Studies on ionic mass transfer with insert helical tape promoters in batch fluidized beds

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Augmentation of mass transfer coefficients, due to the presence of helical tape promoters in batch fluidized beds has been presented. Mass transfer coefficients have been evaluated from the measured limiting current densities and the concentrations of the reacting ions. The variables studied are the geometric parameters of the promoter-tape width, pitch and diameter of the promoter rod, the flow rate of the electrolyte, void fraction and particle diameter. It is found that $k_L$ increased with increased flow rate and particle diameter. The increase in tape width and diameter of the promoter rod resulted in slightly increased mass transfer coefficients. Pitch of the promoter showed negligible effect on $k_L$.

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

The introduction of insert promoter in fluidized bed (compound augmentation) makes the transport process more rapid. Venkateswarlu et al. obtained mass transfer data with coaxially placed discs on a central rod and reported about 12-fold augmentation. A critical value $e/s=0.26$ for increasing and decreasing coefficients was reported. Sitaraman studied ionic mass transfer with string of spheres in fluidized beds. The limiting currents were measured on the surface of the sphere and the confining wall of the fluidized bed. The variables studied are pitch, diameter of the sphere, diameter of the particle and solids concentration. Wall and surface mass transfer coefficients have been reported, with the string of spheres placed axially. The wall mass transfer coefficients decreased with increase in spacing. Rao and Raju employed co-axially placed cones on a rod (CPCR) as internal in fluidized beds, for the studies in mass transfer. The effects of cone diameter, cone spacing, particle size and void fraction on mass transfer were studied. Twenty-fold improvement in mass transfer coefficients over the smooth tube data were reported. The cone spacing and cone angle showed a definite change in the flow patterns of the flowing fluid past the reacting surface. Maximum coefficients were observed at the maximum cross-section of the cone. Mass transfer data in presence of ring promoter and cylindrical and mesh type promoters revealed significant increase in mass transfer coefficients.

The use of swirl flow generating promoters as insert promoters, was found to be a good augmentative technique and easy to be incorporated in the existing system. Bergles made an exhaustive survey on evaluation of techniques to enhance heat and mass transfer. Several experimental investigations on augmentation techniques were summarized and a selection criterion for a specific promoter was given in terms of pumping power performance. Studies on ionic mass transfer using helical tapes as promoter in forced convection flow of the electrolyte showed significant increase in coefficients with increase in tape width and diameter of the promoter rod. Five to ten-fold augmentation in mass transfer coefficient was observed. Heat transfer studies employing the swirl flow generating promoters has been reported in the literature.
Ravi et al.\textsuperscript{13} reported a maximum of 25-fold improvement in mass transfer coefficient due to the effect of coaxially placed discs on a rod as internal in fluidized beds. Raju et al.\textsuperscript{14} reported negligible effect of coil diameter and pitch on mass transfer, for the studies on effect of wires wound on the central rod as promoter in fluidized beds. Employing compound augmentation technique to obtain higher heat and mass transfer coefficients has been reported in the literature\textsuperscript{15-18}.

Based on the literature review, the present study is undertaken to investigate the effect of helical tape in fluidized bed on mass transfer.

**Experimental Procedure**

The schematic diagram of the experimental unit is shown in Fig. 1. The equipment essentially consists of a re-circulating tank, a centrifugal pump, two rotameters, an entrance calming section, a test section, an exit calming section and thermo wells. The test section is provided with a number of micro electrodes fixed flush with its surface at equal spacing (0.01 m).

The details of the helical tape promoter are shown in Fig. 2. A 0.0016 m thick copper strip is bent to the helical shape and welded to the promoter rod. This assembly forms the helical tape promoter. The promoter is mounted in the test section coaxially by means of gland nuts and positioned by supporting grid. The equipment and the helical tape promoter are the same as that used in earlier studies\textsuperscript{7}. The electrolyte consisted of equimolal solutions of potassium
ferricyanide and potassium ferrocyanide with an excess of indifferent electrolyte (0.5N)-sodium hydroxide. 100 L of the electrolyte is prepared in the storage tank. After inserting the promoter in the column, known volume of the solids is introduced into the test section and the required flow rate of the electrolyte is adjusted by operating the control and by pass valves. The bed is expanded to the desired height and the flow rate and bed heights are noted. Limiting current data are measured at point copper electrodes for the reduction of potassium ferricyanide ion and for the oxidation of potassium ferrocyanide ion.

