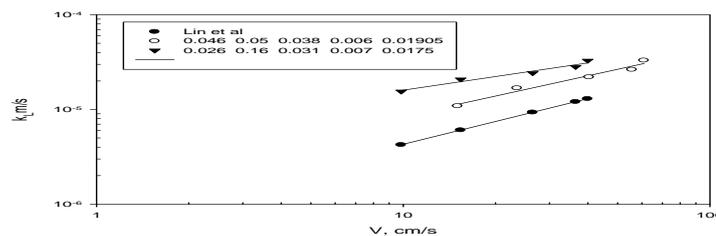


Fig: 4 Augmentation level graph

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H. Effect of Length of the Coil (L_c):

Length of the coil has strong influence on mass transfer. Entry region coils guide the fluid element and transform the axial flow into swirl flow. As the length increases transformation of flow from axial to swirl is intense which can be observed physically at the start of the experiment. The mass transfer coefficient is supposed to increase to a maximum value followed by a decreasing zone as indicated in the earlier study by Murali Mohan et al [21] but in the present case the swirl is increasing in monotonous manner. It may be attributed due to the higher velocities obtainable in annular conduits. Therefore, annular conduits support longer entry region coils to enhance swirl flow. To observe the possible peak L_c value, further study is required with larger length of the coil. The figure: 5 reveals as the length of the coil increases mass transfer increases. The coils with $L_c=12, 16$ has reasonably higher augmentation. The coils with L_c of 5, 9 have shown lower augmentation capacity as they have insufficient surface of the coil wire element to transform the flow sufficiently into swirl and crossing the values of empty conduit. It can be concluded that coil lengths of 5, 9 cm are not suitable for the augmentation.

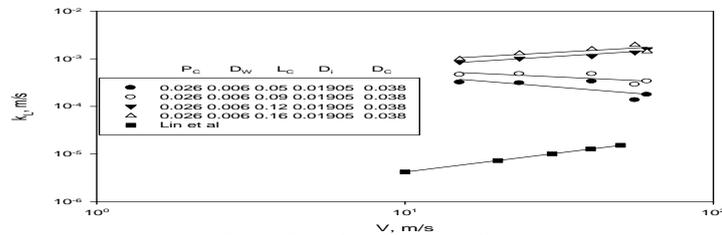


Fig: 5 Effect of length of the coil

I. Pitch of the coil:

Pitch of the coil is defined as distance per cycle. Pitch of the coil is varied from 1.6 to 4.6 cm. Figure: 6 reveals, as the pitch increases mass transfer coefficient marginally increases up to pitch of 3.6 followed by a decrease. On further increase in pitch, a decrease in mass transfer was recorded. This observation was in line with many earlier workers (1, 2, 3, and 4). But the pitch that records maximum mass transfer coefficient is different for different studies. In the present study the pitch 3.6 cm was recorded as maximum augmenting one, hence it is recommended for obtaining maximum augmentation.

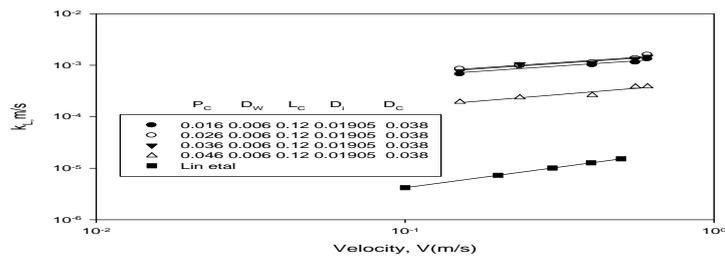


Fig: 6 Effect of pitch of the coil on mass transfer

J. Effect of Coil Wire Diameter:

The coil wire diameter has sufficient influence on mass transfer coefficient. Figure: 7 reveal that mass transfer coefficient is increasing with increase in diameter of the coil wire. It may attributed that larger the coil wire diameter has greater surface area. The surface area of the coil drags the fluid element and transforms the axial flow to the swirl. But some amount of energy is consumed as the coil retards the momentum of the fluid.

