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Studies on Mass Transfer in Annular Conduits with Coaxially Placed Entry Region Vane Assembly as Turbulence Promoter in Homogeneous Flow

T. Penta Rao, P. Rajendra Prasad, V. Sujatha*
Electro Chemical Research Laboratory, Department of Chemical Engineering, A.U. College of Engineering (A), Andhra University, Visakhapatnam, Andhra Pradesh, India

Abstract

Studies on mass transfer in annular conduits with coaxially placed entry region vane assemblies as turbulence promoter in homogeneous flow were presented in this paper. The electrolytes used were equimolal potassium ferricyanide, potassium ferrocyanide and excess sodium hydroxide. Limiting current data had been obtained for the reduction of potassium ferricyanide ion. 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 promoters – diameter of the vane(d_v) from 0.02 to 0.04 m, angle of the vane (γ) from 15° to 60°, sectorial angle (α) / number of the vanes (N) from 4 to 8. The correlation is extended to a wider range of parameters by virtue of the law of the wall. Experimental mass transfer function in context to geometric parameters have been developed and presented.

$$\bar{g}(h^+) = 0.20347\times10^{-8}[\mathrm{Re}_m{}^+]^{1.792}\left(\frac{V^2}{d_{e.}g}\right)^{-0.583}(\tan\gamma)^{-0.034}\left(\frac{2\Pi}{\alpha}\right)^{0.0071}\left(\frac{d_V}{d_e}\right)^{-1.961}$$

Keywords: annular conduit, augmentation, entry region vane, mass transfer, modeling

Abbreviations: b, buffer; **e,** equivalent diameter; **Fr,** Froude group; **i,** interface; **o,** wall; **t,** total of molecular and eddy; **v,** vane; **v,** viscous; **v-b,** viscous buffer region

****Corresponding Author***
E-mail: praophd@gmail.com

INTRODUCTION

Process intensification has long been pursued with the following objectives namely reduction in equipment size that results in reduction in product cost, debottlenecking of the process. Flow of electrolyte through annular conduits with coaxially placed insert promoter generates a variety of flow fields. The turbulence promoters have a good command in electro chemical reactors such as electro winning, refining, electro organic synthesis etc. Efforts have been continued on the investigation in the field of achieving energy efficient mass transfer cells with assembly of vanes.

The studies on turbulence promoters that are directly relevant to the present study are summarized. 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 vane assembly as turbulence promoter. In pursuit of this several strategies have been devised and implemented. Mahinpey *et al*.[2] pressed an electrochemical technique with the ferri-ferrocyanide system to obtain transient mass transfer coefficients for smooth pipes. The diffusion controlled transfer is in good agreement with the heat transfer solution. Chiou[3] made experimental investigation for the augmentation of heat transfer coefficient in forced convection heat transfer. Nagaoka *et al*.[4] studied the effects of various types of guide vanes and coiled wires on the local heat transfer coefficient and pressure drop for water flowing through a long 2.2 inch I.D tube. Changal Raju[5] obtained data on mass transfer at wall electrodes using limiting current technique. Rajendra Prasad[6] analyzed ionic mass and momentum transfer with coaxially placed spiral coils as turbulent promoter in homogeneous flow and fluidized beds. He also carried out experiments using ferri-ferro cyanide system by limiting current technique. Smith Eiamsa – ard *et al*.[7] studied heat transfer, friction loss and enhancement efficiency behaviors in a heat exchanger tube that was equipped with propeller type swirl generators at several pitch ratios (PR). They also carried out experiments for many blade numbers of the propeller (N = 4/6/8) and for different blade angles (θ = 30°/45°/60°). The influences of using the propeller rotating freely, on heat transfer enhancement, pressure loss, and enhancement efficiency were reported. The vanes of the swirl generator were designed to be adjustable to obtain several swirl intensities. Yapici *et al*.[8] investigated of local mass transfer behavior at the inner rod and outer pipe wall of an annular test section in decaying annular swirl flow generated by axial vane – type swirl generators. Four swirl generators with vane angles of between 15 and 60° to the axis of the duct were used. Yapici *et al.*[9] presented the correlations of local mass transfer at the inner rod and the outer wall in annular decaying swirl flow generated by axial vane swirl generators. Four swirl generators with vane angles in the range 15°–60° to the duct axis were used. Zaherzadeh *et al.*[10] studied the decaying swirl flows created by tangential vane swirl generators. Of all the tangential vane swirl generator configuration parameters, the width has the largest influence on the heat–transfer rate. Yapici *et al*.[11] carried out electrochemical study of local mass transfer behavior in decaying annular swirl flow. Initially, flow visualization experiments were conducted to observe the general behavior of the flow. It was found that the swirl angle decays exponentially along the tube. Ji *et al*.[12] the effects of spacer grids and mixing vanes on critical heat flux (CHF) have been experimentally investigated for low–pressure water at low, using two different types of test sections: An obstruction – type spacer and a split – vane type mixing vane were used for the annulus and round tube test sections, respectively. Yilmaz *et al.*[13] investigated experimentally the heat transfer and friction characteristics of a decaying swirl flow. The swirling motion of the air was produced by a radial guide vane swirl generator. The vanes of the swirl generator were designed to be adjustable to obtain different swirl intensities. Different guide vane angles (15°, 30°, 45°, 60°, and 75°) were used for the swirling flow experiments. Mehmet Yilmaz *et al*.[14] studied the effect of the geometry of the deflecting element in the radial guide vane swirl generator on the heat transfer and fluid friction characteristics in decaying swirl flow. Betul Ayhan Sarac *et al*.[15] carried out experiments to investigate heat transfer and pressure drop characteristics of a decaying swirl flow in a horizontal pipe. The decaying swirl flow is produced by the insertion of vortex generators with propeller-type geometry, a kind of passive heat enhancement tools. Algawair *et al*.[16] studied the thermal development in a stationary cooling passage which consists of two straight ducts of square cross section, with inclined ribs on two opposite sides connected by a square – ended U – bend. Thundil Karuppa Raj *et al.*[17] focused on arriving at best vane angle from aerodynamic aspects for the combustion applications. The flow parameter involved the selection ofappropriate turbulence model for the prediction. Khalil *et al.*[18] experimentally investigated the heat transfer and pressure drop characteristics of turbulent swirling air flow through a sudden expansion pipe with different swirl angles and different sudden expansion ratio. The effects of the sudden expansion ratio, Reynolds number, vane angle and swirl generator location on the heat transfer and pressure drop were examined. Ahmadvand *et al.*[19] studied the influences of axial vane swirler on heat transfer augmentation and fluid flow. The swirl generators were installed at the inlet of the annular duct to generate decaying swirling pipe flow and different blade angels were examined. Present investigation is therefore under taken and essentially deals with the evaluation of mass transfer rate at the wall through limiting current technique, in presence of coaxially placed entry region vane assembly as turbulence promoter in homogeneous flow.

