Mass Transfer with Equilateral Triangular Plate as Turbulence Promoter in Circular Pipe

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ABSTRACT: *Mass transfer data were obtained in circular conduit using an electrochemical technique with a potassium ferri-ferro cyanide couple. In circular conduit coaxially placed entry region equilateral triangular plate was used as turbulence promoter. The study comprised of evaluation of mass transfer rates at the outer wall of the electrochemical cell. Mass transfer coefficients were evaluated from the measured limiting currents. The study covered a wide range of geometric parameters such as side of the plate (S_p), thickness of the plate (T_p) and distance of the plate from the entrance of the test section (h). The results revealed that the mass transfer coefficient increased with increase in velocity, side of the plate (S_p), thickness of the plate (T_p) and decreased with increase in distance of the plate from the entrance of the test section (h). Within the range of variables covered, the augmentation achieved in mass transfer coefficients were up to 5.2 fold over the tube flow in absence of promoter. The entire mass transfer data were correlated with $g(h^+)$ and roughness Reynolds number. The following correlation was reported out of the study.*

$g(h^+)=1.0308\,(Re^+)^{0.0525}\,(\phi_1)^{0.2037}(\phi_2)^{0.16571}(\phi_3)^{-0.0527}(Sc)^{0.3227}$

Where $\phi_1=S_p/d$, $\phi_2=T_p/d$, $\phi_3=h/d$ are dimensionless groups, d is diameter of test section.

Keywords: *Mass transfer, equilateral triangular plate, turbulence promoter*

I. INTRODUCTION

Several researchers carried out extensive work to identify and establish different type of plate assemblies for enhancing heat, mass and momentum transfers in the reactors. In the operation of electrochemical reactor cells in the fields of electro-winning, refining, electro organic synthesis, etc., the significant importance of the cell plate characteristics, like its roughness, geometry, etc., has been well recognized. Lin et al [1] studied mass transfer rates with Ferri-Ferrocyanide systems in diffusion controlled reactions and Bergles [2] conducted an extensive review to evaluate an appropriate technique for improving heat and mass transfer. Several studies were also conducted by inserting string of spheres [3], string of discs [4], spiral coils [5], coaxially placed cones [6], axial rods with twisted tapes mounting [7], discs [8], orifices [9], across the flows in the conduits for increasing mass and momentum transfer. Coaxially placed tape-disc assembly was reported as a good turbulence promoter, thereby increasing mass transfer [10]. However, effects of coaxially placed equilateral triangular plate in circular conduits on mass transfer rates in case of forced convection flow of electrolyte have not been studied earlier and accordingly the present study was undertaken by the author to evaluate the benefits of turbulence on mass transfer by utilizing equilateral triangular plate placed coaxially in circular conduits and mass transfer rates at the conduit wall, by applying the limiting current technique. Pressure drop measurements were also carried out simultaneously to obtain data for computing power losses in the system.
Table 1 shows the parameters covered in the present study.

II. EXPERIMENTAL

Schematic diagram of experimental set up is shown in figure 1. It is similar in layout to that used in earlier studies [9, 10]. It essentially consisted of a storage tank (TS), centrifugal pump (P), rotameter (R), entrance calming section (E_1), test section (T) and exit calming section (E_2). The storage tank is cylindrical copper vessel of 100 liter capacity with a drain pipe and a gate valve (V_1) for periodical cleaning. A copper coil (H) with perforations is provided to bubble nitrogen through the electrolyte. The tank is connected to the pump with a 0.025m diameter copper pipe on the suction line of the centrifugal pump. The suction line is also provided with a gate valve (V_2). The discharge line from the pump splits into two. One served as a bypass line and controlled by valve (V_3). The other connects the pump to the entrance calming section (E_1) through rotameter. The rotameter is connected to a valve (V_4) for adjusting the flow at the desired value. The rotameter has a range of 0 to $166\times10^{-5}m^3/s$. The entrance calming section consisted of 0.05 m ID circular copper pipe with a flange and is closed at the bottom with a gland nut (G). The up-stream side of the entrance calming section is filled with capillary tubes to damp the flow fluctuations and to facilitate steady flow of the electrolyte through the test section. It is made of a graduated Perspex tube of 0.36m length with point electrodes fixed flush with the inner surface of the tube. The point electrodes are made out of a copper rod and machined to the size. They are fixed flush with the inner surface of the test section at equal spacing of 0.01m. Exit calming section is also of the same diameter copper tube of 0.5 m long, and it is provided with a flange on the upstream side for assembling the test section. It has gland nuts (G) at the top and bottom ends to hold the central tube. Two thermo wells (t_1, t_2) were provided, one at upstream side of the entrance calming section and the other at the down stream side of exit calming section for measurement of temperature of the electrolyte. Equilateral triangular plate serving as turbulence promoter is made of Nylon of various sizes with a provision to fix it rigidly within the test section. The plate is placed concentrically in the test section. The promoters used are shown in photograph in figure 2. The details of equilateral triangular plate promoter are shown in figure3. The limiting current measuring equipment consisted of multimeter of Motwane make which has 0.01mA accuracy and vacuum tube voltmeter is used for potential measurements. The other equipments used in circuit are rheostat, key, commutator, selector switch, and a lead acid battery as the power source. The commutator facilitated the measurement of limiting currents for oxidation and reduction process under identical operating conditions by the change of polarity while the selector switch facilitated the measurements of limiting currents at any desired electrode. The circuit diagram used for the measurement of limiting currents is shown in the figure 4.