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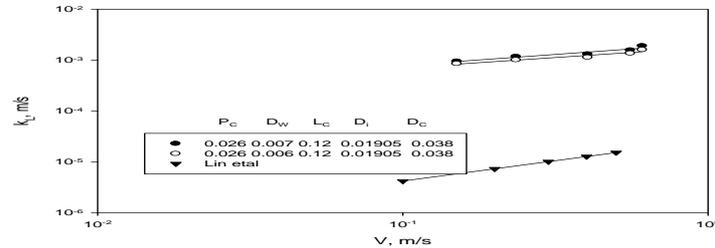


Fig: 7 Effect of coil wire diameter as parameter

K. Effect of Diameter of the Coil:

Coil diameter has strong influence on mass transfer coefficient. To know the effect of coil diameter, a graph is drawn shown as figure: 8. Coil diameters were varied as 3.1cm, 3.8cm. The coil which is in the middle of the cross section has greater augmentative capacity as it encounters fluid elements of higher velocities there by transformation of axial flow to swirl flow is greater. The coil that is placed near the wall encounters low velocity fluid that was caused by the formation of boundary layer. The fluid elements away from the wall, i.e near to centre have greater influence. Lesser coils provide greater augmentation at higher superficial velocity.

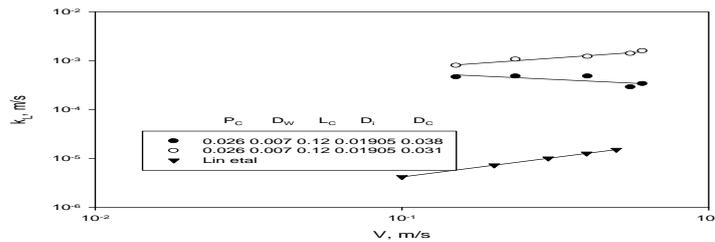


Fig: 8 Effect of coil diameter on mass transfer

L. Augmentation Capacity:

Augmentation capacity of the promoter can be judged by the augmentation factor defined as k_L/k_{L0} . A graph is drawn as augmentation factor versus Reynolds number for two sets of data which were nearly minimum and maximum respectively and shown as figure: 9. The maximum augmenting set exhibited a minimum near the Reynolds number of 14000 followed by an increase. The minimum augmenting one is nearly uniform with marginal augmentations. A careful selection of promoter would yield optimum conditions for the operation.

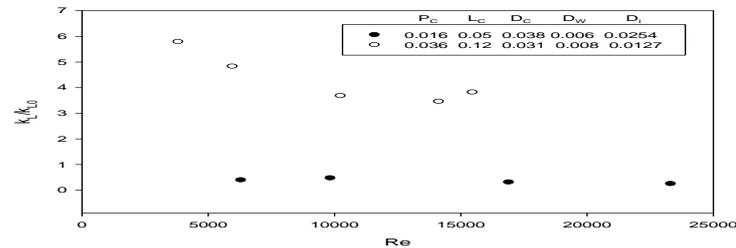


Fig: 9 Level of augmentation for homogeneous flow

M. Energy enhancements over the data of smooth pipe flow

The energy requirement for unit area of the cell is calculated by the following equation.

$$E = \frac{Q \Delta P}{(\pi d L + \pi d_i L)}$$

The energy loss in the case of pipe without any insert in them is indicated by E_0 . The

energy factor is defined as E/E_0 . A graph is drawn as energy factor versus Reynolds number and presented as figure: 10. These figures reveal energy factors are decreasing with Reynolds number.

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N. Performance of the entry region coil promoter

Performance factor (η) is the ratio of augmentation factor to energy factor and defined by the following equation.

