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Mass transfer in circular conduit with coaxially placed twisted tape–disc assembly as turbulence promoter

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ABSTRACT

Studies on the effect of coaxially placed entry region twisted tape-disc assembly as turbulence promoter on mass transfer rates in forced convection flow of electrolyte were conducted. 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 pitch of the tape (T_P), length of the tape (T_L), width of the tape (T_W), diameter of the disc (D_d) and tape-disc distance (h). The results revealed that the mass transfer coefficient increased with increase in velocity, diameter of the disc (D_d), length of the tape (T_L), width of the tape (T_W) and decreased with increase in pitch of the tape (T_P) and tape-disc distance(h). Within the range of variables covered, the augmentation achieved in mass transfer coefficients were up to 5 fold over the tube flow in absence of promoter. Mass transfer rates were analyzed with *roughness mass transfer function* and *roughness Reynolds number*. The following correlation was reported out of the study.

$$g(h^+) = 343.95\,(Re^+)^{-0.176}\,(\phi_1)^{0.244}\,(\phi_2)^{-0.001}\,(\phi_3)^{-0.033}\,(\phi_4)^{0.402}\,(\phi_5)^{0.016}\,Sc^{-0.345}$$

1. Introduction

Several theoretical and experimental studies on heat and mass transfer are being carried out to identify an appropriate augmentation technique suitable to a given system in recent years.The various techniques adopted are the use of (a) insert promoters (b) converging and diverging sections, (c) the vibration and rotation of fluid or the transfer surface, (d) the location of crossflow elements and (e) the use of fluidizing solids. Recirculating flow patterns are developed in a flowing fluid by employing the above technique s that generate intense turbulence.More turbulence scours away the boundary layer at the reacting surface thus providing more surface of contact for heat and mass transfer. The following investigations are reported in literature using the insert promoters.

The insert turbulence promoters were of several kinds. Among them use of baffles [1], stirrers [2], liquid jets [3], spargers [4], and various other geometrical bodies immersed in the flow and the use of two phase [5]. The swirl flow generating promoter is found to be a good augmentative technique and can easily be incorporated in the existing system. Bergles [6] reviewed several techniques and types of promoters. Use of displaced promoters or insert promoters had been gaining importance. Augmentation in mass transfer coefficients were reported with the use of string of helical – wire coil-inserted tubes [7], helical tapes [8], spiral coils [9], coaxially placed cones [10], twisted tapes mounted on a central annular rod [11]. Studies on ionic mass transfer using helical tapes [8] as promoter in forced convection flow of electrolyte showed increase in coefficients with increase in tape width and increase in diameter of the promoter rod. A five fold augmentation in mass transfer coefficient was observed in the range of variables studied. Sitaraman [12] reported wall and surface mass transfer coefficients with the string of spheres placed axially in a circular column. The wall mass transfer coefficients increased with decrease in spacing. Rao and Raju [13] employed coaxially placed cones on a rod as internal for the studies in mass transfer for homogeneous flow of the electrolyte. The spacing between the cones and cone angle showed a definite change in the flow pattern of the flowing electrolyte passed the reacting surface. Maximum coefficients were observed at the maximum cross-section of the cone. Mass transfer data in presence of ring promoter [14] and cylindrical and mesh type promoters [15] revealed significant increase in mass transfer coefficients. Several works [16–19] on heat transfer were reported in literature employing the swirl flow generating promoters. Discs [20] placed across the flow in conduit would generate form friction both in upstream and downstream sides,

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Nomenclature

h^+	Dimensionless roughness height, h/d
$g^+(Re^+,Sc)$	*Mass transfer function* defined by Eq. (8)
$g(h^+)$	*Roughness mass transfer function* = $(St/St_o) + R(h^+)$
FR	Fully rough value defined by Eq. (7)
J_D	*Mass transfer factor* (k_L/V). $Sc^{2/3}$
Re	*Reynolds number* = $dV\rho/\mu$
Re^+	*Roughness reynolds number* = (h/d). $Re.\sqrt{(f/2)}$
R (h^+)	*Roughness momentum transfer function* = $2.5\ln(2h/d) + \sqrt{(2/f)} + 3.75$
St	*Stanton number* = k_L/dSt
u^+	Dimensionless velocity, u/u^*
y^+	Dimensionless radial distance from the wall, $y\,u^*/\nu$
St_o	Stanton number for conduit without internals
Sc	Schmidt number $\mu/\rho D_L$
f	Friction factor, $\Delta p\ d\ g_c/2LV^2\ \rho$
A_o	Area of electrode, m^2
C_o	Concentration of ferricyanide ion, kg-mole/m^3
d	Diameter of test section, m
D_L	Diffusivity of reacting ion, m^2/sec
D_d	Disc diameter, m
$\in$	Eddy viscosity, m^2/s
$\in_D$	Eddy diffusivity, m^2/s
ρ	Density of fluid, Kg/m^3
Δp	Pressure drop, N/m^2
L	Length of test section, m
F	Faraday's constant = 96,500 C/g-mol
V	Velocity of electrolyte, m/s
g	Acceleration due to gravity, m/sec^2
g_c	Gravitational constant
h	Distance between tape and disc, m
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 ions transferred
T_P	Pitch of tape, m/turn
T_W	Width of tape, m
T_L	Length of tape, m
u	Local velocity, m/s
u^*	Friction velocity = $\sqrt{(\tau_W g_c/\rho)}$, m/s
Y_4	$G(h^+)/(\phi_1)^{0.244}\ (\phi_2)^{-0.001}\ (\phi_3)^{-0.033}\ (\phi_4)^{0.402}\ (\phi_5)^{0.016}\ Sc^{-0.345}$