EXPERIMENTATION

The schematic diagram of experimental set up is shown in Figure 1. The equipment essentially consisted of a recirculation tank, a centrifugal pump, rotameter, and an entrance calming section, a test section and an exit calming section. The test section was made of a graduated Perspex tube of 0.44 m length with point electrodes which are fixed flush on the inner surface of an outer wall of the test section at an equal spacing of 1 cm. The point electrodes were made out of a copper rod and machined to the size. The promoters was mounted in the test section coaxially by means of gland nuts and positioned by supporting grid. Entry region vanes assembly as turbulence promoter was made of copper with provision to fix it rigidly within the test section. The vanes are made from different discs with diameter 2, 3, 4 cm each. Each disc has centrally located circular perforation. Discs were cut into different sectorial pieces. The sectorial angle was varied as 90, 60, 45 yielding 4, 6, 8 vanes, respectively. Vanes are mounted on a central rod with varying angle (γ). Where (γ) is the angle made with vertical axis of central rod and it varied as 15°, 30°, 45°, and 60° with axis. Thus made vane mounted central rods were inserted axially into the column. So that vanes are located at the entrance of the test section. Limiting currents were measured at the wall, on the downstream side of the vane assembly. In another case vane assembly was fixed such that its location is at the extreme end of test section. The details of the test section for downstream entry region vane assembly are shown in Figure 2. After inserting the promoter in the column, 80 litres of equimolal solution of 0.01 N of Potassium ferricyanide and 0.01 N of Potassium ferrocyanide with 0.5 N sodium hydroxide as electrolyte was prepared in the storage tank. The electrolyte is Newtonian and it has density of 1023 kg/m^3. The limiting current data were obtained for the case of reduction of ferricyanide ion in annular conduit in the presence of entry region vane as insert promoters in homogeneous flow. The concentration of the electrolyte is maintained constant throughout the experiment, small changes of temperature of electrolyte offers changes in Schmidt number. The solution is kept in dark and closed recirculation tank. 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 (100 mV) and the corresponding current values were measured as the area of the wall electrode was relatively larger than 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. Limiting current data were measured at point copper electrodes for the reduction of potassium ferricyanide ion. The photographs of entry region vane promoters are shown in Figure 3. This type of limiting current measurement with current potential data has been practiced by the procedure followed by the similar to the works of Lin *et al.*[1] and several workers in earlier works.[5,6] 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_L, ρ. Thermometers are attached at both ends of the column. The electrochemical reaction involved is given below:

$$[Fe(CN)_6]^{-3} + e^- \rightarrow [Fe(CN)_6]^{-4} \qquad \text{Eq. (1)}$$

The limiting current was indicated by a small increase in current for a sharp increase in voltage.