The limiting current is indicated by a small increase in voltage for a sharp increase in current. The experiments are repeated by varying the volume of the solids \( V_s \), diameter of the particle \( d_p \), pitch of the helical tape \( p \), tape width \( w \) and diameter of the promoter rod \( d_R \). Mass transfer coefficients are calculated by the expression,

\[
k_L = \frac{I}{\ln(AFC)} \quad \text{... (1)}
\]

The viscosity \( \mu \) and density \( \rho \) of the electrolyte are obtained using Oswald viscometer and specific gravity bottle respectively. The temperature is noted for each run to an accuracy of \( \pm 0.1 \)°C. Since the concentration of the electrolyte in the present study is the same as that used in the studies of Lin et al.\(^{19} \), diffusivity \( D_L \) values are taken from their data and are corrected according to the temperature maintained in the present experiment. The void fraction \( \epsilon \) is calculated using the following equation:

\[
\epsilon = 1 - \frac{V_j}{(V_j - V_p)} \quad \text{... (2)}
\]

The range of variables covered is given in Table 1.

### Table 1—Range of variables covered

<table>
<thead>
<tr>
<th>Variable</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow rate of the electrolyte, ( Q \times 10^6 ) m(^3)/s</td>
<td>49</td>
<td>707</td>
</tr>
<tr>
<td>Pitch of the helical tape, ( p \times 10^2 )</td>
<td>1</td>
<td>15</td>
</tr>
<tr>
<td>Width of the helical tape, ( w \times 10^2 )</td>
<td>0.3</td>
<td>1.2</td>
</tr>
<tr>
<td>Diameter of the promoter rod, ( d_R \times 10^2 )</td>
<td>0.95</td>
<td>1.9</td>
</tr>
<tr>
<td>Particle diameter, ( d_p \times 10^2 )</td>
<td>0.29</td>
<td>0.684</td>
</tr>
<tr>
<td>Void fraction, ( \epsilon )</td>
<td>0.383</td>
<td>0.97</td>
</tr>
<tr>
<td>Schmidt number, ( Sc )</td>
<td>719</td>
<td>1331</td>
</tr>
<tr>
<td>Modified Reynolds number, ( ((Rep(1-\epsilon)) )</td>
<td>142</td>
<td>1,000,923</td>
</tr>
</tbody>
</table>

**Results and Discussion**

Literature indicates, that, the augmentation of \( k_L \) due to the presence of helical tape promoter in homogeneous flow can be attributed to (i) increase in velocity consequent to increase in the obstruction area and (ii) swirl flow generated by the promoter and its interaction with axial flow. In case of fluidized beds, the interstitial velocity (being very high compared to superficial velocity) and the convective movement of the solids generate intense turbulence and contribute to the improvement in mass transfer coefficient. It is an interesting case to study the compound effect that is the presence of helical tape promoters in fluidized beds on mass transfer coefficients.

Augmentation of mass transfer coefficients with the helical tape promoter is illustrated in Fig. 3 by plotting mass transfer coefficient against superficial velocity. Plot A in Fig. 3 represents the experimental data for the case of promoter in a fluidized bed. Plot D represents smooth tube data that is the predicted data from the equation of Lin et al.\(^{19} \) for the case of homogeneous flow of electrolyte and plot C is the
Experimental data with promoter having the dimensions: $p = 0.15 \text{ m}, \ w = 0.003 \text{ m}$ and $d_R = 0.0095 \text{ m}$ in homogeneous flow. The mass transfer data in fluidized beds in the absence of the promoter is shown by the plot B.

The comparison of plots A and D shows the following augmentation in coefficients. At a velocity of $0.075 \text{ m/s}$, 18.1-fold augmentation in coefficient is noted due to the presence of the promoter in fluidized beds over the smooth tube coefficients and the improvements decrease as the velocity is increased. $k_L$ values in the present study are 2.66-fold higher than those obtained due to the presence of the promoter and the present mass transfer data are 31.4 percent higher over the $k_L$ values obtained in a fluidized bed without promoter. The reason for improvement can be attributed to the swirl flow generated by the promoter, the increased interstitial velocity and convective movement of solids.

The effects of the geometric variables of the promoter in fluidized beds on mass transfer coefficients are shown in Figs 4 & 5. The increase in the value of the pitch has negligible effect on mass transfer coefficients (figure not shown). However, the increase in tape width slightly increased the mass transfer coefficients as shown in Fig. 4. The increase in the diameter of the promoter rod marginally increased the coefficients as represented in Fig. 5. The effect of the particle diameter is shown in Fig. 6 by plotting the mass transfer coefficient against the velocity. In the present study, the particle diameter has been varied from 0.0029 to 0.00684 m. The plots in Fig. 6 indicate, that, the coefficients increase with increase in the particle size.

