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Studies on Mass and Momentum Transfer at the Outer Wall of a Circular Conduit with Entry Region Spiral Tape Wound on Rod as Turbulence Promoter in Homogeneous Flow

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Abstract

In this study, an experimental investigation is carried out for augmentation of mass transfer coefficients in homogeneous flow by inserting spiral tape wound on rod in a circular conduit. Mass transfer coefficients are evaluated from the limiting current densities and the concentrations of the reacting ions. The variables studied are the geometric parameters of the promoter width, height, pitch of the promoter and the flow rate of the electrolyte, each parameter effect on mass transfer and momentum transfer are investigated. Experiment is conducted for 48 promoters with varying geometric parameters. Reynolds number range covered in the experiment is 4853–14533. Improvement in mass transfer is assessed by comparing the obtained mass transfer coefficient (k_L) values with the smooth tube data. It is found that k_L increased with increased flow rate. The increase in tape height and width of the promoter resulted in slightly increased mass transfer coefficients. Pitch of the promoter showed marginal effect on k_L.

Keywords: *Turbulence promoter, spiral tape wound, limiting current densities, turbulence promoter, homogeneous flow*

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INTRODUCTION

The Process intensification brings paradigm change in process design. It improves the performance of the process equipment. Process intensification offers cost effective process design for sustainable development. Process intensification offers debottlenecking in selected operations. Sometimes it may leads to safer design. Many augmentation techniques are envisaged and tested for their efficiency.

Augmentation or process intensification techniques are of great interest in engineering designs to increase the performance of processes. In general, enhancing the heat and mass transfer by the use of passive method is more popular and applied to many engineering applications. One of the earliest works on augmentation is Lin *et al.*[1] studied mass transfer rates in diffusion controlled electrochemical reactions in order to obtain design information for electrochemical processes in circular and annular flow device. These passive methods do not require the extra external power sources. Some of the examples of these turbulence promoter devices are rough surfaces, extended surfaces, wire coil, and the swirl flow generating devices like twisted tape, helical tape, snail entry, etc. are prominent.

Performance of the systems can also be increased by active methods like rotation, vibration and application of electro-static field but complexity in construction and operation involved with make them not viable. Swirl generators with varying geometry enhance heat /mass transfer. Extensive work has been reported in literature[2–8]. The advantage of these types of promoters is harnessed with coaxially placed twisted tape insert promoters[9–14] and studies on these are found extensively in literature. Entry region twisted tapes, spiral coils offered efficient transfer processes.

Earlier investigations in heat and mass transfer motivated the author to pursue mass transfer in circular conduits with entry region spiral tapes wound on rod. The promoter element is very simple to manufacture with less cost and easy to maintain the systems. The entry region spiral tape wound on rod promoters or other swirl generating devices inserted in the conduit provide swirling flow and the swirl propagates further along the length of the column. Present study is confined to a test section length of 44 cm only but its influence is much longer with some decay in augmentation. It enhances intensity of the turbulence in the conduit. The swirl induces tangential component of velocity and causes improved mixing in the core and extend to wall region thereby enhanced in attractive forces resulting in higher augmentation. Insertion of the entry region spiral tape wound on rod is anticipated to augment transfer coefficient with relatively lower pressure losses.

The study of mass transfer in developing flows is of special importance for the design of electrochemical reactors. The analysis of heat/mass development in the entrance region in ducts or annuli has been widely considered. In most of these studies, it is assumed that the velocity and temperature or concentration distributions at the entrance are uniform and the axial distribution of both momentum and heat/mass can be neglected.

The heat and mass transfer problems are analogous except for the simplifying assumptions for the development of the equations. Due to the high values of the Schmidt number in electrolytic medium, the heat and mass boundary layer thicknesses are very different. The use of swirl generators has long been recognized[15–25] as a means of enhancing mass transfer in electrochemical cells.

Turbulent swirling flows are encountered in many chemical engineering applications. For example swirl is commonly employed in combustion systems and chemical processing plants, in order to increase fluid mixing thereby enhanced heat and mass transfer rates, and subsequently improve the efficiency or the degree of stability of a process.

The objective of the present work is to suggest mass and momentum transfer models by conducting experiments with entry region spiral tape wound on rod as the entry region swirl generator. The present work reports the experimental results of mass and momentum transfer in homogeneous flow electrolyte provided with spiral tape wound on rod promoter placed at the entry region of the tube.

Hence, the present investigation was carried out using entry region spiral tape wound on rod promoter in circular conduit. It deals with the study on mass transfer at electrodes fixed flush with the inside surface of the wall in the presence of spiral tape and pressure drop in homogeneous flow of fluid. The electrochemical diffusion controlled redox reactions for potassium ferricyanide and potassium ferrocyanide couple are used to measure mass transfer coefficient. It has the advantage of reproducibility of limiting current data with simple instrumentation, acquisition of precise data and reacting surface unaltered. The effect of pitch, height, width of the entry region spiral tape wound on rod promoter was studied in homogeneous flow of the electrolyte. Various geometric and dynamic parameters together with their ranges covered in the present study are presented in Table 1.

Experimental data was used to compute average mass transfer coefficients (k_L), mass transfer enhancement ratio or augmentation factor (k_L/k_{L0}), energy factor (E/E_0), performance index $\eta = (k_L / k_{L0})/(E/E_0)$ $= (k_L / k_{L0})/(f / f_0)^{1/3}$.
This study also analyzes the effect of entry region spiral tape wound on rod promoter height, width and pitch of the promoter. Semi empirical mass transfer and momentum transfer models were suggested based on wall similarity concept which is applied to systems with axially placed entry region swirl generators[15–17]. The concept applied successful to similar systems in earlier studies by group of workers in electrochemical laboratories, Andhra University Visakhapatnam[19, 20]. Present investigations have been carried out to obtain,

1. To obtain limiting currents data and pressure drop with entry region spiral tape wound on rod promoter in homogeneous flow.
2. To study the effect of velocity on the mass transfer at wall in the presence of the entry region spiral tape wound on rod promoter for homogeneous flow.
3. To study the effect of geometric parameters, pitch of entry region spiral tape wound on rod (P), height of the entry region spiral tape wound on rod (H), Width of the entry region spiral tape wound on rod promoter (W) on the mass transfer coefficients in homogeneous flow.
4. To obtain generalized correlations for mass and momentum transfer for circular conduits with entry region spiral tape wound on rod promoter.
5. To generate the data on power loss associated with the promoter.

METHODOLOGY

Experimental Procedure

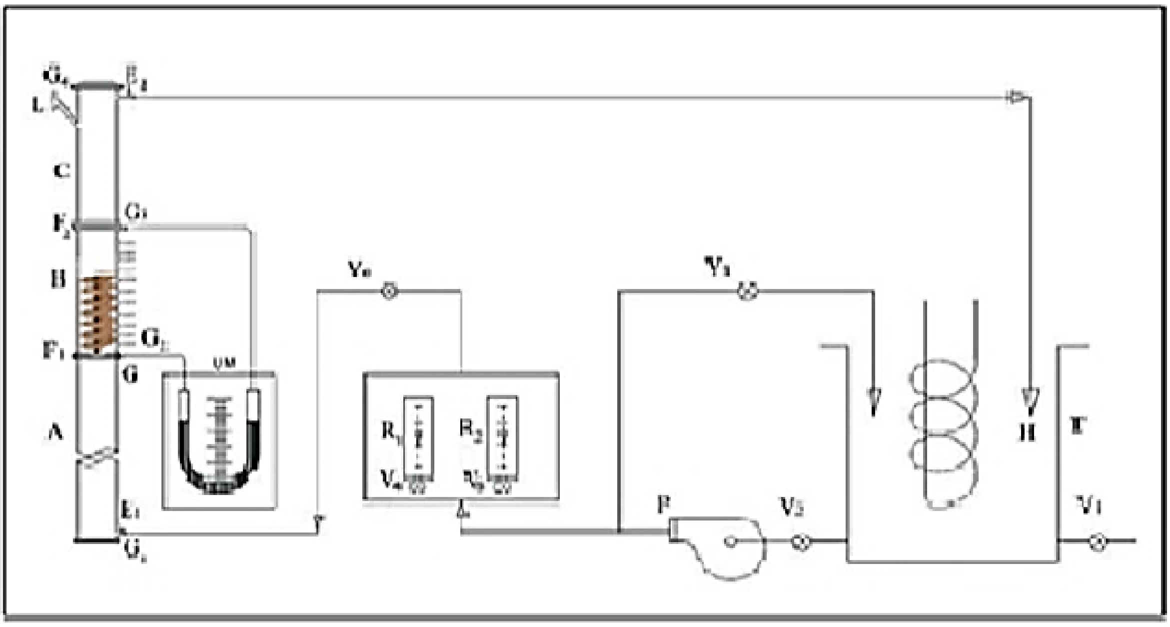
The limiting current data were obtained for the case of reduction of ferri-cyanide ion at the outer wall of a circular conduit with entry region spiral tape wound on rod as turbulence promoter in homogeneous flow.