The ranges of variables covered in homogeneous flow of fluid are presented as the Table 1. Mass transfer coefficients are computed from the measured limiting currents by the following expression:

$$k_L = \frac{i_L}{nFAC_o} \qquad \text{Eq. (2)}$$

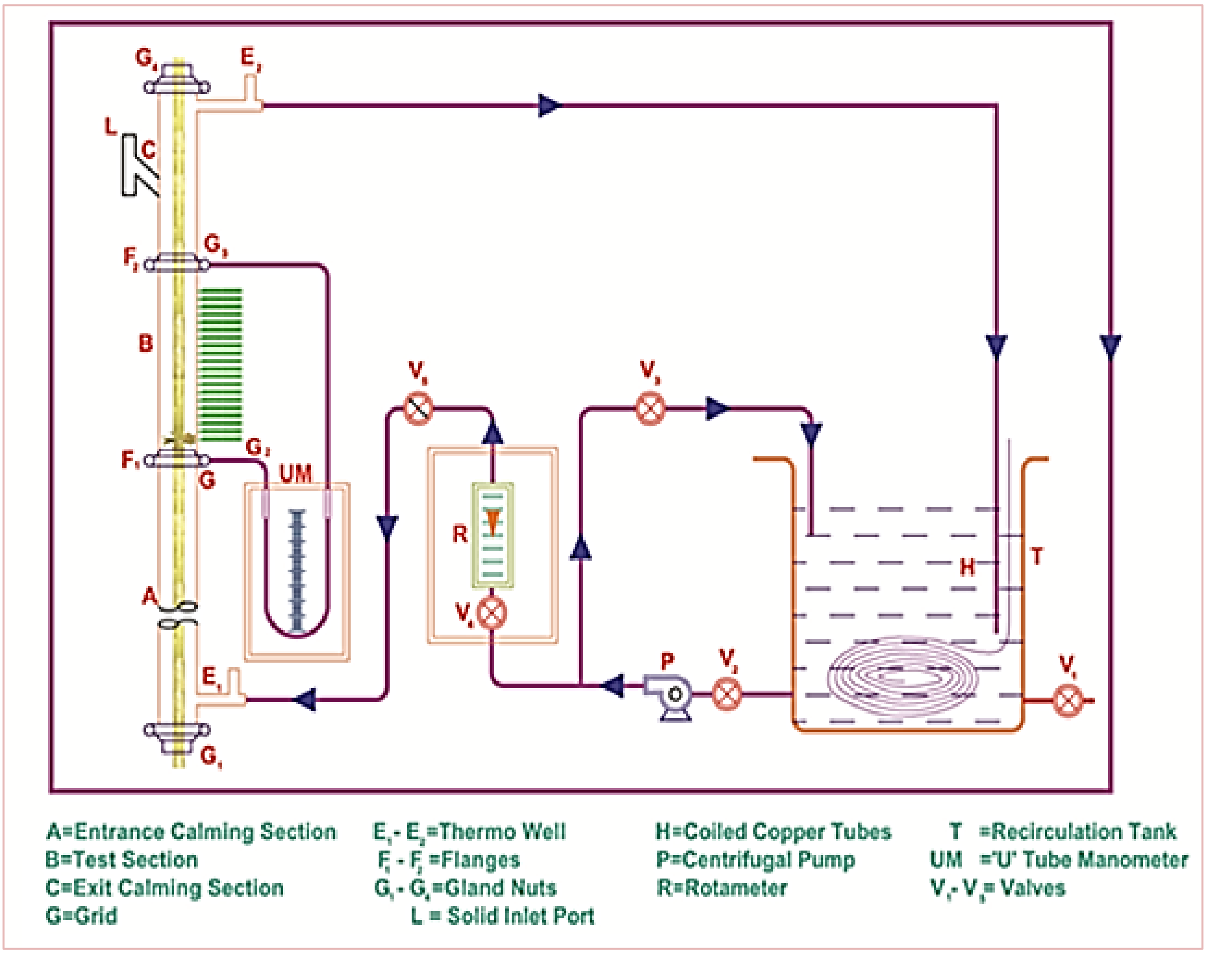

Fig.1: *Schematic Diagram of The experimental Setup*

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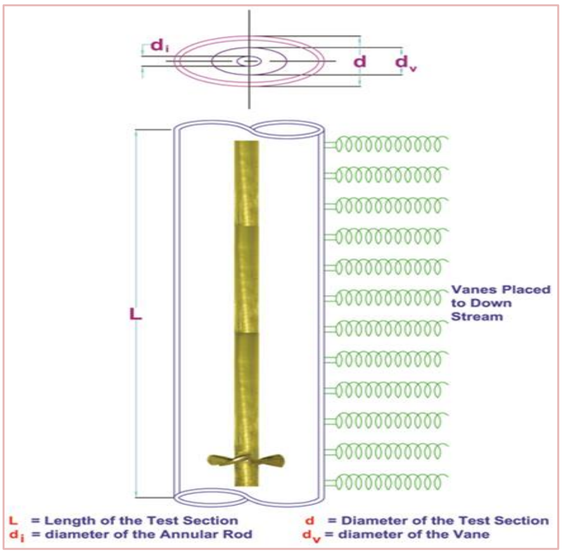