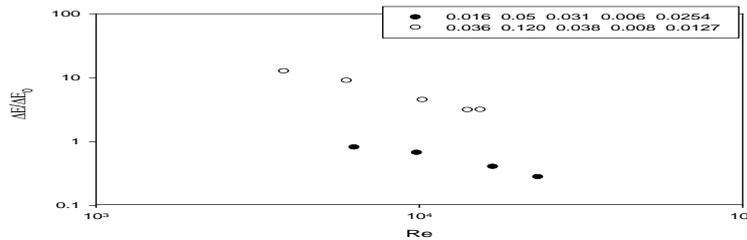


Fig: 10 variation of augmentation factor with Reynolds number

$$\eta = \frac{k_L/k_{L0}}{E/E_0} = \frac{k_L/k_{L0}}{\Delta P/\Delta P_0}$$

A graph is drawn energy factor with Reynolds number for two different sets with coils of varying geometric configuration as shown in inset and shown as figure. 10. The figure reveals the energy factor is decreasing with Reynolds number. Further increase in Reynolds number would remain constant which is could be seen when range flow rate increased further.

The efficiency η is a measure for efficiency of the promoter. Efficiency of the promoters under study could be judged from graphs of η versus Reynolds number. A graph is drawn as performance factor versus Reynolds number and shown as figure: 11. The Performance is increasing linearly with Re. The promoter producing maximum turbulence is augmenting better and the efficiencies are increasing steeply indicating higher augmentation at lower flow rates.

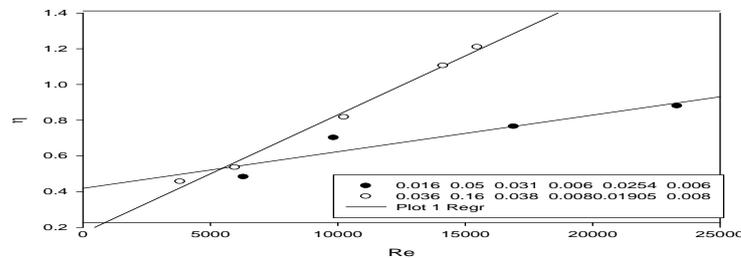


Fig: 11 Variation of effectiveness factor with Reynolds number

IV. DEVELOPMENT OF CORRELATIONS FOR MASS TRANSFER

Flow of electrolyte through circular conduit with entry region coil as insert promoters will establish mass and concentration profiles and was shown in figure: 12. 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 that is independent of time.
2. The turbulent 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. The mass flux varies in the radial direction. The mass flux varies linearly with y, and is represented by the equation.
- 4.

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

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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,

$$N_{i(v-b)} = k_{(v-b)} (c_i - 0) \tag{7}$$

Flux at the interface towards the axis,

$$N_{i(t)} = -k_{(t)} (c_i - c_b) \tag{8}$$

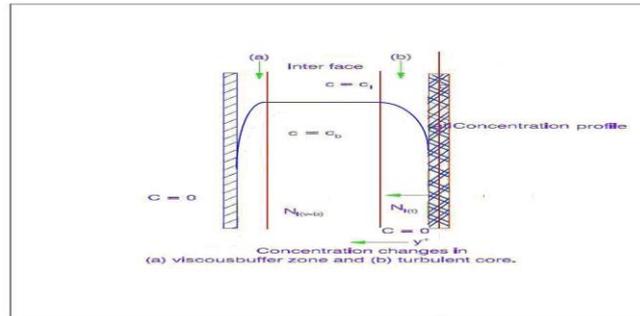


Fig. 12 Mass and Concentration Profiles

5. The shear stress is constant in the radial direction. Deissler and Eian [12] have found that the velocity and concentration profiles are relatively insensitive to shear stress distribution for fully developed turbulent fluid flow, hence can be assumed constant.
6. In the viscous buffer zone the eddy diffusivity and eddy viscosity ratio varies along with the distance from the wall and is independent of Sc. Direct numerical simulations presented by Lyons et al [13] suggest Sc to be unity at the wall. Hence, in the present case it is assumed that as $y^+ \rightarrow 0$, $Sc=1$.
7. The eddy diffusivity controls transfer process in viscous-buffer zone, while eddy viscosity controls the transport in turbulent core.

