Forced Convection Solid-Liquid Mass Transfer at a Surface of Tube Bundles under Single Phase Flow

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Solid-liquid mass transfer characteristics of in-line tube bank were investigated by measuring the rate of diffusion-controlled dissolution of copper surface in dichromate solution. Variables studied were the number of rows in the tube bank, physical properties of the solution, and flow rate of the solution. The data were correlated for the conditions: $937 < Sc < 1300$, $173 < Re < 385$, $1 < N < 5$, by the equation $Sh = 2.68\ Re^{0.465}\ Sc^{0.33}\ N^{-0.35} + 35.35$.

The addition of Polyox WSR 301 as a drag reducing agent leads to a decrease in the mass transfer coefficient, which ranged from 49 to 83 % depending on the mass fraction of the polymer, number of tube bundles and the liquid flow rates.

Key words:
Solid-liquid mass transfer; mass transfer coefficient; tube bank; drag reducing agent; single-phase flow

Introduction

The flow of fluids, heat transfer, and mass transfer in tube banks represents an idealization of many industrially important processes. Typical examples include filtration, flow in biological systems, tubular heat exchangers, flow and heat transfer in fibrous media as encountered in polymer processing and in insulation materials, etc. Extensive studies[1–8] have been conducted for the heat transfer to or from a bank (tube bundle) in cross flow. However, little work has been done in the analogous field of mass transfer to or from tube bundle. In the area of mass transfer, several studies focused on different geometries. *Sedahmed* et al.[9–11] studied the solid-liquid mass transfer in fixed bed of Raschig ring using different modes of stirring namely gas sparging, single phase flow and two phase flow. *Zaraa* et al.[12] studied the solid-liquid mass transfer in fixed bed of spheres using gas sparging as a mode of stirring. *Nosier* et al.[13] measured the rate of solid-liquid mass transfer from horizontal cylindrical surfaces of different diameters using a gas sparging as a mode of stirring. *Soltan* et al.[14] studied the mass transfer behaviour of a flow by fixed bed electrochemical reactor under different hydrodynamics conditions *Nosier* et al.[15] measured the rate of solid-liquid mass transfer at helical coils in bubble columns. He found that the mass transfer coefficient decreases with increasing the number of active rings per coil. *El-Shazly* et al.[16] studied the

solid-liquid mass transfer at an Oscillating Packed Bed of Raschig rings. *Nosier*[17] studied the liquid-solid mass transfer at gas sparged tube bundles. He found that the mass transfer rate decreases with increasing the number of arrays.

The objective of the present work is to study the solid-liquid mass transfer at the surface of tube bundle using the single-phase flow as a mode of stirring. Another objective is to study the effect of addition of different amount of Polyox WSR 301 as a drag reducing agent to the fluid on the mass transfer coefficient.

The study of mass transfer at the surface of tube bundle under single phase-flow will enable the prediction of the rate of diffusion-controlled processes which can occur at the tube bank surfaces, e.g. diffusion-controlled corrosion. The tube bundle can also be used as a catalytic surface to conduct liquid-solid catalytic heterogeneous chemical and biochemical reactions, in the case of biochemical reactions an immobilized enzyme can be fixed on the tube bundle. In this case the tube bundle plays the dual role of being a heat exchanger and a catalyst support.

Experimental

The experimental setup is shown in Fig. 1 it consists of a rectangular cross-section column (12 · 12 cm), a glass storage tank, a plastic- head centrif-
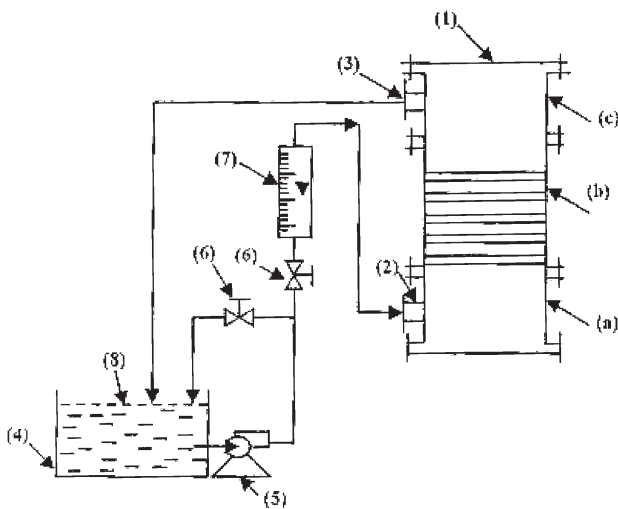
F i g . 1 – *1 – rectangular column (a – inlet section, b – working section, c – outlet section). 2 – liquid inlet. 3 – liquid outlet. 4 – storage tank. 5 – plastic centrifugal pump, 6 – control valves. 7 – rotameter. 8 – electrolyte level*