Data on limiting currents for the case of reduction of ferricyanide ion is obtained for fluid flow in circular conduits in the presence of triangular plate as insert promoter. The following electrode reaction is involved.

Cathodic reduction of ferricyanide ion:

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

Initially blank runs are conducted with indifferent electrolyte (sodium hydroxide solution) alone to ensure that the limiting currents obtained in the subsequent runs are due to diffusion of reacting ions (Ferri cyanide ion) only. The electrolyte was pumped at a desired flow rate (through the test section) by operating the control and by-pass valves. After steady state is attained, potentials are applied across the test electrode and wall electrode in small increments of potentials (100mV) and the corresponding currents were measured for each increment. In view of the large area of the counter electrode in relation to the test electrode nearly constant potential is maintained at the test electrode. Since the potential values are not of criteria in the present study, the limiting currents were determined from the measurements of applied potentials and currents as has been done in several earlier works [9, 10]. The attainment of limiting current is indicated by the constancy of current with a large increase in the potential. Mass transfer coefficients are computed from the measured limiting currents by the following equation:

$$k_L = i_L/nFAC_0 \quad \text{……(2)}$$

Pressure drop measurements are also taken simultaneously using U-tube manometer with Carbon tetrachloride as manometric liquid.

III. RESULTS AND DISCUSSION

Introduction of co-axially placed equilateral triangular plate in a circular conduit alters the flow pattern in cell by generating eddies and wakes. These eddies generally consume large amount of energy because of their circulatory nature. The eddies will in turn influence shear forces near the wall region which in turn reduce the thickness of the concentration boundary layer, there by augmenting mass transfer rates. At higher flow rates, velocity through constriction between plate and wall of the test section dominates, while the energy utilized for the wakes and eddies becomes marginal and thereby, most of the energy is utilized. Table 2 indicates the exponent on velocity of the present study together with the other works. The exponent on velocity is comparable to that in the studies on mass transfer with different turbulence generating systems.

IV. Effect of geometric parameters

Effect of side of equilateral triangular plate (S_p):

Side of triangular plate has strong influence on mass transfer coefficient k_L. k_L versus velocity of electrolyte (V) is drawn for different sides of plate and is shown in figure 5. Various sides of triangular plate used in the present study are S_P=0.025m, 0.030m, 0.035m, 0.040m. Mass transfer coefficient increases with increase in side of triangular plate. The augmentation in mass transfer coefficient is 1.04 times over the smooth tube [1] for side of plate 0.025m at a velocity of 0.3936m/s while the augmentation is 1.64 times over the smooth tube [1] for the side 0.040m at the same velocity of 0.3936m/s.

Effect of plate thickness (T_p):

In figure 6, mass transfer coefficient k_L is drawn against velocity to study the effect of plate thickness on mass transfer by keeping all the other parameters constant. The thickness of the plate used in the present study are T_P=0.005m, 0.020m, 0.040m, 0.060m. Mass transfer coefficient increases from1.52 times to 5.23 times as the thickness of the plate increases from 0.005m to 0.060m at the velocity of 0.3936 m/s.