O. Model Development

In turbulent core, the intensity of eddies will be higher than the v-b zone. Therefore, during the transfer process, the resistance to the exchange of mass between the bulk fluid and the solid surface is often confined to the viscous and buffer region. The total resistance to the transfer process is the sum of the resistances in the viscous-buffer zone and turbulent layer, represented by Aravinth, S [14]

$$\frac{1}{k} = \frac{1}{k_{v-b}} + \frac{1}{k_t} \tag{9}$$

Equation 9 represents a two-layer resistance separated by an interface, similar to that proposed by Hugh mark [15]. The total resistance in the v-b zone and the turbulent core is represented by equation 9 and are similar to the boundary layer resistance and the resistance corresponding to random eddies in the region beyond the boundary layer of Hughmark [15]. For a fully developed turbulent flow, the shear stress and the mass flux can be written as,

$$\tau = (\mu + \rho\varepsilon) \frac{du}{dy} = \rho (v + \varepsilon) \frac{du}{dy} \tag{10}$$

$$N = (D + D_e) \frac{dc}{dy} \tag{11}$$

In the viscous-buffer region

Equation 11 on integration with the boundary conditions: At $y=0$, $c = 0$ and at $y = y_i^+$, $c = c_i$

$$\int \frac{dc}{N_{i(v-b)}} = \int \frac{dy}{D + D_e}$$

Substitution of equation 10 in 11 gives.

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$$\frac{\Delta c}{N_{i(v-b)}} = \frac{1}{\sqrt{\tau_0/\rho}} \int_0^{y_1^+} \frac{dy^+}{\frac{Sc}{1} + \frac{D_e(y^+)}{\nu}} \tag{12}$$

Combining equation 7 and 12 yields,

$$\frac{1}{k_{v-b}} = \frac{1}{\sqrt{\tau_0/\rho}} \int_0^{y_1^+} \frac{dy^+}{\frac{Sc}{1} + \frac{D_e(y^+)}{\nu}} \tag{13}$$

In the turbulent region

As the transport is mainly by eddy means, the molecular diffusivity and the viscosity can be neglected in the turbulent core. Combining equation 10 and 11 and integrating along the turbulent layer with the boundary conditions: $c=c_b$ at $u = u_b$ and $c=c_i$ at $u = u_i$, yields.

From equation 11 / 10

$$\frac{dc}{du} = \frac{N_{i(t)}}{\tau_0} \left(\frac{v_t}{D_t} \right) \tag{14}$$

Substitution of equation 8 in 14

$$\frac{1}{k_t} = \int_{y_1}^0 \frac{-du}{\tau_0} \left(\frac{v_t}{D_t} \right) = \frac{-(u_i - u_b)}{\tau_0} \cdot \Phi \tag{15}$$

$$\frac{1}{k_t} = \frac{\Phi u_b}{\tau_0} \left(1 - \frac{u_i/u^*}{u_b/u^*} \right) = \frac{\Phi u_b}{\tau_0} \left(1 - \frac{u_i^+}{u_b^+} \right) \tag{16}$$

In turbulent core $u_m \cong u_b$, $u_m^+ = u_b^+ = \sqrt{\frac{2}{f}}$ 17

Substitution of equation 17 in 16

$$\frac{1}{k_t} = \frac{\Phi u_b}{\tau_0} \left(1 - u_i^+ \sqrt{f/2} \right) \tag{18}$$

The resistance in series definition

Equation 13 and 18 can be added using the resistance in series definition, i.e equation 9

$$\frac{1}{k} = \frac{1}{\sqrt{\tau_0/\rho}} \int_0^{y_1^+} \frac{dy^+}{\frac{Sc}{1} + \frac{D_e(y^+)}{\nu}} + \frac{\Phi u_b}{\tau_0} \left(1 - u_i^+ \sqrt{f/2} \right) \tag{19}$$