Fig.2: *Details of the Test Section for Down Stream Entry Region Vane Assembly*

Fig.3: *Photograph of entry region vane promoters*

Table 1. *Range of Variables Covered in the Present Study.*

Variable	Minimum	Maximum
Diameter of the vane (d_V), m	0.02	0.04
Angle of the vane (γ)	15	60
Sectorial angle (α), degree	90	45
Number of the vanes (N)	4	8
Reynolds number, Re	2900	10,700
Schmidt number, Sc	846	1116

RESULTS AND DISCUSSIONS

Local Variation of Mass Transfer along the Length of the Column

Experiments were conducted with entry region vane promoter assembly in homogeneous flow of electrolyte. Local limiting currents were measured at the outer wall of test section by means of point electrodes fixed flush with the test section. The local limiting currents obtained were plotted against distance from 11 cm after the start of the test section *i.e.*, 11 cm after the test section, where entry region sectorial vanes placed on annular rod. This can be seen from the Figure 4. The limiting current values are found to fluctuate with distance, indicating oscillatory behavior, but the oscillating tendency is dampened with the length of the test section.

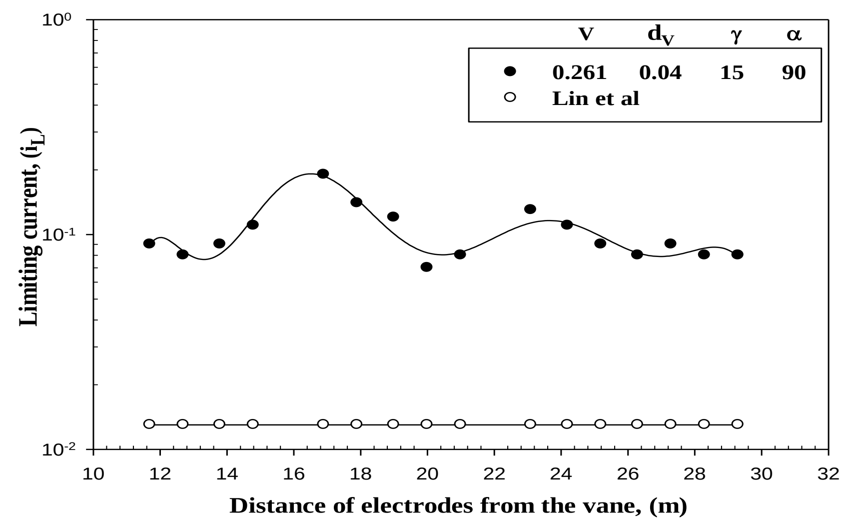

Fig. 4 : Variation of limiting current with distance of electrodes from the vane at a down stream of velocity, V=0.261m/s.

Figure 4 is a plot of local limiting current versus distance of electrodes from the vane assembly for the set mentioned in inset. The figure reveals limiting current (i_L) is fluctuating with distance due to shock waves generated in the fluid. Limiting current (i_L) values rise to a peak value followed by number of peaks and transfers. These peaks dampen quickly at the distance reached to 30 cm. Augmentation of limiting current over Lin *et al.*[1] ranges from 5.76 to 14.3%. It is found to augment 7-fold over Lin *et al.*[1] at a velocity of 0.261 m/s.

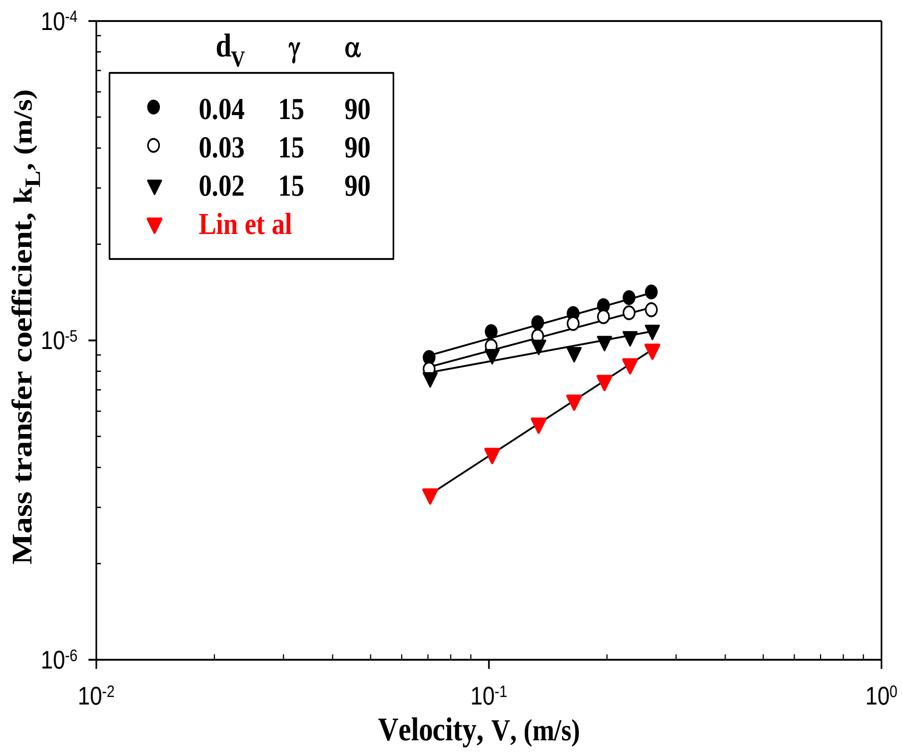

Fig. 5 : Variation of mass transfer coefficient with velocity - Effect of diameter of the vane (d_V)