Effect of location of plate inside the test section (h):

As the distance of the plate from the entrance of the test section varied, extent of turbulence also varied because of change in circulating pattern and it is extended to both plate region and down stream region to plate region. Mass transfer coefficient (k_L) versus velocity of electrolyte for different distances of the plate(h) from the entrance of the test section are plotted and is shown in figure 7. Mass transfer coefficients are decreased from 1.8 to 1.23 over Lin et al [1] for the smooth tube, while the distance of the plate from the entrance of the test section increases from 0.14m to 0.30m

V. DEVELOPMENT OF CORRELATIONS

The data on mass transfer with equilateral triangular plate as turbulence promoter could well be calculated in the lines done in earlier studies [10]. Correlation of data using colburn J_D factor with Reynolds number yielded the following equation

$$J_D = 0.43641(Re)^{-0.38926} \qquad \text{............(3)}$$

Average deviation = 58.55, Standard deviation = 87.56
By incorporating dimensionless geometrical groups, the following correlation is yielded

$$J_D=0.163\times10^{-3}(Re)^{-0.3007}(\phi_1)^{0.9926}(\phi_2)^{0.4541}(\phi_3)^{-0.5566}(Sc)^{1.3054} \qquad \text{.............(4)}$$

Average deviation = 28.598, Standard deviation = 37.815
Where $\phi_1=S_p/d$, $\phi_2=T_p/d$, $\phi_3=h/d$, S_c which are dimensionless groups.

The above equation show large deviation. So mass transfer data are calculated in the lines similar to earlier studies [10] by using roughness mass transfer function $g(h^+)$ in place of 'J_D' and roughness Reynolds number Re^+ in place of Re. The side of plate S_P is chosen as effective geometric parameter.
$R(h^+)$ and Re^+ are defined as follows

$$R(h^+)=2.5\ln[2S_P/d)]+\sqrt{(2/f)}+3.75 \qquad \text{..............(5)}$$

$$Re^+ = (S_P/d).Re.\sqrt{(f/2)} \qquad \text{..............(6)}$$

$$g(h^+)=S_t/S_{to} + R(h^+) \qquad \text{..............(7)}$$

The following correlation is obtained without incorporating geometrical groups.

$$g(h^+)=3.3294\ (Re^+)^{0.1202} \qquad \text{............(8)}$$

Average deviation = 14.064, Standard deviation = 22.665
The following correlation is obtained by incorporating dimensionless geometrical groups and Schmidt number.

$$g(h^+)=1.0308\ (Re^+)^{0.0525}(\phi_1)^{0.2037}(\phi_2)^{0.16571}(\phi_3)^{-0.0527}(Sc)^{0.3227} \qquad \text{.............(9)}$$

Average deviation = 5.984, Standard deviation = 10.047
Correlation plot for equations (9) is presented in the figure 8.

VI. COMPARISON OF CORRELATIONS

For a selected set of geometric parameters correlation factor for mass transfer (Y_1) is plotted against Re^+, for comparison data with other studies namely Rao [14]. Having comparable geometric parameters, are computed with present method is shown in figure 9. The data falls close to the present study indicating correlation presented in the present work is comparable.

$$Y_1 = g(h^+) / (S_P/d)^{0.2037}(T_P/d)^{0.1657}(h/d)^{-0.0527}(Sc)^{0.3227} \qquad \text{..............(10)}$$

VII. CONCLUSIONS

Mass transfer coefficients are increasing with increase in velocity. Mass transfer coefficients are increasing with increase in side of plate (S_p). Mass transfer coefficients are increasing with increases in thickness of the plate (T_p) and decreases as distance of the plate (h) from the entrance of the test section increases. In the present study, it is found that side of plate (S_p) =0.040m, plate thickness (T_p)= 0.060m, distance of the plate from the entrance of the test section (h) =0.14m, offered maximum augmentation. A maximum augmentation of 5.23 folds is observed over smooth tube flow without turbulence promoter. Correlations developed based on semi theoretical considerations. Wall similarity concept is applied for the present case.
Correlations developed for mass transfer:

$$g(h^+)=1.0308\ (Re^+)^{0.0525}(\phi_1)^{0.2037}(\phi_2)^{0.16571}(\phi_3)^{-0.0527}(Sc)^{0.3227}$$