F i g . 2 – *Arrangement of tube bank in the column. S_L = longitudinal pitch, S_T = transverse pitch. D = tube diameter, $S_T = S_L = 2D$, D = 8 mm*

ugal pump, and a rotameter. The rectangular column was made of transparent prespex and had 80 cm height. The vertical column was divided into three sections, namely, the inlet section, the working section, and the outlet section. The working section which had a height of 30 cm, consisted of five arrays of copper tubes. The tube rows of a bank were aligned in the direction of the liquid velocity. The tube diameter was $d = 8$ mm; the transverse pitch and longitudinal pitch measured between the tube centres were equal to $d = 16$ mm. Each array consisted of six tubes of 12 cm length. The working section was preceded and followed by an empty inlet and outlet section. Each of the two empty sections was 25 cm in height. The arrangement of the tube bank is schematically shown in Fig. 2. For each run, 10 liter of fresh $K_2Cr_2O_7$–H_2SO_4 solution were placed in the glass storage tank and was circulated through the tube bank using a plastic-head centrifugal pump. The change of $K_2Cr_2O_7$ concentration with time was determined by withdrawing 5 ml samples at 3 min intervals from the storage tank. Concentration of dichromate was determined by titration against standard 0.01 mol l^{-1} ferrous ammonium sulphate using diphenylamine indicator.[18] Solution flow rate through the tube bank was regulated by means of a valve and measured by a calibrated rotameter. Experiments were carried out at temperatures ranging from 23 to 26 °C. The superficial liquid velocity ranged from $v = 2.5$ to 4.4 cm s^{-1}. The initial concentration of $K_2Cr_2O_7$ solution was kept constant at 0.003 mol l^{-1}, while the concentration of H_2SO_4 was varied from 0.5 to 1.5 mol l^{-1}. The active number of arrays in the tube bank was controlled by insulating part of it with Teflon tape. In order to study the effect of drag
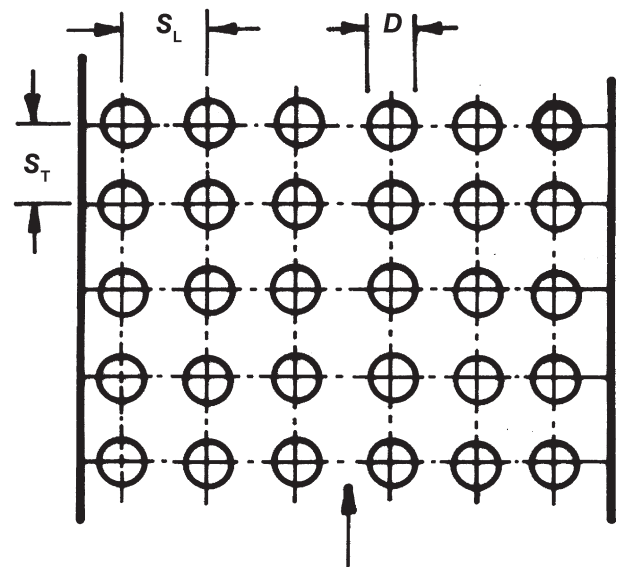
reducing agents on the solid/liquid mass transfer, the polymer polyox WSR 301 of the molecular mass $6 \cdot 10^6$ were used in the present study. The polymer fraction ranged from $w = 10$ to $50 \cdot 10^{-6}$. All solutions were prepared using A. R. grade chemicals and distilled water.