In Fig. 7, the coefficients are plotted against the solids fraction $(1-\varepsilon)$. The plots show that the coefficients steadily increase with increase in the solids fraction till a value of 0.1 to 0.2 is attained and there-
after the coefficients remain nearly constant. The $k_L$ obtained at any time in a batch fluidized bed can be assumed to be due to the turbulence created by particle movement and that of fluid velocity. As the fluid velocity increases, the concentration of solids decreases. The contribution of the fluid turbulence increases and that of particle movement decreases in such a way that they are self-compensatory. So the mass transfer coefficient remains more or less same. As the fluid velocity decreases, exactly the reversal happens, till the solid concentration $(1-\varepsilon)$ reaches a value of about 0.2, below which, the turbulence created to increase the mass transfer coefficient is mostly because of the fluid flow and very small contribution is from particle movement. Similar observations have been noted with regard to trends in coefficient studies in batch fluidized beds \cite{20}, insert promoter in fluidized beds \cite{3} and cross-flow elements in fluidized beds \cite{21}.

The experimental data using Richardson and Zaki \cite{22} relationship reveals that the superficial velocity bears a functional relationship with voidage as,

$$Re_p \propto \varepsilon^n \quad \ldots \quad (3)$$

Present mass transfer data obtained for the different helical tape promoters are shown in Fig. 8 with $\varepsilon$ as a function of $Re_p$ at $d_p = 0.0049$ m. The mass transfer data in a fluidized bed for $d_p = 0.0049$ m is shown in the same figure. It is apparent from the plots that the presence of promoter has not affected the nature of fluidization and the slope of the line is same as that reported by Richardson and Zaki \cite{22}. The data are correlated following the method of development of generalized correlations as presented in earlier

![Fig. 8](image_url) - Plot of experimental data in accordance with Richardson and Zaki correlation.

![Fig. 9](image_url) - Correlation plot of experimental data.
studies \(^3,13,14\) in terms of the modified \(J_0\) factors \((J_0\varepsilon)\), modified Reynolds numbers \([Re_p/(1-\varepsilon)]\) and pertinent dimensionless groups of the promoter. The regression analysis of the data yielded the following equation with standard deviation of 9.31 percent and the average deviation of 7.58 percent

\[
J_D \varepsilon = 0.36[Re_p/(1-\varepsilon)]^{0.25} (\rho/d_c)^{0.06} (w/d_c)^{0.072} (d_t/d_c)^{0.23}
\]

Fig. 9. Mass transfer data of earlier studies. The reason being the smooth flow produced by the tape and its interaction with axial flow may have resulted in more turbulence. The present data are consistently higher than the data obtained by Raju et al. \(^1,14\) for the presence of wires wound on rod in fluidized beds.

Conclusions

It may be concluded from the results reported here that, (i) mass transfer coefficient increases with increase in diameter of the particle \((d_p)\), (ii) the increase in the value of width \((w)\) and pitch \((p)\) of the helical tape have marginal effect on the mass transfer coefficient, (iii) increased diameter of the promoter rod resulted in slight increase in \(k_t\), (iv) mass transfer coefficients increased with increase in solids fraction \((1-\varepsilon)\) up to 10 to 20 percent and remained nearly constant thereafter and (v) the \(k_t\) values are enhanced up to 18.1-fold over the smooth tube coefficients.

Nomenclature

\begin{align*}
A &= \text{cross-sectional area of the electrode, m}^2 \\
C_i &= \text{concentration of the reacting ions, Kg moles/m}^3 \\
d_c &= \text{diameter of the conduit, m} \\
d_p &= \text{diameter of the particle, m} \\
D_t &= \text{diffusivity of the electrolyte, m}^2/\text{s} \\
d_k &= \text{diameter of promoter rod, m} \\
F &= \text{Faraday, 96500 coulombs/equivalent} \\
I &= \text{limiting current, A} \\
k_t &= \text{mass transfer coefficient, m/s} \\
p &= \text{pitch of the helical tape, m} \\
Q &= \text{volumetric flow rate of electrolyte, m}^3/\text{s} \\
u &= \text{superficial velocity based on conduit diameter, m/s} \\
V_t &= \text{volume of the fluidized bed, m}^3 \\
V_p &= \text{volume of promoter, m}^3 \\
V_s &= \text{volume of solids, m}^3 \\
w &= \text{width of the helical tape, m} \\
\varepsilon &= \text{void fraction} \\
\mu &= \text{viscosity of the electrolyte, Ns/m}^2 \\
p &= \text{density of the electrolyte, Kg/m}^3 \\
\delta &= \text{tape thickness, m} \\
\end{align*}

Dimensionless groups

\[
J_0 = \text{mass transfer factor, } (k_t/u) \cdot Sc^{0.23} \\
Re_p = \text{Reynolds number, } d_p u / \rho \mu \\
Sc = \text{Schmidt number, } \mu / (D_t \delta)
\]

References

Articles