Reduction of ferri-cyanide ion at cathode as presented below as in Eq. (1):

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

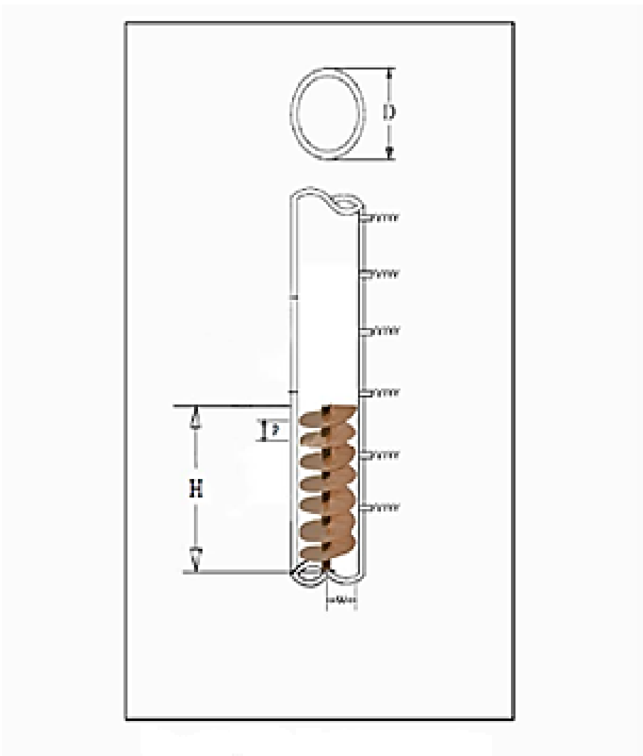
Eighty liters of equimolal solutions of 0.01N Potassium ferricyanide and 0.01N Potassium ferrocyanide with 0.5N NaOH as excess indifferent electrolyte was prepared. Ferrocyanide ion concentration in the electrolyte was estimated by volumetric method using standard potassium permanganate solution[1] while the concentration of ferricyanide ion was estimated using iodometric method[2]. The viscosity and density of the solution at different temperatures were measured with Ostwald Viscometer and specific gravity bottle respectively.

The point electrodes in the test section were polished with 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 were conducted with only sodium hydroxide solution to ensure that the limiting currents obtained were due to diffusion of reacting ions (Ferricyanide ion) only.



A: Entrance calming section; B: Test section; C: Exit calming section; F: Flanges; G1G4: Gland nuts; H: Coiled copper tubes; P: Centrifugal pump; R1, R2: Rotameter; T: Recirculation tank; Vi–V6: Valves; E1–E2: Thermo well; D: Grid; L: Solid inlet port.

Fig. 1: *Schematic Diagram of the Experimental Setup.*



H : Height of the spiral tape wound on rod, P : Pitch of the spiral tape wound on rod;

W : Width of the spiral tape wound on rod, D : Diameter of the conduit

Fig. 2: *Details of the Test Section.*

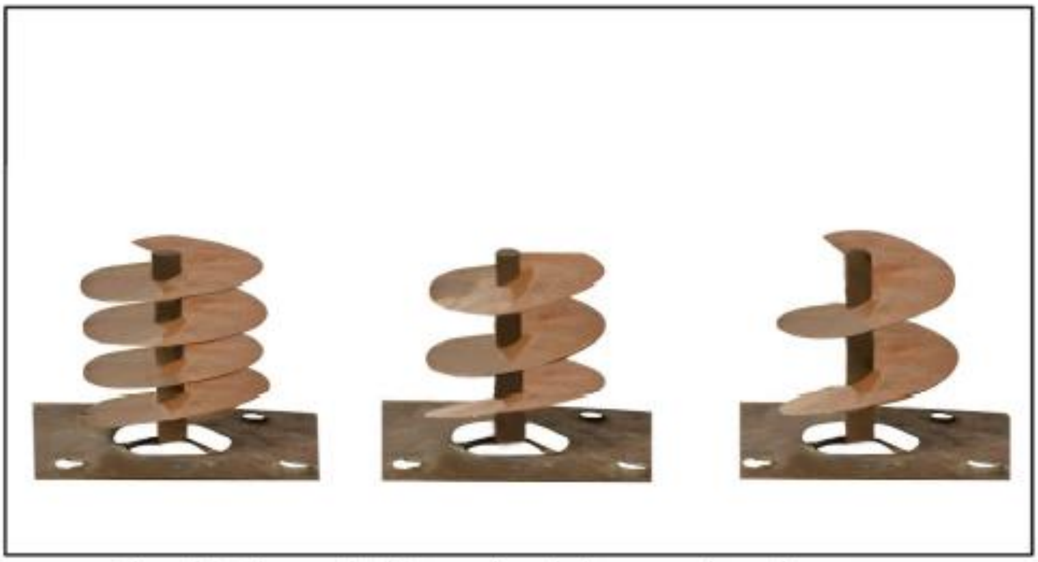


***Fig. 3:** Photograph of Entry Region Spiral Tape Wound on Rod Promoters.*

The electrolyte was pumped at a desired flow rate (through the test section) by operating the control and by-pass valves. After the attainment of steady state, potential was applied across the test electrode and wall electrode in small increments of potential (100 mV) and the corresponding current values were measured for each increment. As the area of the wall electrode was relatively large in comparison with 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 were only measured from the current and potential data. The measurement of limiting current in the present study was adopted as in the earlier works[3–9]. A sample plot of potential versus current from which the limiting currents were obtained can be seen in the Figure 3. The experiment was repeated by changing the flow rate of the electrolyte and the limiting currents were taken for each flow rate.

Measurement of Limiting Current

The plot of current versus potential data in Figure 4 shows that the increase in potential increased the current up to certain value and further increase in potential maintained nearly the constant current value. This shows that for a sharp increase in potential a small increase in current was noted, which is the limiting current. Mass transfer coefficient was computed from the measured limiting current by the following Eq. (2):

$$k_L = \frac{i_L}{nFAC_o} \quad \ldots \quad (2)$$

Pressure drop for each flow rate was measured simultaneously by using a U-tube manometer with Carbon tetrachloride as manometer liquid.

Precautions to be taken are:

a) The temperature generally remained constant for any one measurement. If the temperature change was more than 0.1 ºC, the run was rejected.
b) Reproducibility of data was often tested by repeating the experiments under identical conditions.
c) The recirculation tank containing the electrolyte was covered with black lid and nitrogen seal was maintained by passing nitrogen gas through the electrolyte.

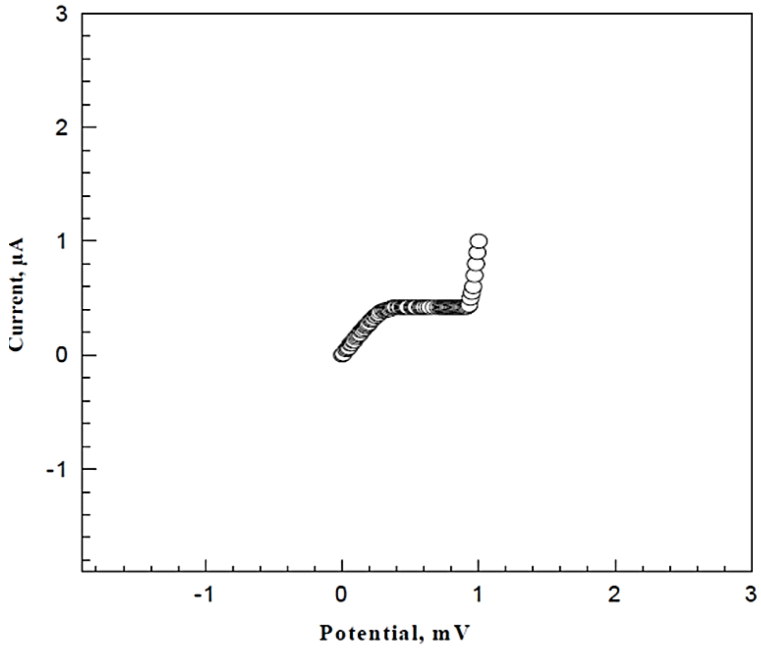


Fig. 4: *Variation of Current with Potential.*

Experimental Setup

The schematic diagram of the experimental set up is shown in Figure 1. The layout is similar to that used in earlier studies[1–8]. It essentially consisted of a recirculation tank (T), an entrance calming section (A), a test section(B), an exit calming section (C), thermo wells (E_1, E_2), flanges (F_1,F_2), gland nuts (G_1 to G_4), coiled copper tube (H), pump (P), rotameters (R_1, R_2), recirculation tank (T), U tube manometer (UM) and valves (V_1 to V_6).

The recirculation tank was a cylindrical copper vessel of 100 liter capacity with a drain pipe and a gate valve (V_1) for periodical cleaning of the tank. A copper coiled tube (H) with perforations was provided to bubble nitrogen through the electrolyte. 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 (V_2). The discharge line from the pump was divided into two. One served as a bypass line and controlled by valve (V_3). The other line connected the pump to the entrance calming section (A) through rotameter. The rotameter was connected to a valve (V_4) for adjusting the flow rate at the desired rate. The rotameter has a range of 0 to 9.3×10^{-4} m^3/s. The entrance calming section was circular copper pipe of 0.05 m ID provided with a flange and closed at the bottom provided with a gland nut (G_1). The entrance calming section was filled with capillary tubes to damp the flow fluctuations and to facilitate steady flow of the electrolyte through the test section.

The details of the test section are shown in Figure 2. It was made of a graduated perspex tube of 0.44 m length provided with point electrodes fixed flush with the inner surface of the tube. 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 test section at equal spacing of 0.02 m. The diameter of the exit calming section was also of the same diameter of the entrance calming section made of copper tube of 0.05 m, and it was provided with a flange on the upstream side for assembling the test section. It has gland nuts (G_2, G_3) at the top and bottom ends. The 0.05 m ID column through which the electrolyte was pumped was constructed by assembling

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the three sections the entrance calming section, the test section and the exit calming section with the flanges F_1, F_2 and the gland nuts G_1 to G_4. Two thermo wells (E_1, E_2) were provided, 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.

The spiral tape wound on rod is fixed at the entrance of the test section with the help of flanges. It served as turbulence promoter in the present study. The entry region spiral tape wound on rod was made from a copper tape of 0.003 m thickness. The copper tape of varying height and width was spiral tape wound on rod such that it gives the desired pitch values. The promoter thus made provided several tape promoters with different values of pitch, height and width. The promoter was welded to a flange and placed concentrically in the test section with the help of flanges attached to the test section and the entrance calming section.