Applying the assumption 12 that eddy viscosity controls the transfer process in turbulent core. Hence $\Phi = 1$.

$$\frac{1}{k} = \int_0^{y_1^+} \frac{dy^+}{\frac{Sc}{1} + \frac{D_e(y^+)}{\nu}} + \sqrt{2/f} - u_i^+ \tag{20}$$

$$\frac{1}{k} = \frac{1}{St \cdot u_b} = \frac{1}{St \cdot \sqrt{2/f}} = \frac{\sqrt{f/2}}{St} \tag{21}$$

Substitution of equation 21 in 20

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$$\frac{f/2St-1}{\sqrt{f/2}} + u_i^+ = \int_0^{y_i^+} \frac{dy^+}{\frac{1}{Sc} + \frac{D_e(y^+)}{\nu}} = g(Re_m^+, Sc) \quad 22$$

$$\bar{g}(h^+) = g(h^+) (Re_m^+). F(Sc)$$

$\bar{g}(h^+)$ is taken as the product of two independent functions namely $g(h^+)$ and $F(Sc)$.

$g(h^+)$ is a function of (Re_m^+) and $F(Sc)$ is a function of Sc .

$F(Sc)$ is taken as $Sc^{2/3}$ in line with Lin et al. From the earlier studies [9, 14], u_i^+ is same as $R(h^+)$

Where $R(h^+) = 2.5 \log(2D_w / d_e) + \sqrt{2/f} + 3.75$

' f ' is friction factor obtained from measured pressure drops. The function u_i^+ = identically equal to momentum roughness function = $R(h^+)$. The Reynolds number was modified and defined as follows separately for homogeneous flow defined in the following equations.

Homogeneous flow

$$Re_m^+ = \left(\frac{D_w}{d_e}\right) \cdot Re \cdot \sqrt{f/2}$$

$$f = \frac{\Delta p \cdot d_e \cdot g_c}{2 \cdot L \cdot V^2 \cdot \rho}$$

$$g(h^+) = \left(\frac{(f/(2St)-1)}{\sqrt{f/2}} + R(h^+) \right)$$

$$\bar{g}(h^+) = Sc^{0.666} \cdot \left(\frac{(f/(2St)-1)}{\sqrt{f/2}} + R(h^+) \right)$$

$$g(h^+) = \left(\frac{(f/(2St)-1)}{\sqrt{f/2}} + R(h^+) \right)$$

Correlation for Mass Transfer in Homogeneous flow:

The data was subjected to regression analysis in terms of Colburn j factor and also with additional geometric groups of the promoter. The correlations developed are associated with very high deviations. Hence an alternative approach was followed. The method utilizes roughness mass transfer function. It is mentioned in the above section. The results were promising and are presented hereunder.

The function $\bar{g}(h^+)$ is influenced by Re_m^+ and geometric parameters.

$$\bar{g}(h^+) = g(Re_m^+, \Phi_1, \Phi_2, \Phi_3, \Phi_4, \Phi_5) \cdot Fr$$

The geometric groups followed are Fr is Froude group

$Fr = V^2 / (d_e \cdot g)$ For Homogeneous flow

To reduce the complexity Froude group is eliminated and the following and the following equation is suggested.

Data yielded the following equation for entry region spiral coil assembly as turbulence promoter.