Dimensionless Groups:

J_D	=	Mass Transfer Factor $(k_L/V).S_C^{2/3}$
Re	=	Reynolds number = $dV\rho/\mu$
Re^+	=	Roughness Reynolds number = $(S_P / d).Re.\sqrt{(f/2)}$
$R(h^+)$	=	Roughness momentum transfer function = $2.5\ln(2 S_P /d)+\sqrt{(2/f)}+3.75$
St	=	Stanton number = k_L/V
St_o	=	Stanton number for conduit without internals
Sc	=	Schmidt number $\mu/\rho D_L$
Sh	=	Sherwood number $k_L.d/D_L$
u^+	=	dimensionless velocity, u/u^*
y^+	=	dimensionless radial distance from the wall, $y\,u^*/\nu$
$g(h^+)$	=	$S_t/S_{to} + R(h^+)$

Nomenclature:

d	=	Diameter of test section, m
D_L	=	Diffusivity of reacting ion, m^2/sec
E	=	Energy consumed using triangular plate in the conduit, N/m^2
E_o	=	Energy consumed for empty conduit, N/m^2
f	=	Friction factor, $\Delta p\, d\, g_c / 2LV^2 \rho$
ΔP	=	Pressure difference, N/m^2
F	=	Faraday's constant = 96,500 coulombs/g-mol
g	=	Acceleration due to gravity, m/sec^2
g_c	=	Gravitational constant.
i_L	=	Limiting current, amp
k_L	=	Mass Transfer coefficient, m/s
k_o	=	Mass transfer coefficient of the empty conduit, m/s
L	=	Length of Test section, m
n	=	Number of electrons transferred
Q	=	Volumetric flow rate, m^3/s
S_t	=	Side of plate, m
T_t	=	Thickness of plate, m
h	=	Location of the plate from the entrance of the test section, m
u	=	Local velocity, m/s
u^*	=	Friction velocity = $\sqrt{(\tau_w g_c / \rho)}$, m/s
V	=	Average velocity, m/s
y	=	Radial distance from the wall, m
Y_1	=	$g(h^+) / (S_P/d)^{0.2037} (T_P/d)^{0.1657} (h/d)^{-0.0527} (Sc)^{0.3227}$

Greek letters:

$\in$	=	Eddy viscosity, m^2/s
$\in_D$	=	Eddy diffusivity ,m^2/s
μ	=	Viscosity of fluid, Kg/m. sec
ν	=	Kinematic viscosity ,m^2/s
ρ_c	=	Density of manometer fluid, Kg/m^3
ρ	=	Density of fluid, Kg/m^3
τ_w	=	Shear stress, N/m^2

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Table: 1 Range of variables covered in the present study

Variable	Minimum	Maximum	Max/Min
Side of equilateral triangular plate, S_P , m	0.025	0.040	1.6
Thickness of equilateral triangular plate, T_P , m	0.005	0.060	12
Distance of the plate from entrance of the test section, h, m	0.14	0.30	2.14
Velocity V, m/s	0.0984	0.3936	4
Reynolds Number, Re	5264	21059	4
Schmidt Number, Sc	870.3	1040	1.19

Table 2:

Author	Promoter	System	Exponent on velocity	Range of Re
Klaczack [12]	Spiral coil	Mass transfer	0.520	1700-20000
Sujatha [7]	Tapes mounted on a rod	Mass transfer	0.490	1348-30605
Venkateswarlu [4]	String of discs	Mass transfer	0.498	3300-18650
Sitaraman [3]	String of spheres	Mass transfer	0.556	100-34000
Sarveswara Rao [6]	String of cones	Mass transfer	0.431	690-20200
Changal Raju [11]	Wires wound on a rod	Mass transfer	0.490	1500-20000
Nageswara Rao [10]	Tape-disc assembly	Mass transfer	0.485	1300-12000
Teja Latha et al [13]	Square grooved Serrated disc	Mass transfer	0.205	1933-19337
P Jagannadha Rao[14]	Square plate assembly	Mass transfer	0.482	5856-15226
Present work	Equilateral triangular plate	Mass transfer	0.495	5264-21096