Greek letters

ϕ_1	(T_L/d) = Dimensionless group
ϕ_2	(T_W/d) = Dimensionless group
ϕ_3	(T_P/d) = Dimensionless group
ϕ_4	(h/d) = Dimensionless group
ϕ_5	(D_d/d) = Dimensionless group
μ	Viscosity of fluid, kg/m s

thus generated turbulence continued to show their effect on wall mass transfer coefficients to longer lengths along the cell. Twisted tapes and discs were useful insert promoters. In earlier investigations where twisted tapes as entry region swirl generators and string of discs were employed as promoters, significant augmentation in heat and mass transfer were reported. Studies on the effect of coaxially placed twisted tape-disc assembly in circular conduits on mass transfer rates in case of forced convection flow of electrolyte had not been reported. Based on literature review this investigation was therefore undertaken using twisted tape-disc assembly as turbulence promoter and essentially dealt with the evaluation of mass transfer rate at the outer wall through limiting current technique. Parameters covered in this study were compiled in Table 1.

2. Experimental setup

The experimental setup used for the study was similar to those used in earlier studies [8,20]. Schematic diagram of experimental set up was shown in Fig. 1. It was essentially consisted of a storage tank (TS), centrifugal pump (P), rotameter (R), entrance calming section (E1), test section (T) and exit calming section (E2). The storage tank was cylindrical copper vessel of 100 l capacity with a drain pipe and a gate valve (V1) for periodical cleaning. A copper coil (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 (V2). The discharge line from the pump was split into two. One served as a bypass line and controlled by valve (V3). The other connected the pump to the entrance calming section (E1) through Rotameter. The Rotameter was connected to a valve (V4) for adjusting the flow at the desired value. The Rotameter had a range of $0–475 \times 10^{-6}$ m3/s. The entrance calming section consisted of 0.05 m ID circular copper pipe with a flange and was closed at the bottom with a gland nut(G). The up-stream side of the entrance calming section was filled with capillary tubes to dampen the flow fluctuations and to facilitate steady flow of the electrolyte through the test section. The detail of the test section was shown in Fig. 2. It was made of a graduated perplex tube of 0.64 m length 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. They were fixed flush with the inner surface of the test section at equal spacing of 0.01m. Exit calming section was also of the same diameter copper tube of 0.5 m long, and it was provided with a flange on the upstream side for assembling the test section. It had gland nuts (G_4, G_3) at the top and bottom ends to hold the central tube. Two thermo wells (t1,t2) 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. Twisted tape-disc assembly serving as turbulence promoter was made of copper of various sizes with a provision to fix it rigidly within the test section. The twisted tape-disc assembly was placed concentrically in the test section. The limiting current measuring equipment consisted of multimeter of Motwane make which had 0.01 mA accuracy and vacuum tube voltmeter was used for potential measurements. The other equipment used in circuit was 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

Table 1
Range of variables covered in the study.

Variable	Minimum	maximum	Max/Min
Pitch of the Twisted Tape, m/turn	0.02 m/turn	0.12 m/turn	6
Length of the Twisted Tape, m	0.14 m	0.22 m	1.57
Width of the Twisted tape, m	0.01 m	0.03 m	3
Diameter of the of Disc, m	0.02 m	0.045 m	2.25
Distance between Tape and Disc, m	0.05 m	0.25 m	5
Velocity, m/s	0.024 m/s	0.224 m/s	9.33
Reynolds number, *Re*	1285	11985	9.32
Schmidt number, *Sc*	830.8	1251	1.50