Details of the entry region spiral tape wound on rod promoters used in the study are compiled in the Table 1. Some of the promoters used are shown in Figure 3 (photograph of spiral tape wound on rod). Motwane make multimeter of 0.01 mA accuracy and vacuum tube voltmeter were used for measuring the limiting current and potential measurements. The electrical circuit consisted of 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 changing the 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 was shown in the Figure 5.

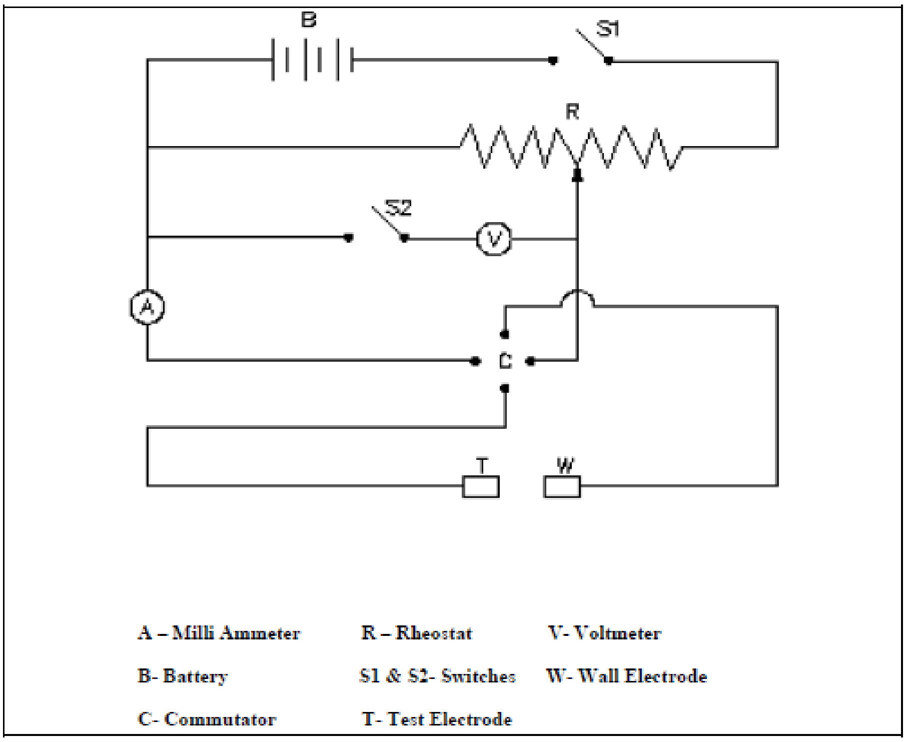

Fig. 5: *Circuit Diagram.*

Table 1: *Details of Entry Region Spiral Tape Wound on Rod Promoters Used in the Present Study.*

S.No	Height of the promoter, m	Width of the promoter, m	Pitch of the promoter, m
1	0.07	0.04	0.01
2	0.07	0.04	0.02
3	0.07	0.04	0.03
4	0.07	0.04	0.04
5	0.07	0.035	0.01
6	0.07	0.035	0.02
7	0.07	0.035	0.03
8	0.07	0.035	0.04
9	0.07	0.03	0.01
10	0.07	0.03	0.02
11	0.07	0.03	0.03
12	0.07	0.03	0.04
13	0.07	0.02	0.01
14	0.07	0.02	0.02
15	0.07	0.02	0.03
16	0.07	0.02	0.04
17	0.05	0.04	0.01
18	0.05	0.04	0.02
19	0.05	0.04	0.03
20	0.05	0.04	0.04
21	0.05	0.035	0.01
22	0.05	0.035	0.02
23	0.05	0.035	0.03
24	0.05	0.035	0.04
25	0.05	0.03	0.01
26	0.05	0.03	0.02
27	0.05	0.03	0.03
28	0.05	0.03	0.04
29	0.05	0.02	0.01
30	0.05	0.02	0.02
31	0.05	0.02	0.03
32	0.05	0.02	0.04
33	0.03	0.04	0.01
34	0.03	0.04	0.02
35	0.03	0.04	0.03
36	0.03	0.04	0.04
37	0.03	0.035	0.01
38	0.03	0.035	0.02
39	0.03	0.035	0.03
40	0.03	0.035	0.04
41	0.03	0.03	0.01
42	0.03	0.03	0.02
43	0.03	0.03	0.03
44	0.03	0.03	0.04
45	0.03	0.02	0.01
46	0.03	0.02	0.02
47	0.03	0.02	0.03
48	0.03	0.02	0.04

RESULTS AND DISCUSSION

The results presented and correlations developed based on nearly 4800 local limiting currents and 240 pressure drop measurements. The study adopted entry region spiral tape wound on rod as turbulence promoter. The promoter enhances turbulence by generating swirl to the axial component of the flow. Limiting currents measured on the outer wall along the test section. The method adopted is limiting current technique. The swirl intensifies local turbulence and the augmentation of mass transfer is resulted. Several fold improvement were recorded for mass transfer. The local limiting currents visualize the local variation of i_L along the length of the column. The local average limiting currents were used for the calculation of average mass transfer coefficient (k_L). Models were developed for mass and momentum was based on wall similarity concept. The data is useful in the designing the energy efficient transfer operations.

Presentation of Experimental and Calculated Data

The measured data consisted of flow rate Q, temperature T, concentration of reacting ion C_0, limiting current i_L, (from current potential measurements), pressure drop Δp. Physical properties of the solution (density ρ, viscosity μ, and diffusivity D_L), diameter of the test section D and dimensions of the promoter viz., pitch of the promoter (P), height of the promoter (H), and width of the promoter (W). The range of variables covered in the present study presented in Table 2.

The calculated data consisted of V, I_L, k_L, Re^+_m, $\bar{g}$, $R(h^+)$, f, Re, Sc, η. Besides these, the calculated data also consisted of various correlation groups involving the geometric variables of the promoter. The diffusivity values (D_L) for temperature for each local limiting current using Equation 3.

Table 2: *Range of Variables Covered in the Present Study.*

Variables	Minimum	Maximum
Volumetric flow rate, $Q\times10^5 m^3/s$	17.3	51.7
Pitch of the promoter, P, m/turn	0.01	0.04
Height of the promoter, H m	0.03	0.07
Width of the promoter, W m	0.02	0.04
Schmidt number, Sc	715.9	1054
Reynolds number, Re	4853	14533

$$T\,D_L/\mu_L = \text{constant}$$

These computed values of viscosity (μ_L) at various temperatures in the range of experimentation have been compiled in Appendix-A. Mass transfer coefficient and effective friction factor values were computed with the following Eq. (3–5).

Mass transfer coefficient,

$$k_L = i_L/nFA_eC_0 \qquad \text{Eq. (3)}$$

Where $A_e = \prod d_e^2/4$,

d_e= diameter of the electrode,

i_L = Local limiting current,

F = faradays constant, 96500 Coulombs/mole,

C_o = concentration of the reacting species,

Friction factor for homogeneous flow

$f = (\Delta p\, D\, g_c) / (2LV^2\rho)$ Eq. (4)

Superficial velocity is computed from the following relation

$V = Q / (\Pi D^2/4)$ Eq. (5)

Q = Volumetric flow rate of electrolyte m^3/s,

D = Diameter of conduit m

The experimental data on mass and momentum transfer is used for development of correlations.

Mass Transfer

Augmentation or process intensification is the order of the day which leads to cost effective and sustainable development. Mass transfer rates were generally augmented with use of promoters. Several techniques were found in literature for the enhancement of heat and mass transfer processes. Passive augmentation devices like axially displaced promoters such as, string of spheres[10], string of discs[12] and streamlined bodies[14] were extensively employed for the improvement of transfer rates. Coaxially placed spiral coils[3] helical coils on a rod[4] were extensively employed. Coaxially displaced threaded rods in circular conduits, central rods with different surface roughness's[13] were employed. All the processes augmented mass transfer processes but the associated energy losses were also high. Entry region spiral coils performed better and found efficient in the earlier studies[3]. The swirl generated by the spiral tape wound on rods at the entry region of the circular conduits propagates along the length of the column over long distances augmenting transfer rates with no further demand in energy. In view of this, it is proposed to test the present promoter for its efficacy. Spiral tape wound on rod promoters of different geometries mentioned in Table 1 were made and inserted co axially at the entry region of the test section and mass transfer rates were computed at the outer wall of the test section from the measured limiting currents. Simultaneous pressure drop data were also measured which helped in evaluating the promoter for its efficacy.

The study essentially comprises of mass transfer intensification with axially displaced entry region spiral tape wound on rod. Mass transfer rates are computed from measured limiting currents. Mass transfer co-efficient were computed from measured local limiting currents. The other variables measured comprises of area of point electrode, and concentration of reacting ion C_o.

Local limiting currents are measured all along the length of test section with point electrodes located and fixed flush to the inner surface. As the turbulence promoter is located at the entrance of the test section, it transforms axial flow into swirl flow. Thus generated swirl progressively intensifies to a peak value and sustains over a considerable length of the conduit and is expected to remain at peak value over a considerable length. It is also expected to decline and reach a value corresponds to a flow of conduit with no insert promoter. To elucidate the flow regimes with length of the column the following analysis is carried out.

A graph is drawn as local limiting current i_L *versus* distance along the test section; and shown in Figure 5. It reveals turbulence is progressively intensified up to a distance of 20 cm from the entrance where the promoter is located. Limiting current values are increasing up to 20 cm, beyond this distance values of limiting currents remains constant, indicating sustenance of turbulence over certain length. In the present experiment a maximum length of the test section of 44 cm. The generated turbulence is found to sustain up is 44 cm. But it may continue for longer lengths and may be probed. After a certain distance the turbulence has to decline and must attain that value of tube with no insert promoter.

Figure 5, 6 and 7 are graphs drawn as i_L *versus* distance with H, W, P as parameters. All these figures reveal the attainment of maximum turbulence is more or less near to 20 cm from the entrance of test section.