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$$\bar{g}(h^+) = 5369.5 \text{Re}_m^{+0.19} \left(\frac{P_C}{d_e}\right)^{-0.19} \left(\frac{L_C}{d_e}\right)^{-0.30} \left(\frac{d_C}{d_e}\right)^{1.19} \left(\frac{d_W}{d_e}\right)^{0.21} \tag{23}$$

Average deviation =10.85, Standard deviation =12.46

Rem⁺ is roughness Reynolds number defined by the following equations for entry region coil assembly as promoters.

$$\text{Re}_m^+ = \left(\frac{d_w}{d_e}\right) \cdot \text{Re} \cdot \sqrt{f/2} \tag{24}$$

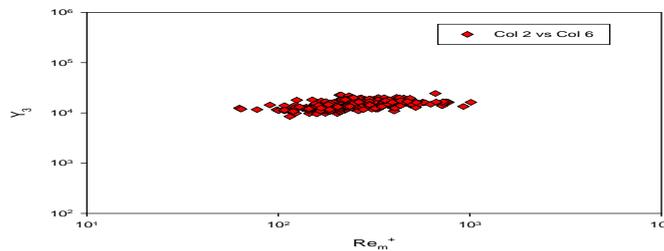


Fig. 13 Correlation graph representing equation 24

The correlation graph for mass transfer in homogeneous flow representing equation 24 is shown in the above figure.

V. CONCLUSIONS

Homogeneous flow:

Mass Transfer:

1. The limiting current value are found to fluctuating little extent with distance indicating oscillatory behavior, but the oscillation tendency is dampened with the length of the test section.
2. The mass transfer coefficient is increasing with the length of the coil. As the pitch increases mass transfer coefficient marginally increases up to pitch of 3.6 followed by a decrease.
3. Mass transfer coefficient is increasing with increase in diameter of the coil wire. Larger coils provide greater augmentation at higher superficial velocity. The augmentations are decreasing to a minimum followed an increase in Reynolds for most of the coils under study

$$\bar{g}(h^+) = 5369.5 \text{Re}_m^{+0.19} \left(\frac{P_C}{d_e}\right)^{-0.19} \left(\frac{L_C}{d_e}\right)^{-0.30} \left(\frac{d_C}{d_e}\right)^{1.19} \left(\frac{d_W}{d_e}\right)^{0.21} \tag{25}$$

Nomenclature:

- A = Area of electrode, m²
- C = constants of correlations of equations
- c = concentration of electrolyte, kg-mole/ m³
- c_l = length of the conduit, m
- d = diameter of the conduit, m
- d_e = equivalent diameter, m
- D = diffusion coefficient, m²/ s
- D_c = diamètre of the coil, m
- D_w = diamètre of the coil wire, m
- D_i = diamètre of the annular rod, m
- D_e = eddy diffusivity, m²/s
- F = faraday's constant = 96,540 coulombs/ g-mole

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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, $y_1 u^*/\nu$

Dimensionless

$g(h)$ = modified mass transfer function for homogeneous flow of fluid = $\left(\frac{(f/(2St)) - 1}{\sqrt{f/2}} + R(h^+) \right)$

$\bar{g}(h)$ = modified mass transfer function for homogeneous flow of fluid = $Sc^{0.666} \cdot \left(\frac{(f/(2St)) - 1}{\sqrt{f/2}} + R(h^+) \right)$

Re_m^+ = modified Reynolds number for homogeneous flow, = $\left(\frac{D_w}{d_e} \right) \cdot Re \cdot \sqrt{f/2}$

$R(h^+) = 2.5 \ln[2(D_w)/d_e] + \sqrt{2/f} + 3.75$

St = Stanton number, k/u_b or k_L/V

Sc = Schmidt number, ν/D

Φ = Ratio between total of molecular and eddy viscosity and Total of molecular and eddy diffusivity, (ν_i/D_i)

$\Phi_1 = P_c/d_e$

$\Phi_2 = L_c/d_e$

$\Phi_3 = D_c/d_e$

$\Phi_4 = D_w/d_e$

$\Phi_5 = D_i/d_e$

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, $kg/m s^2$, $f/2 \cdot \rho \cdot u_b^2$

ν = kinematics viscosity

ν_e = eddy kinematics viscosity

Subscripts

b = buffer

i = interface

o = wall

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p = based on particle diameter

t = total of molecular and eddy

v = viscous, V-b = viscous buffer region

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