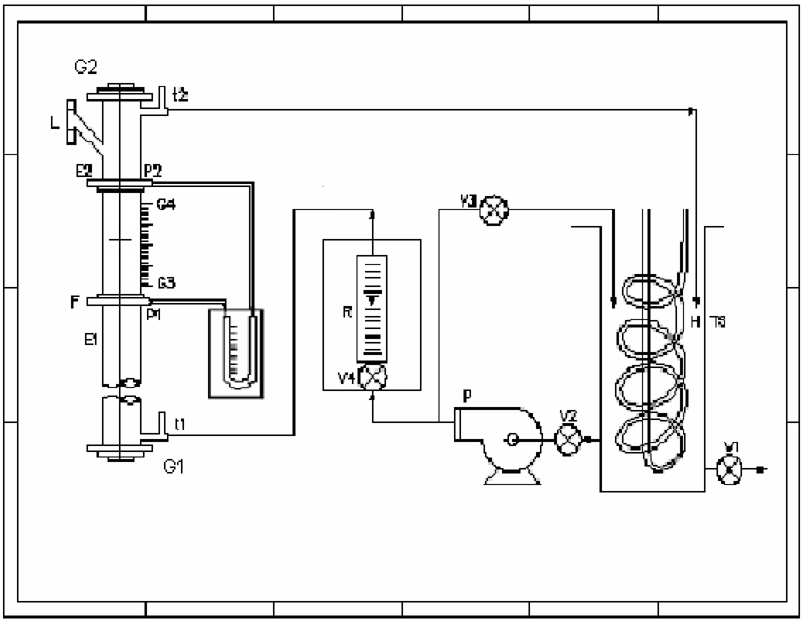


Figure 1: Schematic Diagram of Experimental Setup

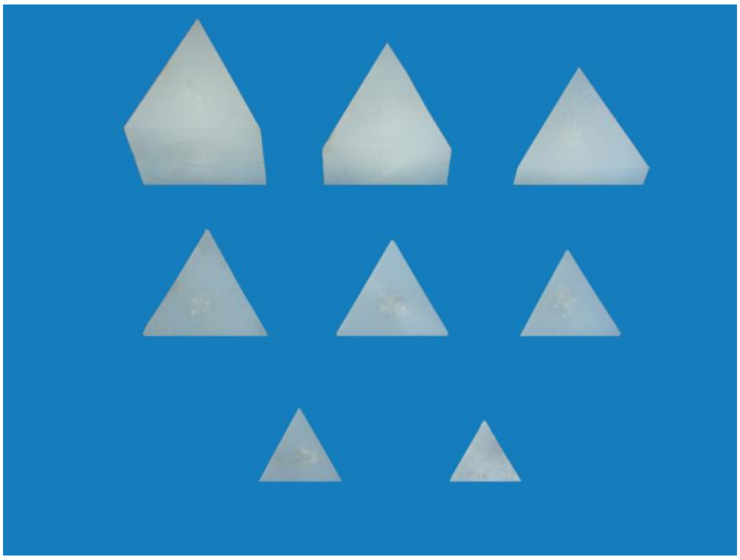
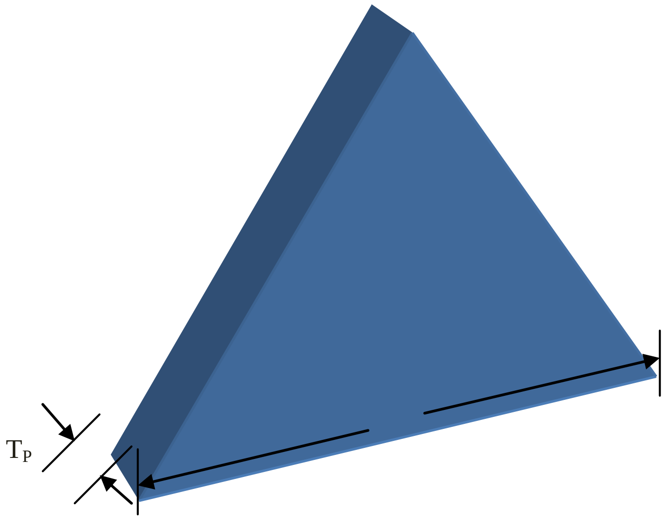