Figure 8 is variation of limiting current density I_L verses distance have exhibited similar trend.

Figure 9 is a graph drawn as Cumulative limiting current i_L versus distance with velocity as parameter. The figure reveals that cumulative i_L is increasing monotonously with distance.

Figure 10 is graph cumulative average limiting current i_L versus distance, which reveals that i_L is found increasing marginally with the length of the column. Hence is concluded that average i_L values are computed for the entire column length of 44 cm and the average k_L values were computed and analyzed in terms of geometric parameters of the promoters.

Augmentation of the promoter is an important index for its effectiveness and can be judged when compared to flow through pipes with no promoter element placed in it.

A graph is drawn as i_L versus Q and shown as Figure 11 for two sets of data for those augmentation maximum and minimum respectively together with the data of Lin *et al.* [1] it is for conduits with no promoter. The figure indicates i_L is increasing with Q and also varying with geometry of promoter. For the same sets of data plotted in Figure 11 is taken and drawn as k_L versus v shown as Figure 12. The graph reveal 14 to17 fold augmentation at a velocity of 0.088 m/s, while that reduces 7 to 10 fold as velocity attains 0.263 m/s.

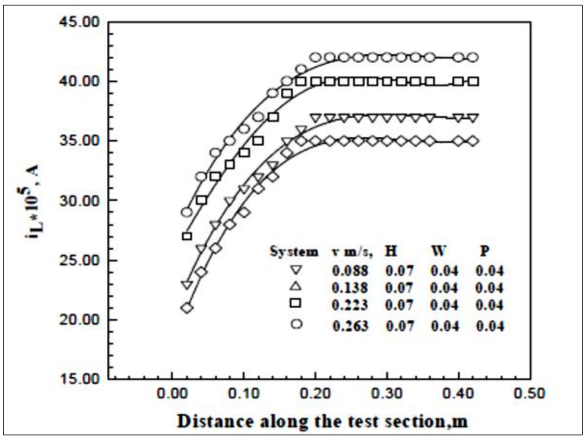

Fig. 6: *Variation of Limiting Current along Test Section.*

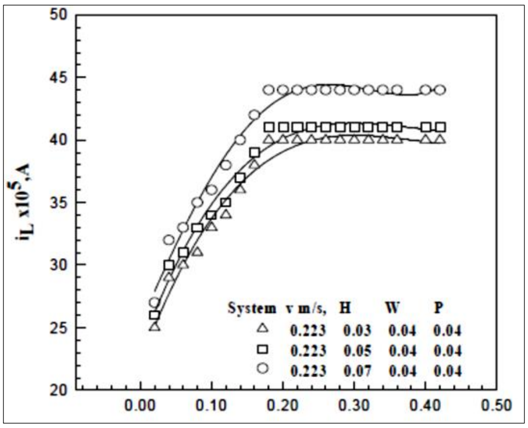

Fig. 7: *Variation of Limiting Current along the Test Section with Variable Height.*

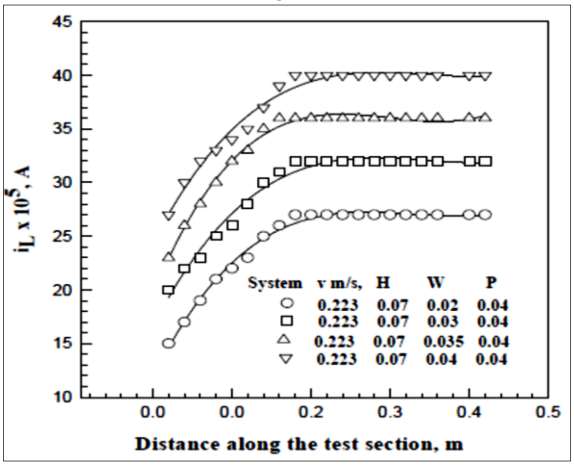

Fig. 8: *Variation of Limiting Current along the Test Section with Variable Width.*

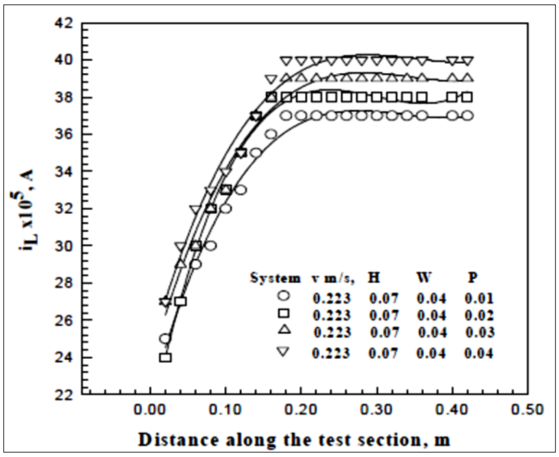

Fig.9: *Variation of Limiting Current along Test Section with Variable Pitch.*

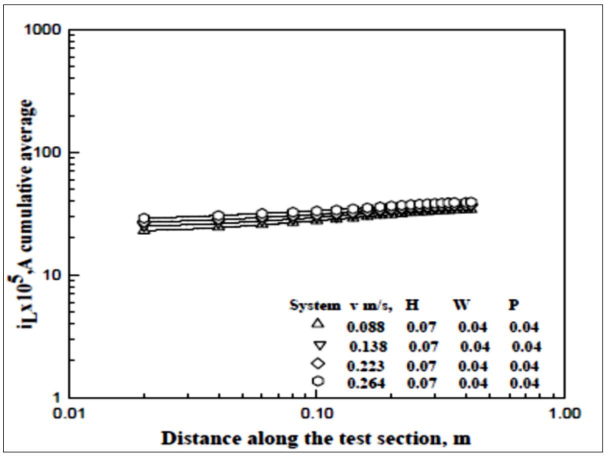

Fig. 12: *Variation of Average Limiting Current along the Test Section for Highest Augment Promoter.*

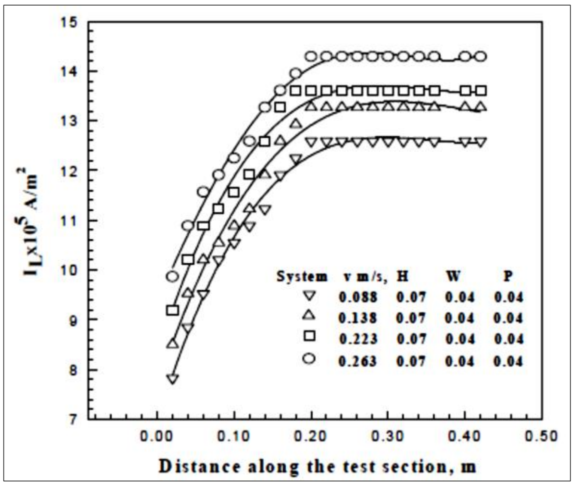

Fig. 10: *Variation of Current Density along the Test Section for Highest Augment Promoter.*

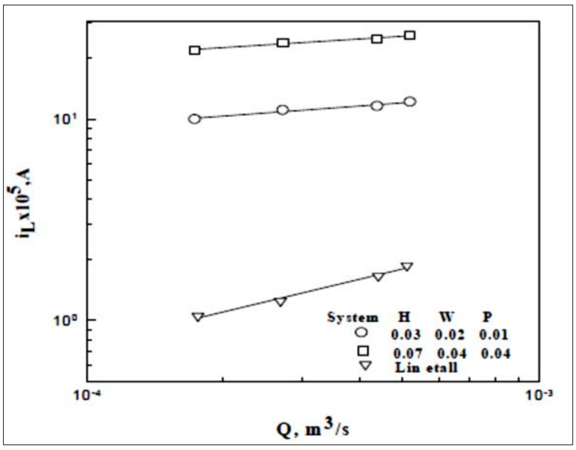

Fig. 13: *Variation of Limiting Current with Volumetric Flow Rate.*

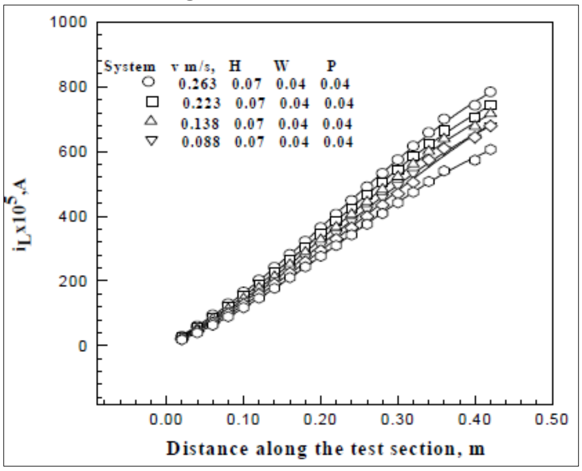

Fig. 11: *Variation of Cumulative Limiting Current along the Test Section for Highest Augment Promoter.*

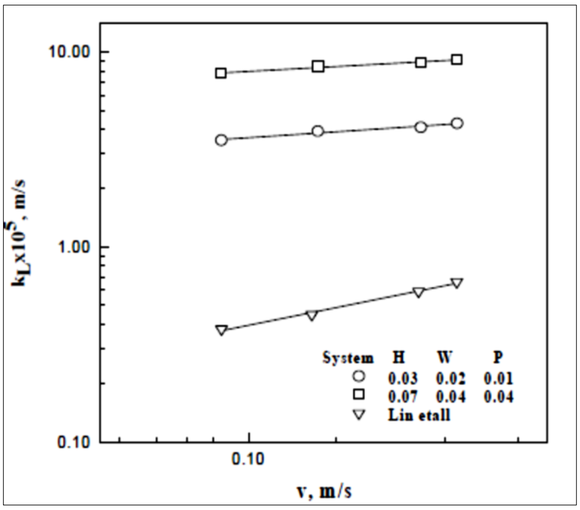

Fig. 14: *Variation of Mass Transfer Coefficient with Velocity.*

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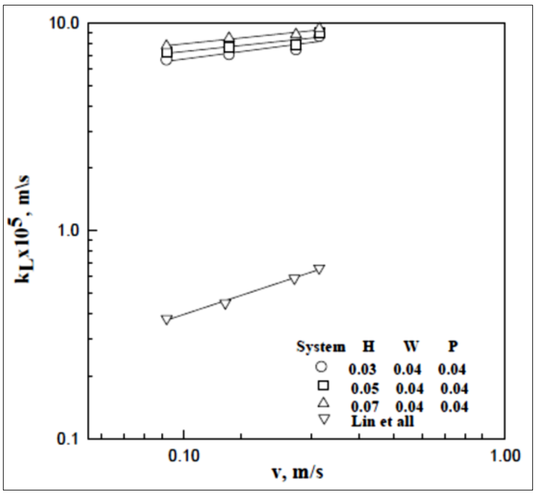