Effect of Diameter of the Vane (d_V) on Mass Transfer

Diameter of the vane is defined as the diameter of the disc from which vanes were cut out into sectorial pieces. Diameter of the vane is varied from 0.02 to 0.04 m. A graph of mass transfer coefficient (k_L) versus velocity (V) is shown in Figure 5, with diameter of the vane as parameter. Lin *et al.*[1] conducted experiments in circular and annular conduits without any promoter inside the conduit and predicted data is shown as a plot in 5. Mass transfer coefficient is found to increase with increase in vane diameter. The augmentations obtained are 2.31–2.72 fold over Lin *et al.*[1] at a velocity of 0.0709 m/s. Larger the vane diameter, greater the friction it offers. It is expected due to its larger surface area and hence its capacity to transform the axial flow into swirl. The swirl scours away the laminar sub layer and hence lowers the resistance to mass transfer and hence higher mass transfer coefficients.

Effect of Angle of the Vane (γ) on Mass Transfer

The Figure 6 shows the effect of angle of the vane (γ) on mass transfer. Tests were carried out using five swirlers with vane angle of 15°, 30°, 45° and 60°, respectively. The figure reveals that as the vane angle increases from 15° to 45°, the mass transfer coefficient (k_L) initially decreased followed by an increase, but as the angle of the vane was increased above 45°, the swirl flow was imparted, and swirl flow was diminished progressively, hence decrease in mass transfer coefficient was observed.

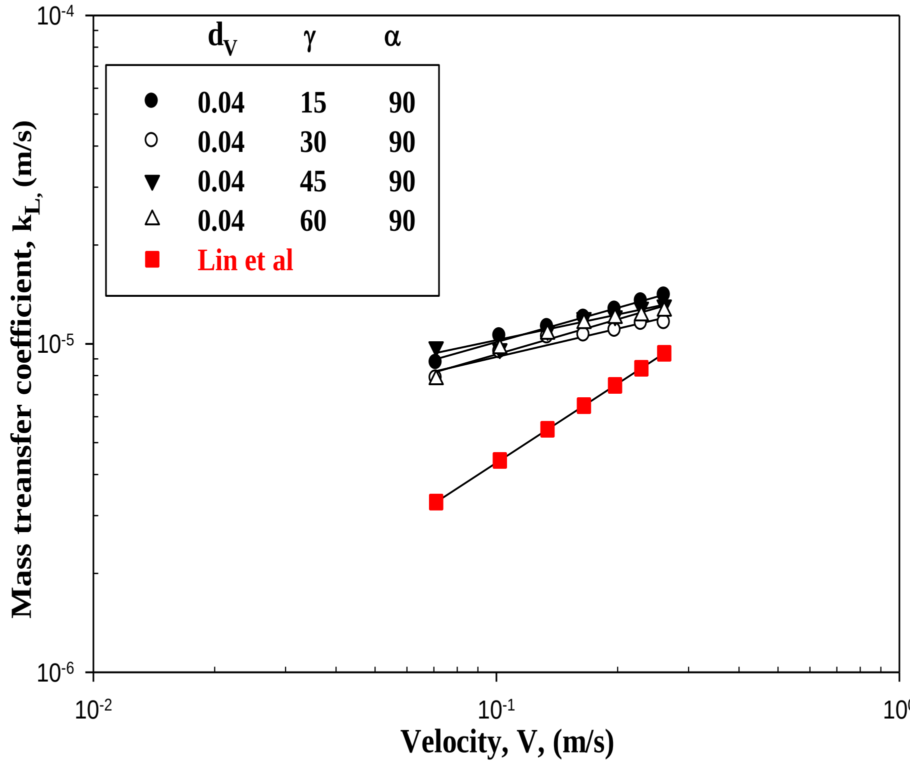

Fig. 6 : Variation of mass transfer coefficient with velocity - Effect of angle of the vane (γ)

Effect of Sectorial Angle (α)/Number of the Vanes *(N)* on Mass Transfer

(α) is sectorial angle of vane in the vane assembly and has the following relation with number of the vanes. $\alpha = 2\pi / N$ (or) $N = 2\pi / \alpha$. Where N= number of the vanes. Sectorial angle (α) and N have the inverse relationship. Values of sectorial angle (α) are varied from 45° to 90°. If the sectorial angle (α) value varies 90°, 60°, 45° the resulting number of vanes are 4, 6, 8 respectively in assembly. A graph is drawn between mass transfer coefficients (k_L) versus velocity with sectorial angle (α) as parameter and shown in Figure 7. In the present study, sectorial angle (α) is varied as 45°, 60° and 90° and the corresponding numbers of vanes are 8, 6, and 4 respectively. The figure revealed the following information. Mass transfer coefficient, increased with increase in velocity. As sectorial angle (α) value decreased, mass transfer coefficient values increased (or) the values of mass transfer coefficient increased with increasing number of vanes. As sectorial angle (α) decreased from 90° to 45°, the corresponding augmentation ranged 2.27–2.72 fold over Lin *et al.*[1] at a velocity 0.0709 m/s. The figure revealed that the vane assembly promoter is effective at lower velocities. As the velocity increased, mass transfer coefficient values with promoter approached the values of Lin et al[1] showing that the promoter is less effective.