Viscosity and density of the solutions used were measured by an Ostwald Viscometer and a density bottle respectively.[19] The diffusivity of dichromate was calculated from literature values[20] and was corrected for the change in temperature using the Stokes-Einstein equation.

Results and discussions

For the present batch recalculating reactor the rate of the diffusion controlled reaction between the tube bundles and the chromate solution is given by the equation

$$-V(\mathrm{d}c/\mathrm{d}t) = k_\mathrm{d} A\, c \qquad (1)$$

Which upon integration yields

$$\ln (c_0/c) = (k_\mathrm{d} A\, t)/V \qquad (2)$$

Fig. 3 represents a typical $\ln (c_0/c)$ vs. t plots from which the mass transfer coefficient (k_d) was obtained under different conditions. Fig. 4 shows the effect of Reynolds number (Re) on Sherwood number (Sh) at different numbers of arrays (N). The data fit the equation:
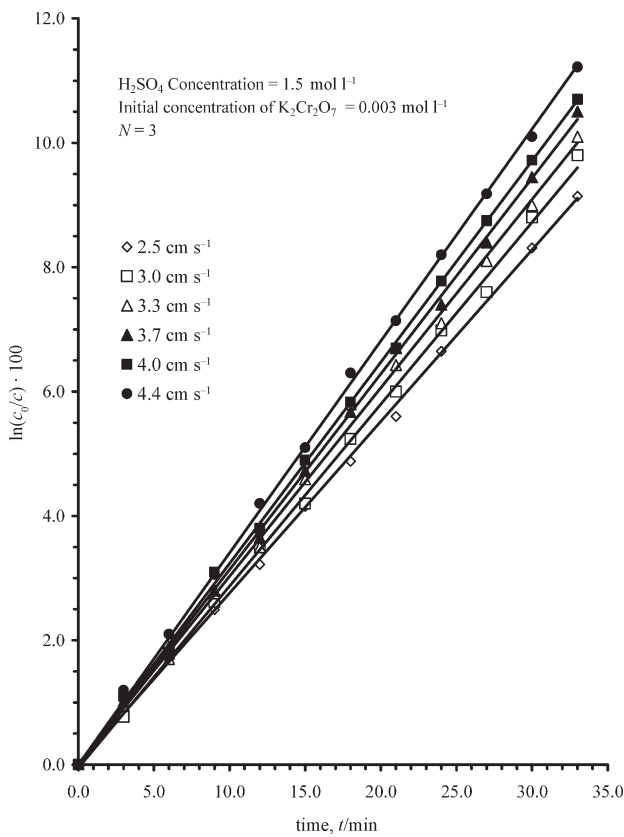
$$Sh = a\, Re^{0.465} \qquad (3)$$

F i g . 3 – $\ln(c_0/c)$ *vs. time*

F i g . 4 – $\log(Sh)$ *vs.* $\log(Re_L)$ *for different numbers of arrays (N)*

The increase in the mass transfer coefficient $(Sh = k_d\, d_t/D)$ with *Re* number is attributed mainly to the increase in the degree of turbulence generated by the tube bundles and the corresponding decrease in the concentration boundary layer thickness (Cf Fig. 5).[21]

The exponent (0.465) is fairly consistent with the value (0.5) predicted from the hydrodynamic boundary layer theory.[22]

Fig. 6 shows that decreasing H_2SO_4 concentrations increases the mass transfer coefficient, probably because the decrease of solution concentration reduces solution viscosity with a consequent increase in Cr^{+6} diffusivity (D) according to Stokes-Einstein equation.[23]

Fig. 7 shows the effect of the number of tube bundles (N) on the mass transfer coefficient at different Peclet number (Pe). The data fit the equation:

$$Sh = b\ N^{-0.35} \qquad (4)$$

The physical significance of the minus exponent (–0.35) means that as the number of tube bundles increases, the mass transfer coefficient (k_d) decreases. These phenomena may be attributed to the progressive local decrease in $[K_2Cr_2O_7]$ – concentration below the bulk value as the solution moves upward past different tubes.
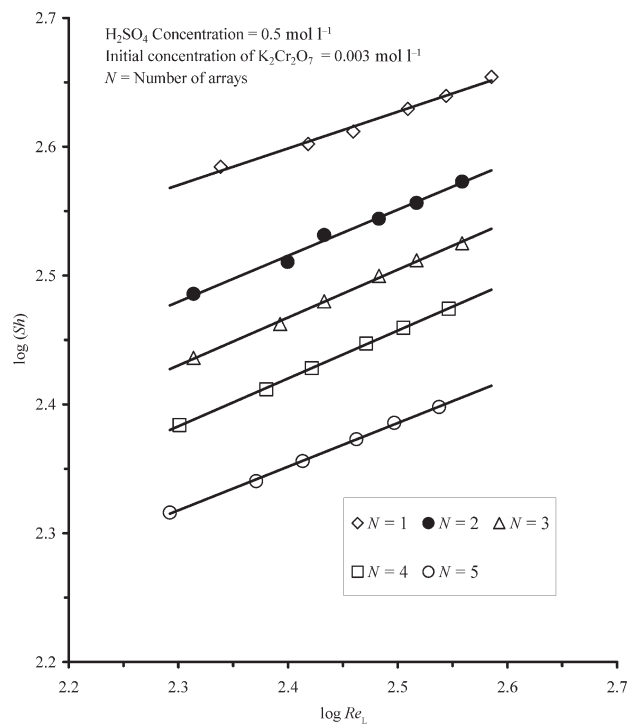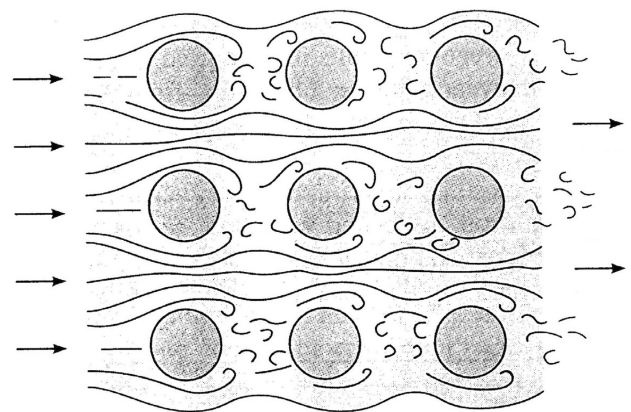

F i g . 5 – *Flow conditions for aligned tubes*

An overall mass transfer correlation was envisaged in terms of the dimensionless groups *Sh* and *Re* usually used in correlating heat and mass transfer data in different geometries. Tube diameter was used as a characteristic length in calculating *Re* number. Additional dimensionless factor was added to the empirical correlation to account the effect of number of tube bundles (N). Fig. 8 shows that for the conditions $937 < Sc < 1300$, $173 < Re < 385$, $1 < N < 5$, the data fit the equation

$$Sh = 2.68\ Re^{0.465}\ Sc^{0.33}\ N^{-0.35} + 35.35 \qquad (5)$$
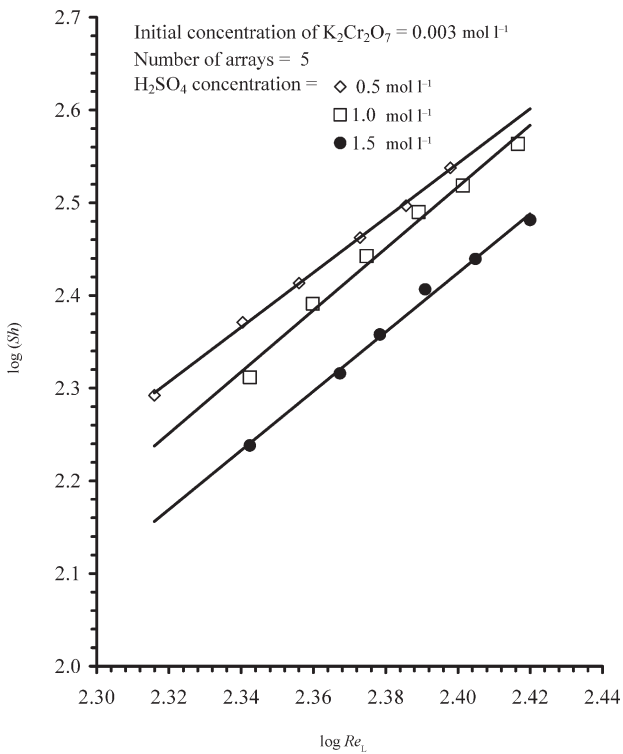
with an average deviation of $\pm\, 4.7\ \%$ (Cf. Fig. 9).