Fig. 15: *Effect of Height on Mass Transfer Coefficient.*

Effect of Height of the Promoter

A graph drawn for k_L versus velocity with height of the promoters as parameter is shown in Figure 14. The figure indicated that insertion of spiral tape wound on rod promoter at the entry region imparts swirl flow to the fluid. The swirl causes thorough mixing. As the fluid passes along the column reduces the thickness of the boundary layer by tractive shearing forces. The figure revealed mass transfer coefficient increase with the increase in velocity of the electrolyte for H values of 0.03 m and 0.07 m. Highest mass transfer coefficient was obtained for the promoter with the height (H) 0.07 m, width (W) 0.04 m and pitch (P) 0.04 m and the enhancement in mass transfer coefficient is 13 fold at a velocity of 0.088 m/s and that enhances to 11 fold at the velocity 0.2638 m/s. A cross plot is drawn as k_L Vs H and is shown in inset.

Effect of Pitch of the Promoter

The effect of pitch of the promoter on mass transfer coefficient is presented below. The mass transfer coefficients obtained for three different promoters with pitch values 0.01, 0.02, 0.03, and 0.04 m per turn are shown in Figure 15.

The figure depicts that the mass transfer coefficient values increased with decrease in pitch of the promoter but the increase is marginal. As the pitch decreases number of turns per meter increases resulting in more number of turns the fluid that passes imparts more swirl to the flow.

The swirl in turn increases the mass transfer coefficient. If the pitch further decreases the distance between the turns become narrow at one point it becomes difficult to the flow pass through it because of high resistance due to the skin friction, consequently low turbulence and hence lower mass transfer rates result.

The earlier workers[3–4] also reported such observations. Mass transfer values increased 8 to 13 times as the velocity varied from 0.2638 m/s to 0.088 m/s. Maximum enhancement was observed for the promoter with the geometric parameters 0.07m height, 0.04 m width, 0.04 m pitch while minimum augmentation was obtained for the tape with the geometry H = 0.07 m, W = 0.04 m and P = 0.01 m pitch.

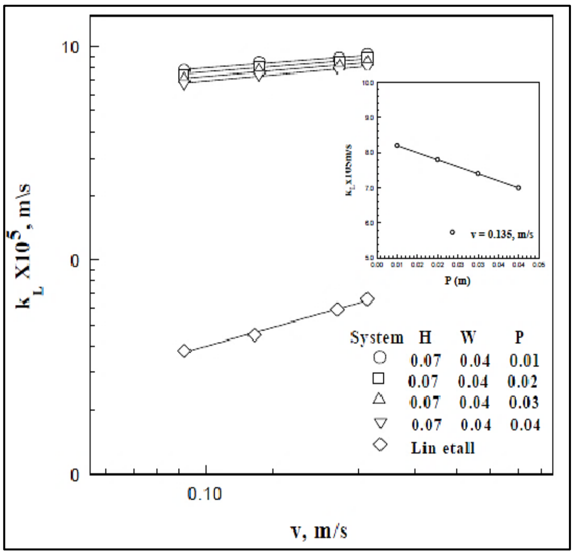

Fig. 16: *Effect of Pitch on Mass Transfer Coefficient.*

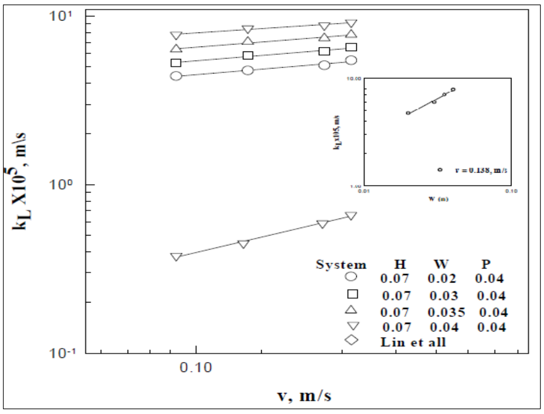

Fig. 17: *Effect of Width on Mass Transfer Coefficient.*

Effect of Width of the Promoter

A graph drawn for k_L versus velocity is presented as Figure 16. The figure reveals the following information. Mass transfer coefficient is increased with velocity. The figure revealed the mass transfer coefficient increased with increase in width of the promoter. It is due to the drag offered by the promoter by which the axial flow of the fluid transforms into swirl flow. The swirl is largely responsible for the augmentation of mass transfer. Enhancement in mass transfer coefficient is ranged from 14 to 8 fold as the velocity increased from 0.088 m/s to 0.2638 m/s. Effect Pitch of pitch on mass transfer coefficient is presented as inset in Figure 15. As width of the tape varies from 0.02 m/turn to 0.04 m/turn, k_L values are enhanced to 0.4 fold. Exponent on W is found to be 0.13.

Augmentation Factor

The capacity of a promoter in enhancing the mass transfer coefficient can be evaluated using the augmentation factor (k_L/k_{L0}). It is the ratio of the mass transfer coefficient obtained due to the presence of the promoter to that of the mass transfer coefficient obtained in the absence of the promoter under the same flow conditions. The augmentation factor versus Reynolds number plots are drawn in Figure 17. Plot A is the data for the promoter that has shown minimum augmentation in the present study. The turbulence promoter that has shown maximum augmentation within the range of variables covered is drawn as plot B. The augmentation factor ranges from 9 to 18 folds at lower Reynolds number. Augmentations obtained presented in Table 3.

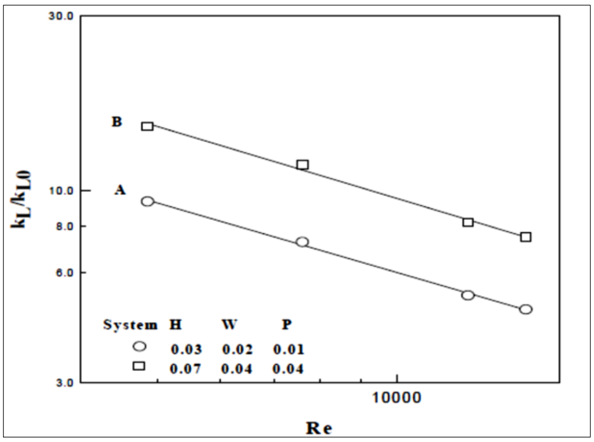

Fig. 18: *Augmentation Factor versus Reynolds Number.*

Table 3: *Improvements in Mass and Momentum Transfer.*

Improvements in Mass transfer				
Plots	Maximum Reynolds number	Improvement	Minimum Reynolds number	Improvement
A	14533	4.7 folds	4853	9.3 folds
B	14533	7.5 folds	4853	15 folds
Improvements in Momentum transfer				
A	14533	12 folds	4853	19 folds
B	14533	26 folds	4853	24 folds

Comparison

The data of present study were compared with similar works of Prasad[3] using spiral coil inserts in circular conduits, Rao[18] twisted tape promoter in circular conduits as shown in Figure 18. The results, when plotted as k_L/k_{L0} against Re for similar geometrical conditions, present study shown higher augmentation in mass transfer coefficients over others.

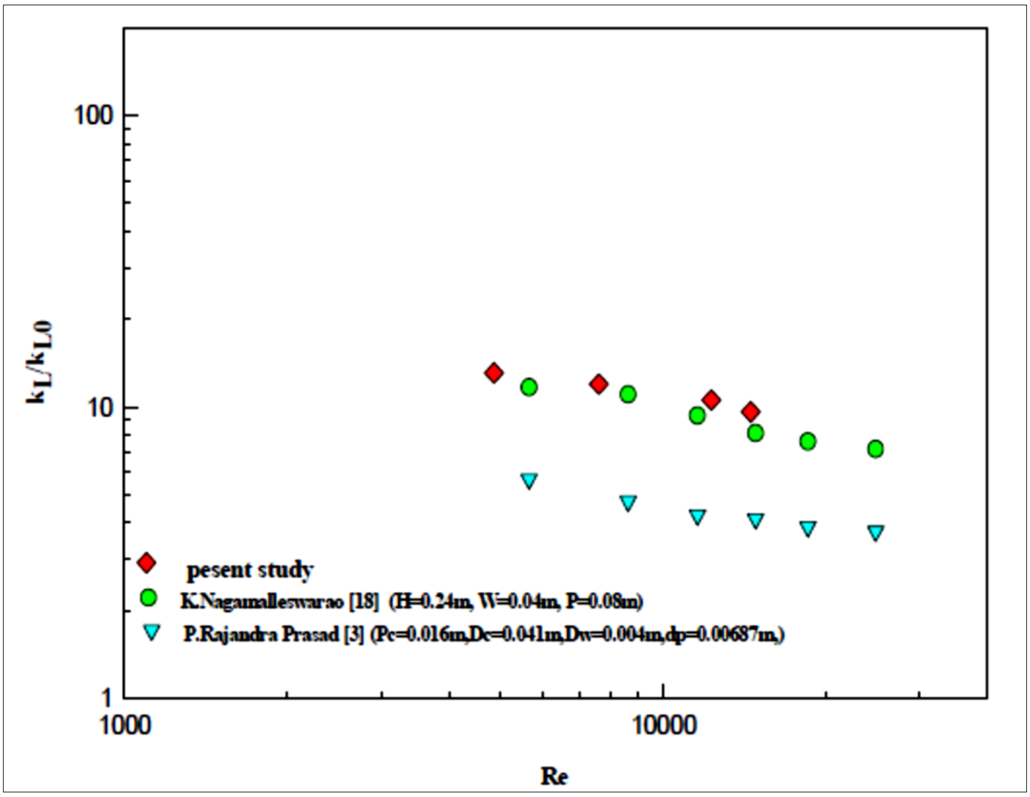

Fig. 19: *Comparison Plot for Augmentation for Homogeneous Flow.*

Momentum Transfer

Friction Factor Enhancement

Figure 19 depicts variation of friction factor with Reynolds number. The friction factor decreased with increasing Reynolds number. The frictional losses are maximum at low values of Reynolds number while those are at relatively high Reynolds number.