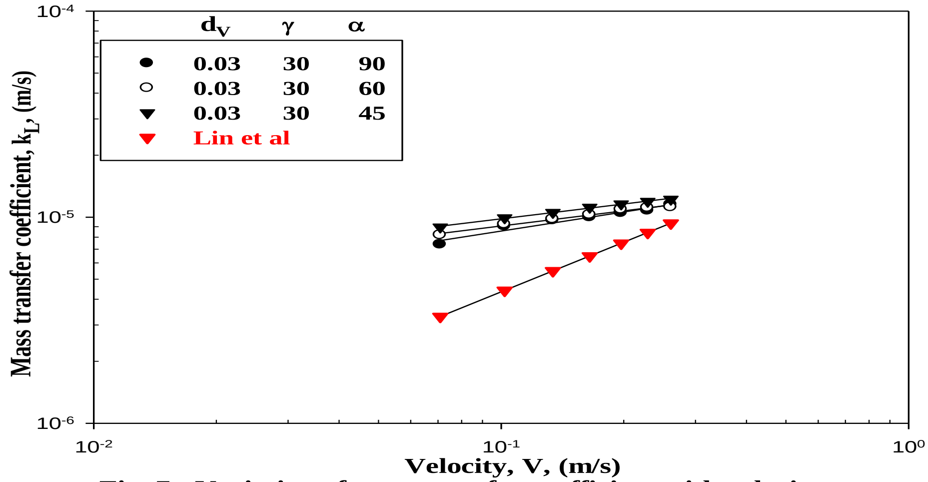

Fig. 7 : Variation of mass transfer coefficient with velocity - Effect of Sectorial angle (α) / Number of the vanes *(N)*

Level of Augmentation for Homogeneous Flow with Velocity

Augmentation Capacity

Augmentation capacity of the promoter is judged by comparing the mass transfer coefficient (k_L) with that obtained from conduit without promoter computed from Lin et al (k_{Lo}). Augmentation factor is the ratio of mass transfer coefficient with and without promoter (k_L/k_{Lo}). Figure 8, is the plot drawn between augmentation factor, (k_L/k_{Lo}) versus velocity. Promoter which yields maximum and minimum augmentation within the range of parameters is covered in the present study. Plot A represents the promoter (d_V=0.04, γ =15°, α=90) which is the highest augmenting set while B is the data of lowest augmenting set among all the promoters of the study. The augmentation decreased with velocity; the decrease in augmentation has reduced as velocity increased and reached a nearly constant value at a higher velocity. Further increase in velocity would yield meager any augmentation but higher throughputs are achievable. Augmentation at a velocity of 0.0709 m/s is 2.37-3.20 folds within the range of variables covered in the study, while it tapered off at a higher velocity of 0.261 m/s from 1.16- to 1.58-fold.

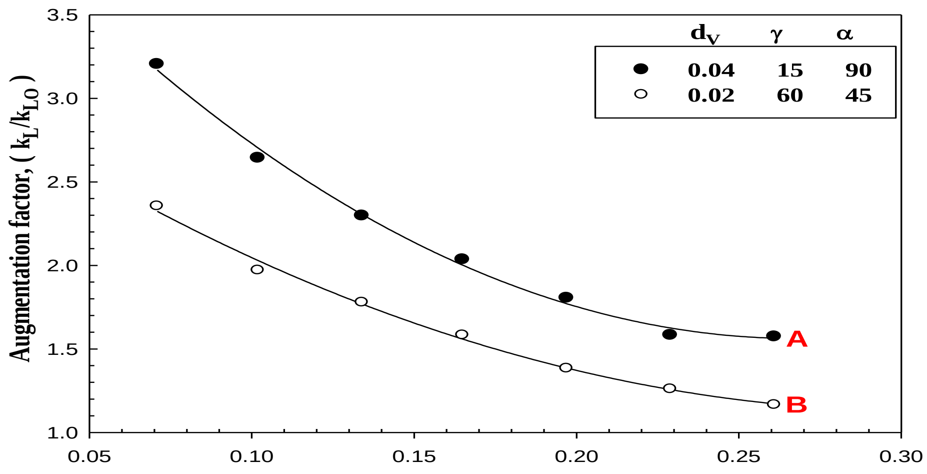

Fig. 8 : Variation of augmentation factor with velocity

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DEVELOPMENT OF GENERALIZED CORRELATIONS

The promoter is placed along the column on the downstream side of the promoter along the wall of test section. Mass transfer coefficients were computed and correlations were developed and presented below along with observed deviations.