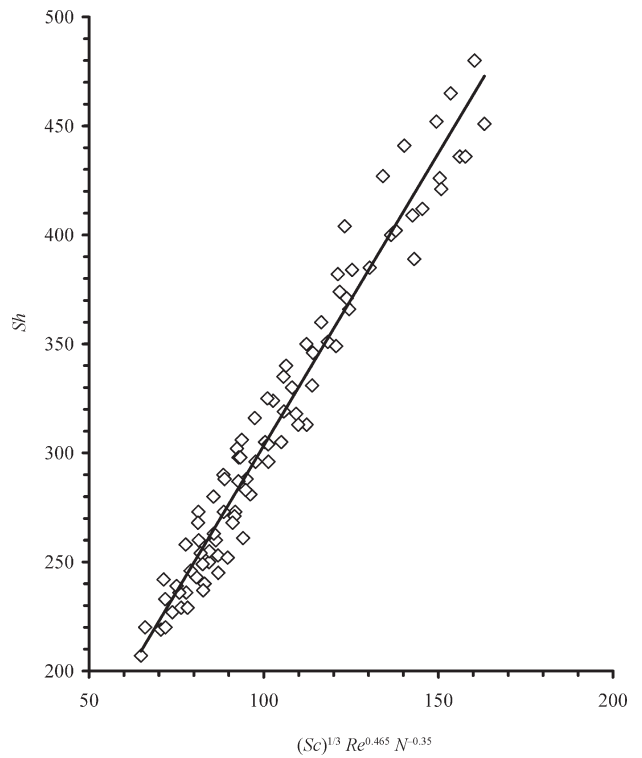F i g . 6 – log(Sh) *vs.* log(Re_L) *at different concentrations of* H_2SO_4

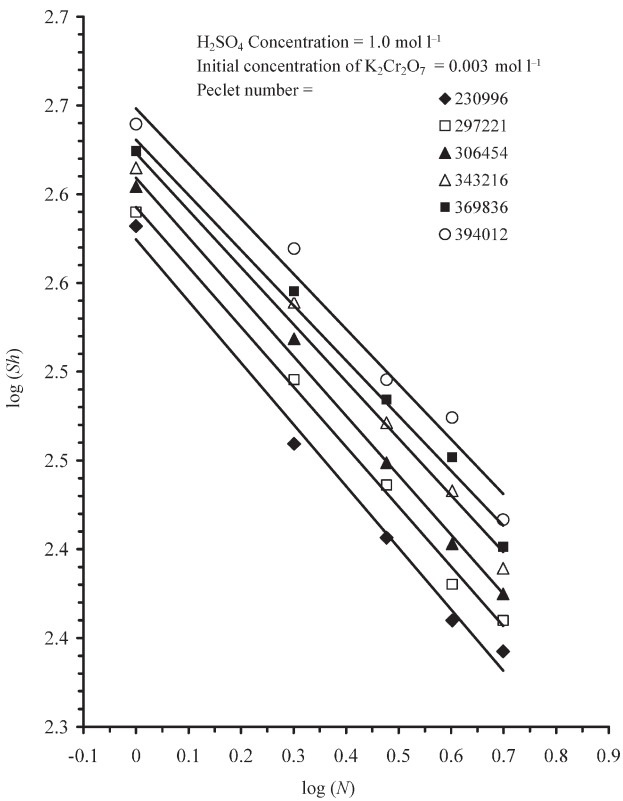F i g . 8 – *Overall mass transfer correlation*