The fluid elements pass through the space between the spiral tape wound on rod and the wall of the test section are guided by the promoter and acquire swirl motion. The fluid elements experience skin friction near the solid boundaries. The flow path changes from axial to swirl progressively resulting in the net increase in local velocity. As the width and height of the spiral tape wound on rod promoter increases, the generated swirl turns intense and exponents on Re lowered indicating intense turbulence.

Plot C in the Figure 19 is the predicted data of Blasius for circular conduits with no promoter while plot A and B are for the sets which augments minimum and maximum forming boundaries of the present study. All sets of data fall within these boundaries. The enhancements in friction factor are 19 to 24 fold at Reynolds number of 4853 while that reduce to 12 to 26 fold at the Reynolds number of 14533. Enhancements observed are presented in Table 3.

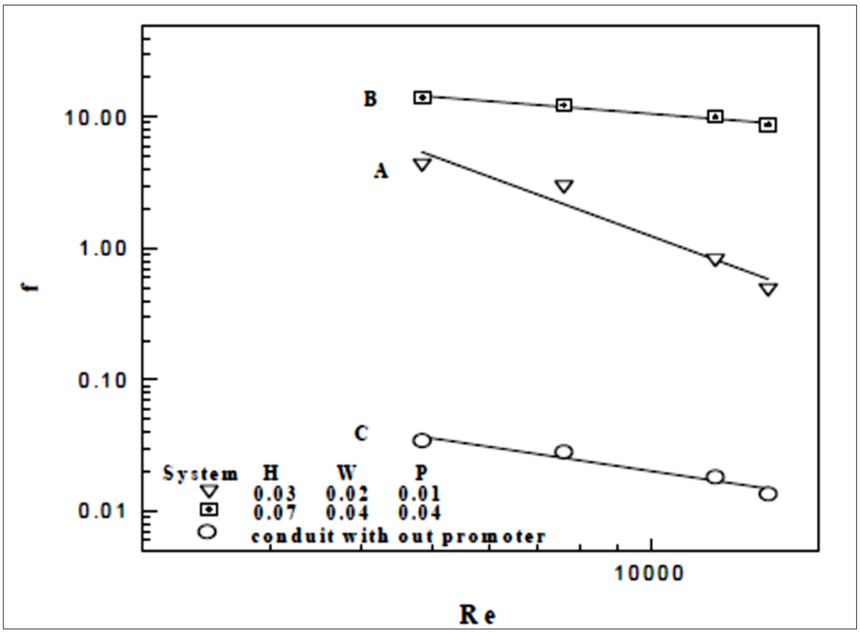

Fig. 20: *Effect of Reynolds Number on Friction Factor.*

Effect of Height of the Promoter

The variation of friction factor with Reynolds number is shown in Figure 20. The figure reveals friction factor values increasing with the increase in height of the promoter. The increase is low at lower velocities while is higher at higher velocities. As the length increases fluid elements gain intense swirl increasing centrifugal forces and the intensity of swirl becomes dominant resulting in higher frictional losses.

Exponent on Re varies with height but marginal when height beyond 0.05 cm indicating the generation of intense turbulence. Enhancements in friction rise to 19 to 24 folds for a Re of 4853 as height increases from 0.03 m to 0.07 m while that reduces to 13 to 26 folds at when Re reaches a value of 14533.

Effect of Pitch of the Promoter

The effect of pitch on friction factor is shown in Figure 20. The figure reveals that the friction factor decreased with increasing Reynolds number and increased with decreased pitch of the promoter. As the pitch decreases the swirl component of the velocity increases resulting in increased skin friction and sliding friction between the fluid layers. The enhancement in friction factor is 18.5 to 22 folds at a Reynolds number of 4853 while tapered off to 11 to 22 as Reynolds number attains 14533.

Exponent on Re decreasing with increase in pitch but the decrease become marginal as the pitch reaches 0.03 cm.

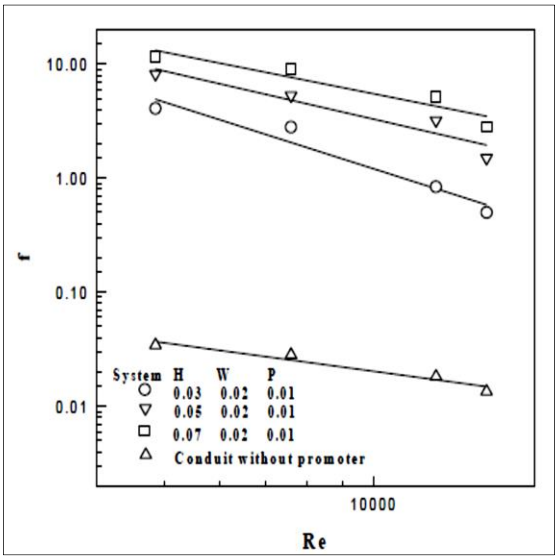

Fig. 21: *Effect of Height on Friction Factor.*

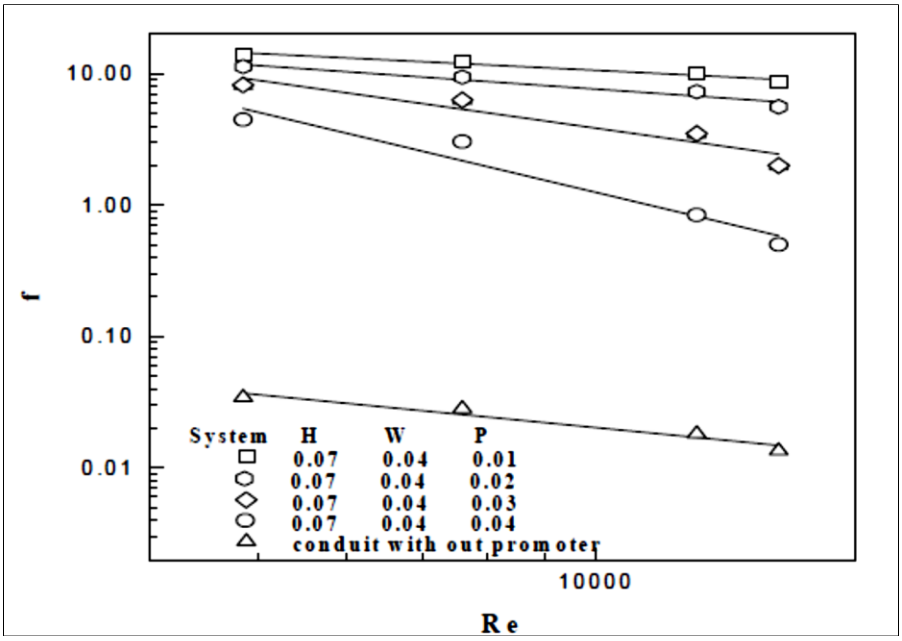

Fig. 22: Effect of Promoter Pitch on Friction Factor.

Effect of Width of the Promoter

A graph is drawn for f versus Re and shown in Figure 22. The figure reveal there is a decrease in friction with width, the decrease not uniform up to a width of 0.3 beyond which a marginal influence is observed. Enhancements of friction factor values range from 17 to 19 fold at a Reynolds number of 4853 while that tapered of 15 to 20 fold at a Reynolds number of 14533.

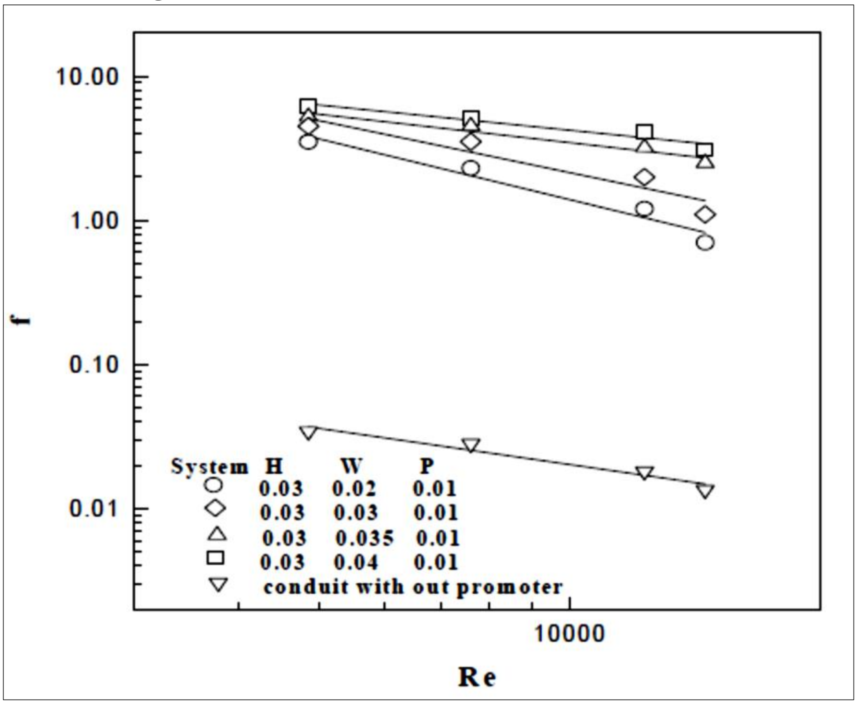

Fig. 23: Effect of Width of the Promoter on Friction Factor.