The data was subjected to regression analysis in terms of Colburn j factor which is applicable only circular conduit flow and not correlated well. The correlations thus developed are associated with very high deviations. Hence an alternative approach was followed. Therefore similar method was followed using $\bar{g}(h^+)$ which a function is of $\mathrm{Re}_m^{\ +}$ and geometric parameters.

$$\bar{g}(h^+) = g(\mathrm{Re}_m^+, \Phi_1, \Phi_2, \Phi_3, \Phi_4 \Phi_5).Fr$$

The geometric groups followed are
Fr is Froude group

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

$\Phi_1 = \mathrm{Re}_m^{\ +}$, $\Phi_2 = V^2/d_{e.}g$, $\Phi_3 = \tan\gamma$,
$\Phi_4 = 2\Pi/\alpha$, $\Phi_5 = d_V/d_e$

Development of correlation has been carried out in the conventional lines by relating j_D factors with Reynolds numbers and other dimensionless groups as in earlier studies.[5,6] The regression analysis of the data yielded the following equation with an average deviation of 7.4588% and Standard deviation of 9.7320%.

The resultant function can be represented as

$$\bar{g}(h^+) = 0.20347\times 10^{-8}[\mathrm{Re}_m^{\ +}]^{1.792}\left(\frac{V^2}{d_{e.}g}\right)^{-0.583}(\tan\gamma)^{-0.034}\left(\frac{2\Pi}{\alpha}\right)^{0.0071}\left(\frac{d_V}{d_e}\right)^{-1.961} \quad \text{Eq. (3)}$$

The correlation graph for mass transfer in homogeneous flow representing Equation (3) is shown in the above Figure 9.

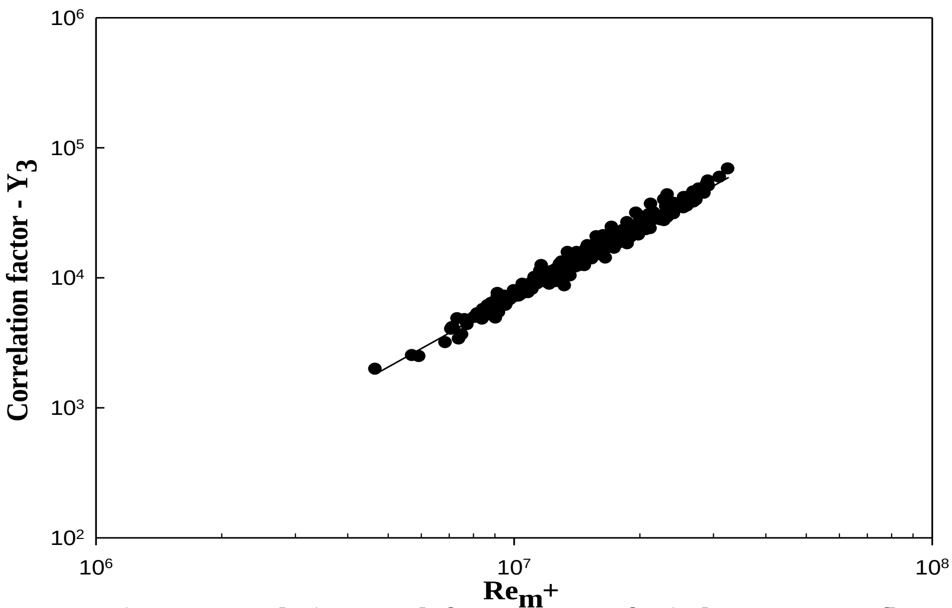

Fig. 9 : Correlation graph for mass transfer in homogeneous flow

COMPARISON OF CORRELATION

Yapici *et al*. experimental data for his promoter was taken and Y_3, $\mathrm{Re}_m^{\,+}$ were computed in line with present analysis and presented in Figure 9A, along with present data. Correlation for the present study is agreeing with Yapici *et al.*[11].