Figure 2: Turbulence Promoters



Note: S_P = Side of Triangular Plate, T_P = Thickness of Triangular Plate

Figure 3: Details of Promoter

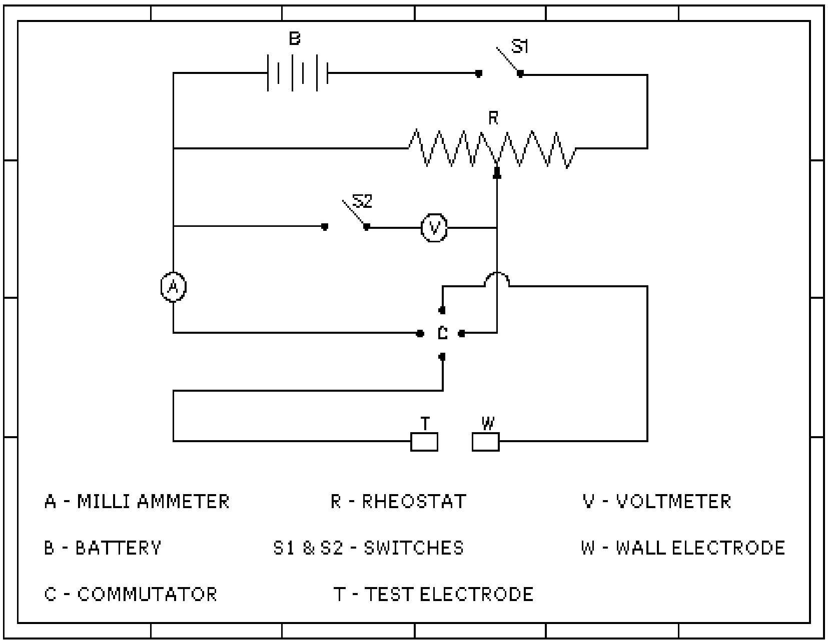
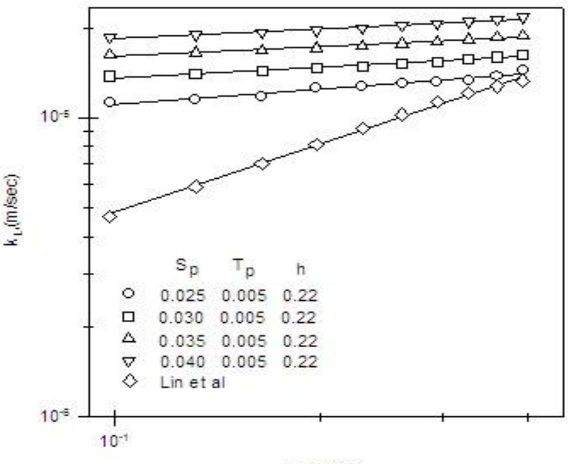
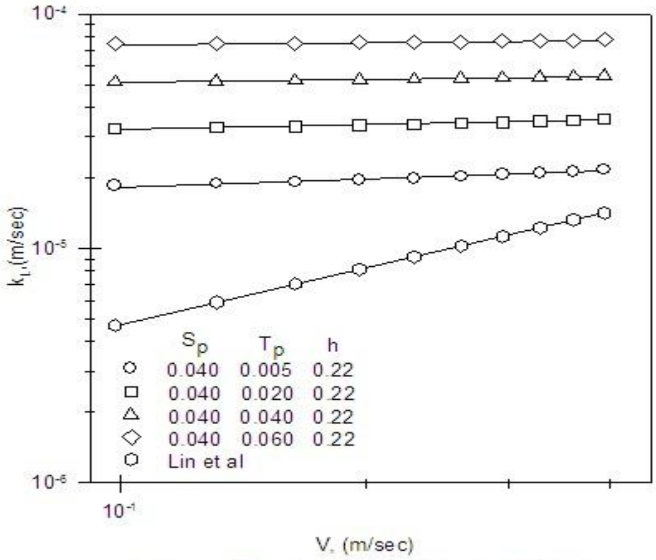