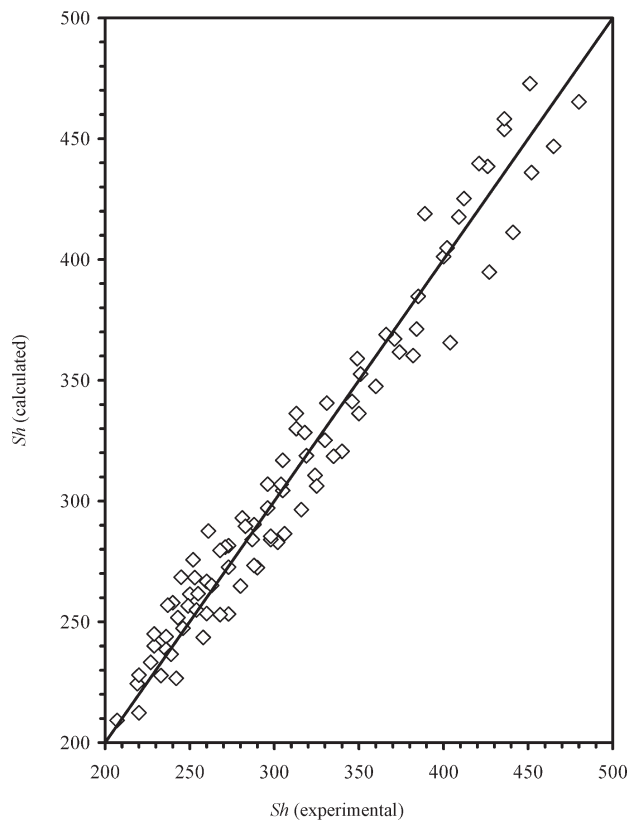F i g . 7 – log(Sh) *vs.* log(Re_L) *at different Peclet numbers*

F i g . 9 – *Sh calculated vs. Sh experimental*

The effect of mass fraction of Poylox on the percentage reduction of mass transfer coefficient is shown in Fig. 10 at different number of arrays. The percentage reduction in k_d was calculated from the formula:

$$\% \text{ reduction in } k_d = [k_{d[blank]} - k_{d[with\ Polyox]}]/k_{d[blank]}$$

The percentage reduction in (k_d) increases with increasing polymer concentration till a certain value is reached beyond which there no further change in the value of (k_d) with increasing polymer mass fraction.

The decrease in (k_d) in presence of polyox drag reducing polymer may be attributed to the ability of polymer molecules to damp the small scale high frequency eddies generated in the wake region be-hinds the tubes in the tube bank. In addition to this the presence of polyox in the solution decreases the mass diffusivity (D) due to the increase in interfa-cial viscosity (μ)[24] in accordance with the Stokes-Einstein equation:

$$D \mu/T = \text{constant}$$

The % decrease in mass transfer coefficient (k_d) ranges from 49 to 83 % depending on the mass fraction of polymer (w), superficial liquid velocity (v_L) and number of tube bundles (N).

Conclusions

1. The number of tube bundles affects the mass transfer coefficient (k_d), the higher the number of tube bundles the lower the mass transfer coefficient.

2. The increase in mass transfer coefficient with the superficial liquid velocity support that the mass transfer in the present study is diffusion – controlled.

3. The data were correlated using a dimension-less equation. This equation can be used to design and operate single-phase reactor that use tube bundles as a catalyst supporting surface and heat exchanger.

4. The addition of Polyox WSR 301 as drag re-ducing agent leads to decrease in the mass transfer coefficient, which ranged from 49 % to 83 % de-pending on the concentration of polymer, superfi-cial velocity and number of tube bundles.

List of symbols

A – active surface area, cm^2

a, b – constants,

c – dichromate concentration at time t, gmol l^{-1}

c_0 – initial dichromate concentration, gmol l^{-1}

d_t – tube diameter, cm

D – dichromate diffusivity, cm^2 s^{-1}

k_d – mass transfer coefficient, cm s^{-1}

V – volume of electrolyte, cm^3

v_L – superficial liquid velocity, cm s^{-1}

Greek letters

μ – electrolyte viscosity, g cm^{-1} s^{-1}

ρ – electrolyte density, g cm^{-3}

δ – diffusion layer thickness, cm

Dimensionless groups

Re – Reynolds number, $\rho v_L d_t/\mu$

Sc – Schmidt number, $\mu/(\rho D)$

Sh – Sherwood number, $k_d d_t/D$

St – Stanton number, k_d/v_L

w – mass fraction

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