Energy Factor

Energy factor is defined as the ratio of energy loss in the conduit with promoter to the conduits without promoter insert (E/E_0) and can be expressed as the friction factor penalty in the presence and absence of the promoter as $(f/f_0)^{1/3}$. Figure 23 is drawn for energy factor against Re for two sets of data which augment maximum and minimum for the promoter in the present study. The energy factor values increased from 1.75 to 5.0 at a Reynolds number of 4853 and that tapered off to 0.75 to 2.5 at a Re of 14533. The energy factor values increased with increase in height (H), width (W) and pitch (P) of the promoter as shown by Figure 24–26.

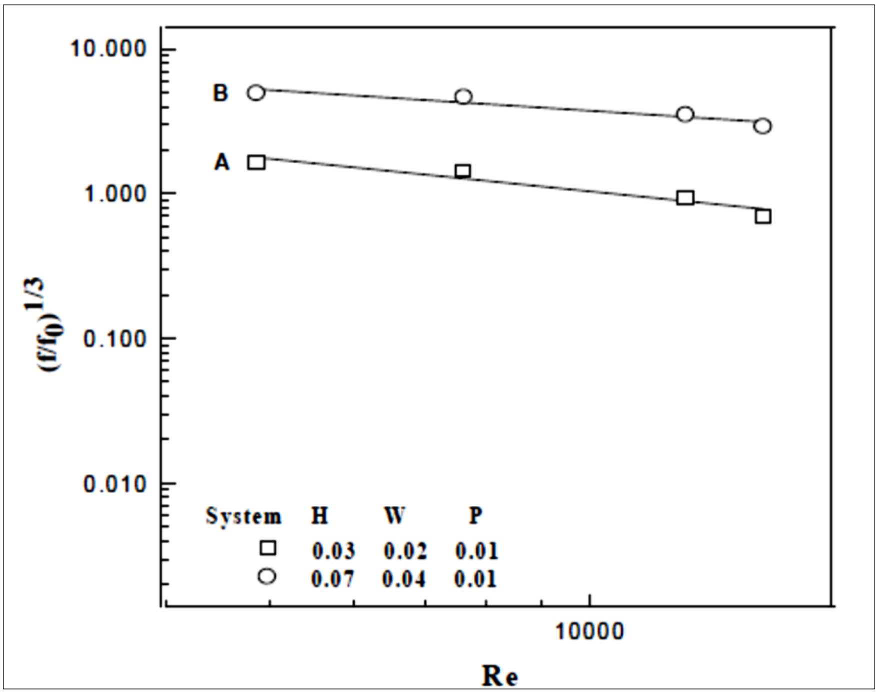

Fig. 24: *Augmentation Plot.*

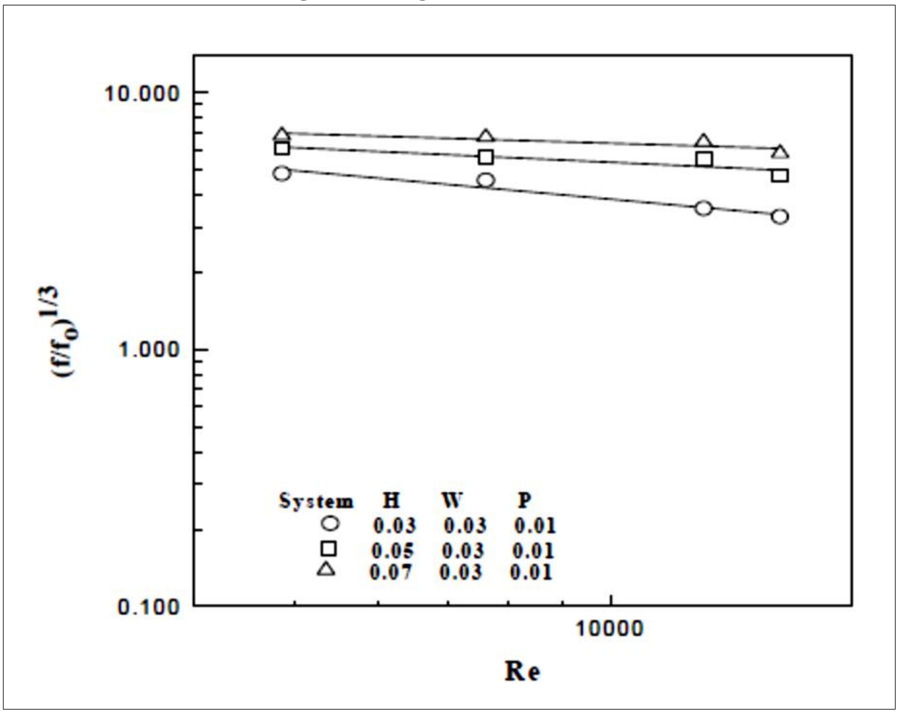

Fig. 25: *Effect of Height on Friction Losses.*

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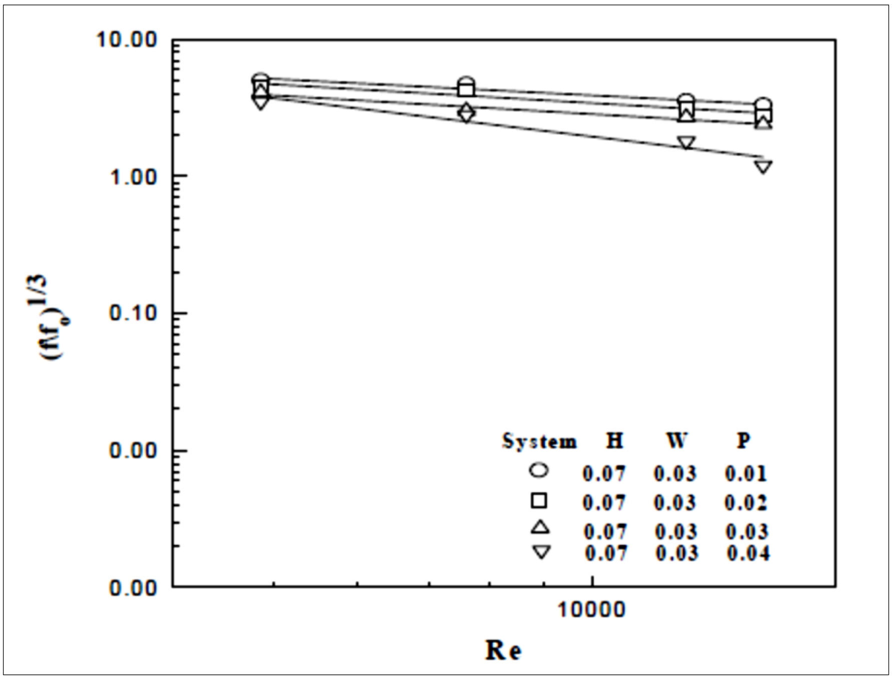

Fig. 26: *Effect of Pitch on Friction Losses.*

Performance Evaluation

Several works[15–23] were reported in literature with the aim of establishing the performance of the promoter. Performance analysis is essential for the evaluation of net energy gain to ascertain whether the spiral tape wound on rod promoter chosen is efficient from the energy point of view. The comparison is made based on the same pumping power with a view of net gain.

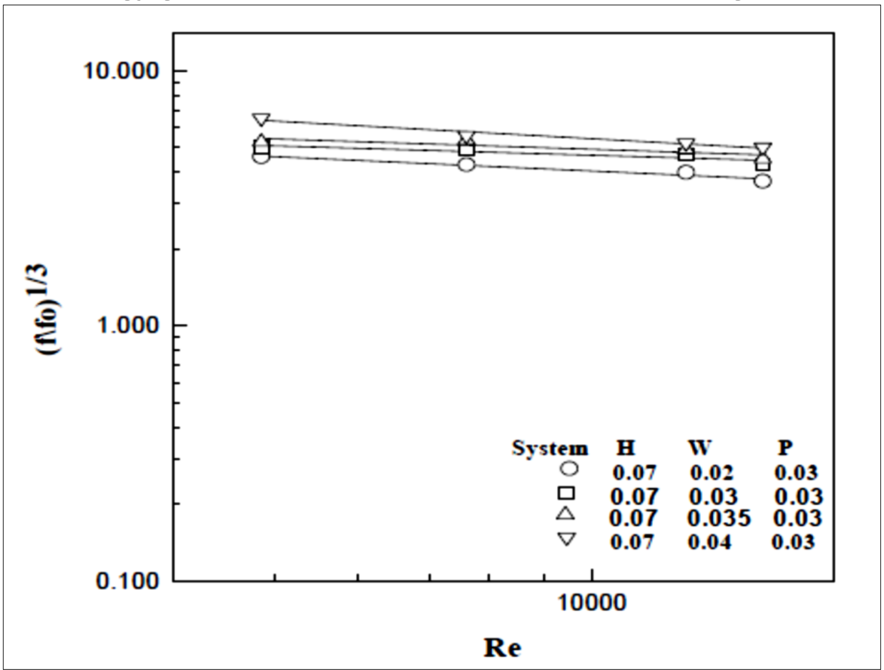

Fig. 27: *Effect of Width on Friction Losses.*

Performance index or efficiency of the promoter is defined as follows.

$\eta = (k_L / k_{L0})/(E/E_0)$. or

$\eta = (k_L / k_{L0})/(f/f_0)^{1/3}$

Figure 27 is a plot of performance index versus Reynolds number for two different promoters that show maximum and minimum augmentation. The performance decreased with increase in Reynolds number. It is also increasing with width, pitch and height of the column.