Figure 4: Circuit diagram



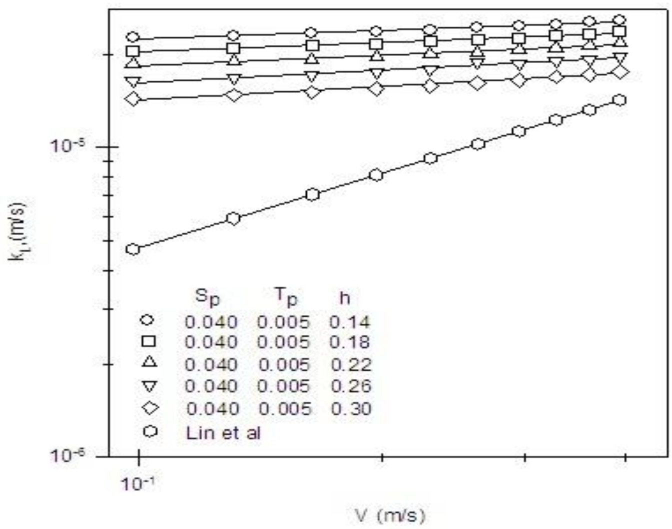
Variation of Mass Transfer Coefficient with Velocity
-Effect of Side of Triangular Plate

Figure 5



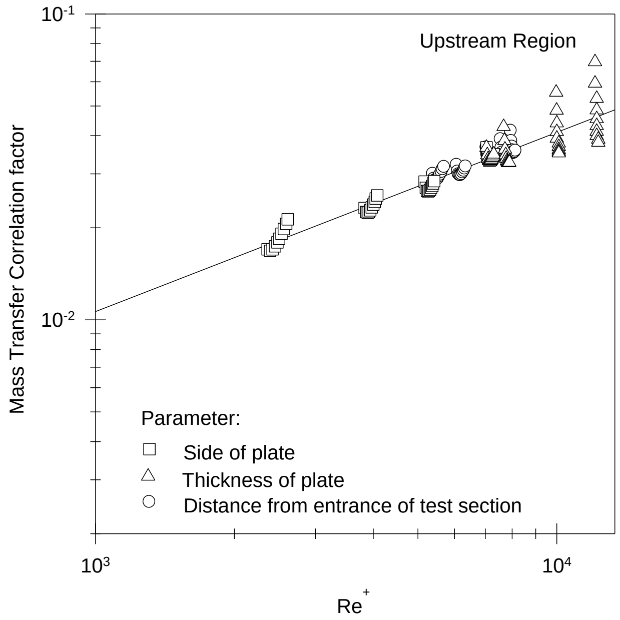
Variation of Mass transfer Coefficient with Velocity
- Effect of Thickness of Triangular Plate

Figure 6



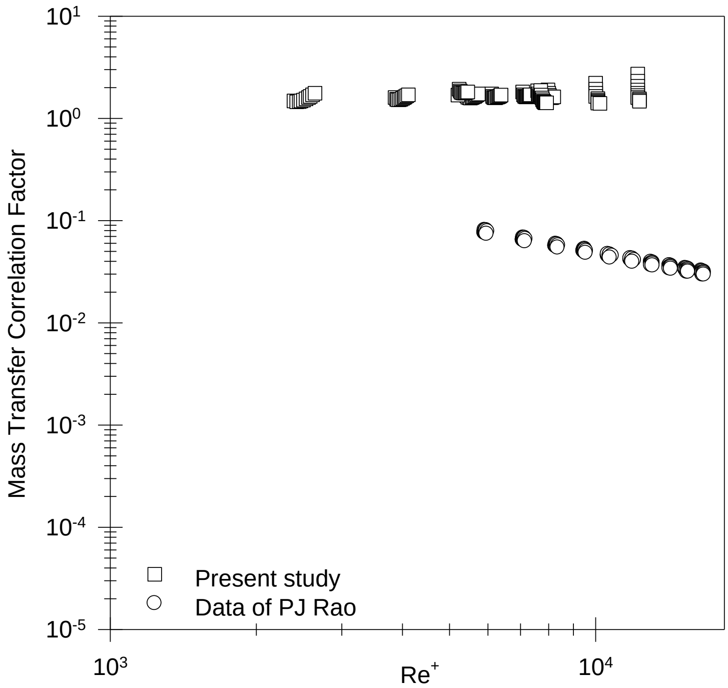
Variation of Mass Transfer Coefficient with velocity
- Effect of Distance of Triangular Plate from
entrance of Test Section

Figure 7



Correlation plot for Equation 9

Figure 8



Variation of CFR with Re^+

-Comparison plot

Figure 9