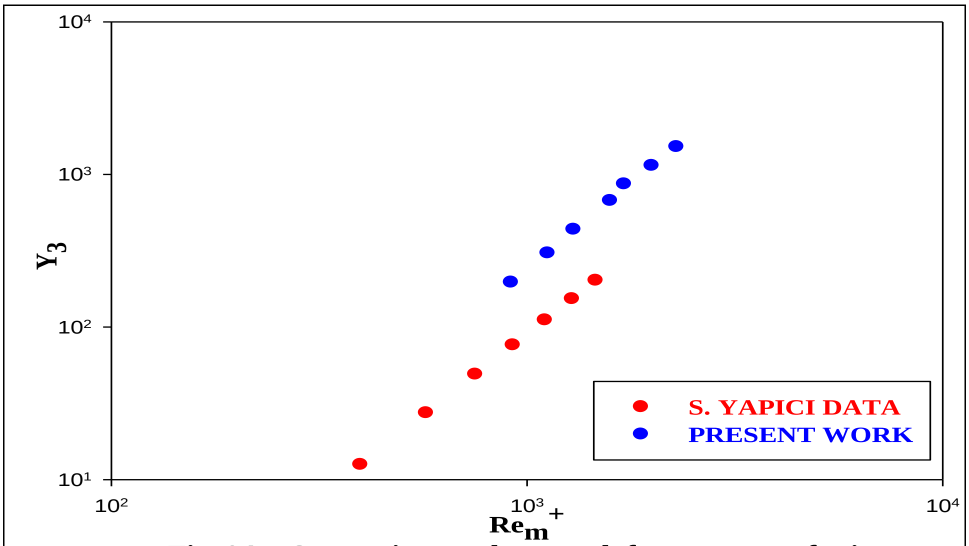

Fig. 9A : Comparison author graph for mass transfer in homogeneous flow

CONCLUSIONS

The figure reveals limiting current (i_L) is fluctuating with distance due to shock waves generated in the fluid. Limiting current values rise to a peak value followed by number of peaks and transfers. These peaks dampen quickly as the distance reached to 30 cm. Mass transfer coefficient (k_L) is increase in velocity and in vane diameter. The augmentations obtained are 2.31–2.72 folds. When the vane angle increased from 15° to 45°, the mass transfer coefficient (k_L) initially decreased followed by an increase, but as the angle of the vane was increased above 45°, the swirl flow was imparted, and swirl flow was diminished progressively, hence decrease in mass transfer coefficient was observed. Mass transfer coefficient, (k_L) increased with increase in velocity.

As sectorial angle (α) value decreased, mass transfer coefficient values increased (or) the values of mass transfer coefficient increased with increasing number of vanes.

The augmentation decreased with velocity; the decrease in augmentation has reduced as velocity increased and reached a nearly constant value at a higher velocity. Further increase in velocity would not yield any augmentation but higher throughputs are achievable. Augmentation at a velocity of 0.0709 m/s is 2.37 to 3.20 folds within the range of variables covered in the study, while it tapered off at a higher velocity of 0.261 m/s from 1.16 to 1.58 fold.

Model developed for mass transfer in homogeneous flow is as follows.

$$\bar{g}(h^+) = 0.20347\times10^{-8}[\mathrm{Re}_m^{\,+}]^{1.792}\left(\frac{V^2}{d_e g}\right)^{-0.583}$$

$$(\tan\gamma)^{-0.034}\left(\frac{2\Pi}{\alpha}\right)^{0.0071}\left(\frac{d_V}{d_e}\right)^{-1.961}$$

Nomenclature

A = Cross-sectional area of the conduit, m^2
A_e= Area of electrode, m^2
C= Constants of correlations of equation 3
C_0= Concentration of electrolyte, kg-mole/ m^3

C_l = Length of the conduit, m
d = Diameter of the test section/conduit, m
d_e = Equivalent diameter of the conduit, (d -di), m
D_L = Diffusivity of reacting ion, m^2/s
d_V = Diameter of the vane, m
γ = Angle of the vane, Radians
α = Sectorial angle *(2Π/N)*/Number of the vanes *(N)*
d_i = Diameter of the annular rod, m
d_p = diameter of the particle, m
D_e = Eddy diffusivity, m^2/s
F = Faraday's constant= 96,540 coulombs/ g-mole
g = Acceleration due to gravity, m/s^2
g_c = Gravitational constant
i_L = Limiting current, Amp
I_L= Limiting current density, amp/m^2
k_L = Mass transfer coefficient, m/s
k_{Lo} = Mass transfer coefficient of empty conduit, m/s
L = Length of the test section, m
N= Mass flux
Q = Volumetric flow rate, m^3/s
R = Radius of the conduit, m
u = Local velocity, m/s
u_i = Velocity at the interface, m/s
u_b = Average velocity, m/s
u^* = Frictional 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 = Distance from the wall, m
y_1 = Distance from wall at which u = u_b
y_1^+ = Dimensionless distance, yu^*/ν

Dimensionless

$g(h^+)$ = Modified mass transfer function for homogeneous flow of fluid
Re_m^+ = Modified Reynolds number for homogeneous flow
St = Stanton number
Sc = Schmidt number

Φ = Ratio between total of molecular and eddy viscosity and Total of molecular and eddy diffusivity (ν_t/D_t)
Φ_1 = Re_m^+
Φ_2 = $V^2/d_e.g$
Φ_3 = $\tan\gamma$
Φ_4 = $2\Pi/\alpha$
Φ_5 = d_V/d_e
n = Number of ions transferred
η = Performance factor

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. $\rho.u_b^2$
ν = Kinematics viscosity
ν_e = Eddy kinematics viscosity

Subscripts

b = Buffer
i = Interface
v = Vane
e = Equivalent diameter
o = Wall
t = Total of molecular and eddy
v = Viscous
v-b = Viscous buffer region

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