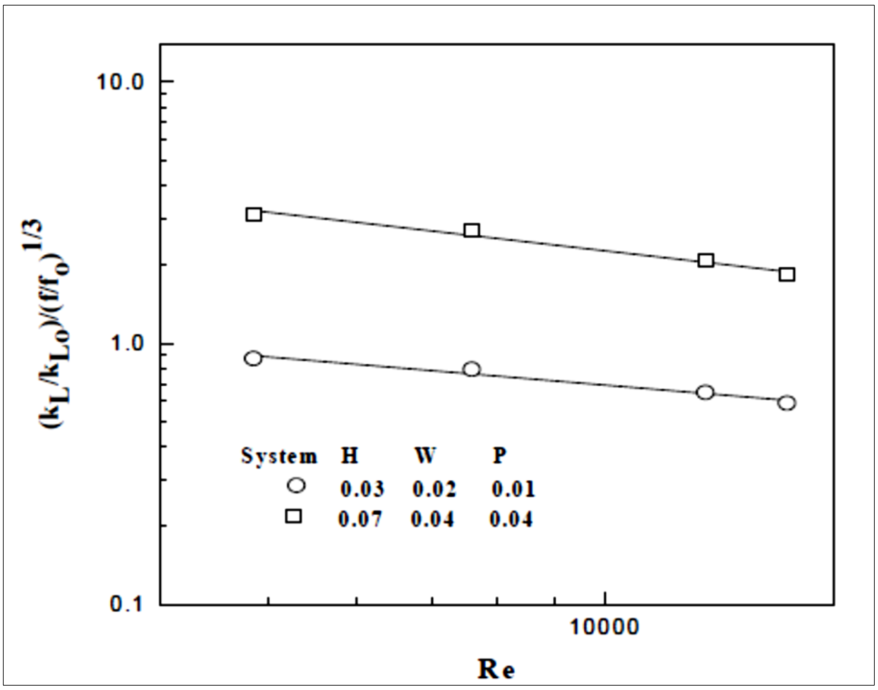

Fig. 28: *Variation of Performance Index with Reynolds Number.*

CONCLUSIONS

1. Mass transfer coefficients are increasing with velocity
2. Mass transfer coefficients are increased with increase in height (H), width (W) of the promoter and decreased with increase in pitch (P) of the spiral tape wound on rod promoter.
3. The spiral tape wound of rod with geometric parameters 0.07 m height, 0.04 m width and 0.04 m pitch given maximum augmentation within the range of variables covered in the present study. A maximum augmentation of 15 fold.
4. Friction factor values are decreasing with Reynolds number.
5. The enhancements in friction factors are up to maximum of 26 folds over a tube flow with no promoter at low Reynolds number.
6. Performance index decreased with increase in Reynolds number
7. Maximum performance index is obtained for the promoter with geometric parameters 0.07 m height, 0.04 m width, 0.04 m pitch.
8. Correlations were developed based on semi theoretical considerations. Wall similarity concept is used in the development of correlations. The developed correlations are as follows.

$$R(h^+) = 0.2049(\mathrm{Re}_m^+)^{0.412}(P/D)^{0.014}(H/D)^{-0.053}(W/D)^{0.128}$$

$$\bar{g} = 14315(\mathrm{Re}_m^+)^{0.528}(P/D)^{-0.122}(H/D)^{-0.092}(W/D)^{-1.487}$$

$$\eta = 0.0033(\mathrm{Re}_m^+)^{0.184}(P/D)^{-0.00082}(H/D)^{-0.0034}(W/D)^{0.612}$$

9. Within the range of variables covered in the present study a maximum efficiency obtained in 3.1.

Nomenclature

D = Diameter of the conduit, m

$\bar{g}$ = modified mass transfer function

$\bar{g} = u_i^+ + ((f/2st - 1)/\sqrt{f/2})$

H = Height of the entry region spiral drive, m

P = Pitch of the entry region spiral drive, m

Re = Reynolds number, $DV\rho/\mu$

$R(h^+)$ = Roughness function for momentum transfer in homogeneous flow

$$= 2.5\ln[2(W/D)] + \sqrt{2/f} + 3.75$$

Re^+_m= Roughness Reynolds number for homogeneous flow

$$= (W/D).\mathrm{Re}.\sqrt{f/2}$$

Sc =Schmidt number = $\mu/\rho D_L$

V = velocity of the fluid, m/s

W = Width of the entry region spiral drive promoter, m

ρ = Density of the fluid, kg/m^3

μ = Viscosity of the fluid, poise

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REFERENCES

1. Lin *et al.* Diffusion controlled electrode reactions. *Industrial and Engineering Chemistry*. 1951; 43(9): 2136–43p.
2. Chiou JP. Experimental investigation of the augmentation of forced convection heat transfer in a circular tube using spiral spring inserts. *Trans. A.S.M.E.* 1987; 109: 300–7p.
3. Prasad RP. Studies on ionic mass transfer with coaxially placed spiral coils as turbulence promoter in homogenous flow and in fluidized beds. *Ph.D Thesis. Andhra University, Visakhapatnam,* INDIA. 1993.
4. Sujatha V. Studies on ionic mass transfer with coaxially placed helical tapes on a rod in homogeneous fluid and fluidized beds. *Ph. D., Thesis, Andhra University, isakhapatnam, INDIA,* 1991.
5. Rao G.R., Sujatha V., Venkateswarlu P. Performance of Helical Tape Promoter in Fluidized Beds. *Indian Chem. Engr. Section A.* 1997; 39(2): 131-6p.
6. Sujatha V., Prasad P.R., Sarma C.B., *et al.* Studies on ionic mass transfer with insert helical tape promoters in batch fluidized beds. *Indian Journal of Chemical Technology*. 2003; 10: 694–700p.
7. Prasad P.R., SujathaV., Sarma C.B., *et al.* Studies on ionic mass transfer with coaxially placed spiral coils as turbulence promoter in homogenous flow and in fluidized beds. *Chemical Engineering and Processing J.* 2004; 43: 1055–62p.
8. Sujatha V., Sarma C.B., *et al*. Studies on ionic mass transfer with coaxially placed helical and on a rod in forced convection flow. *Chemical Engineering and Processing J.* 1997; 36(1): 67–73p.
9. Rao S.S. Studies on ionic mass transfer with coaxially placed cones on a rod in homogeneous fluid and fluidized beds. *PhD. Thesis, Andhra University, Waltair, India*, 1983.
10. Sitaraman T.S. Augmentation of mass transfer with coaxial string of spheres as internals in tubes and

fluidized beds. *Ph.D. Thesis, University of Madras, India,* 1977.

11. Raju C.D. Augmentation of mass transfer at the outer wall of concentric annuli in absence and presence of fluidizing solids effect of wires wound on central rod. *Ph.D. Thesis, Andhra University, Visakhapatnam*, India, 1984.
12. Venkateswarlu P. Studies on ionic mass transfer with coaxially placed discs on a rod as turbulence Promoter. *Ph.D., Thesis, Andhra University, Visakhapatnam, India*, 1987.
13. Webb RL, Eckert RG, Goldstein RJ. Heat transfer and friction in tubes with repeated-rib roughness. *Int. J of Heat and Mass Transfer*. 1971; 14(4): 601–17p.
14. Dawson D.A, Trass O. Mass transfer at rough surfaces transfer massique aux surfaces roughnes. *Int J of Heat and Mass Transfer*. 1972; 15(7): 1317–36p.
15. Rao V.N. Studies on Ionic Mass and Momentum Transfer with co-axially placed twisted tape disc assembly as turbulence promoter in circular conduits. *Ph.D. Thesis, Andhra University, Visakhapatnam, INDIA*, 2004.
16. Mohan V.M. Studies on mass and momentum transfer with coaxially placed entry region coil, disc assembly as turbulence promoters in circular conduit. *Ph. D., Thesis, Andhra University, Visakhapatnam, INDIA*, 2008.
17. Mohan V.M., Kumar C.S., Sujatha V., *et al*. Mass transfer correlation development for the presence of entry region coil as swirl promoter in tube. *International Journal of Thermal Sciences*. 2010; 49: 356–64p.
18. Rao K.N. Studies on mass at the outer wall of a circular conduit with entry region twisted tape as turbulence promoter in homogeneous flow and in fluidized beds, *Ph. D., Thesis, Andhra University, Visakhapatnam, INDIA,* 2011.
19. Chang S.W., Yang T.L. Forced convective flow and heat transfer of upward concurrent air-water slug flow in vertical plain and swirl tubes. *Experimental Thermal and Fluid Science*. 2009; 33: 1087–99p.
20. Eiamsa-ard S., Seemawute P., Wongcharee K. Influences of peripherally-cut twisted tape insert on heat transfer and thermal performance characteristics in laminar and turbulent tube flows. *Experimental Thermal and Fluid Science*. 2010; 34: 711–19p.
21. Promvonge P., Eiamsa-ard S. Heat transfer augmentation in a circular tube using V-nozzle turbulator inserts and snail entry. *Experimental Thermal and Fluid Science*. 2007; 32: 332–40p.
22. Eiamsa-ard S. Study on thermal and fluid flow characteristics in turbulent channel flows with multiple twisted tape vortex generators. *International Communications in Heat and Mass Transfer*. 2010; 34: 1151–61p.
23. Gunes S., Ozceyhan V., Buyukalaca O. Heat transfer enhancement in a tube with equilateral triangle cross sectioned coiled wire inserts. *Experimental Thermal and Fluid Science*. 2010; 34: 684–91p.
24. Dipprey D.F., Sabersky R.H. Heat and momentum transfer in smooth and rough tubes at various prandtl numbers. *Int. J of Heat and Mass Transfer*. 1963; 6(5): 329–32p.
25. Nikuradse J. Laws of flow in rough pipes. *VDI Forsch*. 1933; 361p.