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Mass transfer at the impellers of agitated vessels in relation to their flow-induced corrosion

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Abstract

To investigate the role of mass transfer in the kinetics of flow induced corrosion of agitated vessels impellers, the rate of mass transfer at four blade 45° pitched turbine, four blade flat turbine and six blade disc turbine was studied using the diffusion controlled dissolution of copper in acidified chromate technique. Variables studied were impeller rotation speed, physical properties of the solution, impeller diameter, the presence of baffles in the cylindrical agitated vessel, the presence of suspended solids and the effect of drag reducing polymers. The blank solution data were correlated in the form: $Sh{=}a\,Sc^{0.33}.\ Re^{b}$. The values of a and b were found to depend on impeller geometry.

In all cases the presence of baffles in the cylindrical agitated vessel increases the rate of diffusion controlled corrosion by an amount ranging from 50% to 115% depending on impeller rotation speed. The presence of suspended solids increases the rate of corrosion by an amount ranging from 7% to 70% depending on impeller rotation speed, solid concentration and particle size. The presence of Polyox WSR-301 drag reducing polymer decreases the rate of corrosion by an amount ranging from 5–49% depending on polymer concentration and impeller rotation speed. The economic worth of using drag reducing polymers in agitated vessels was noted. © 1998 Elsevier Science S.A. All rights reserved.

Keywords: Mass transfer; Agitated vessels; Erosion–corrosion; Drag reduction

1. Introduction

Agitated vessels are used widely in chemical, food, pharmaceutical and metallurgical industries to conduct processes such as mixing, liquid–liquid extraction, solid–liquid and gas–liquid reactions, crystallization and dissolution of salts, ore leaching, wastewater treatment, fermentation, etc. In the majority of these operations corrosive solution are used which limit the life time of the agitated vessel and its accessories beside contaminating the contents of the agitated vessel with corrosion products. Study of the corrosion behaviour of agitated vessels and their accessories would assist in their rational design and maintenance. Corrosion of metals involves two simultaneous reactions, namely anodic dissolution of the metal (e.g $M{=}M^{++}{+}2e$) and cathodic reduction of a depolarizer such as dissolved oxygen ($\frac{1}{2}O_2{+}H_2O{+}2e{=}2OH^-$). Side reaction between the cathodic product and the anodic product may lead to the formation of a porous solid film of corrosion product, e.g an oxide on the corroding metal surface. Kinetic studies of industrial corrosion where dissolved oxygen acts as a depolarizer [1–8] have revealed that cathodic reduction of oxygen involves three steps, namely: (i) mass transfer of dissolved oxygen from the solution bulk to the surface of the porous film, the rate of this step (N_1) is given by:

$$N_1 = K_1(C_s - C_1) \tag{1}$$

(ii) diffusion of dissolved oxygen through the porous film to the metal surface, the rate of this step (N_2) is represented by:

$$N_2 = K_2(C_1 - C_2) \tag{2}$$

(iii) reduction of oxygen at the metal surface, the rate of this step is expressed by:

$$N_3 = K_3C_2 \tag{3}$$

Eliminating C_1 and C_2 from the above equations, dissolved oxygen flux (N) under the steady state conditions can be expressed by the equation:

$$N = \frac{C_s}{1/K_1 + 1/K_2 + 1/K_3} \tag{4}$$

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Under conditions which may destroy the film, e.g high shear stress or the presence of suspended solid particles, the resistance of the film to the rate of oxygen diffusion ($1/K_2$) can be neglected and the rate of corrosion may be: (i) diffusion controlled if the chemical step of oxygen reduction is much faster than the liquid phase mass transfer step; (ii) partially diffusion controlled (mixed control); (iii) chemically controlled if the liquid phase mass transfer step is much faster than the chemical step. An argument similar to that used in case of the cathodic oxygen reduction can be applied to the anodic dissolution of the metal. In practice most corrosion processes are under diffusion or under mixed diffusion and chemical control [8].

The prediction of the rate of corrosion in both cases in terms of the oxygen flux Eq. (4) necessitates the presence of a mass transfer correlation from which the liquid phase mass transfer coefficient can be predicted. Although some work has been done to develop mass transfer correlations for geometries such as smooth and rough pipelines [4,5] and the wall of agitated cylindrical and rectangular vessels [9–12], scant attention was given to the rotating impellers of agitated vessels despite the importance of the subject to predicting their rate of erosion–corrosion which occurs frequently [13] especially in the presence of suspended solids.

The aim of this work is to study the rate of mass transfer controlled corrosion of rotating impellers with emphasis on geometries such as four blade 45° pitched turbine, four blade flat turbine and six blade turbine which are used frequently in practice. The present work was carried out using the diffusion controlled dissolution of copper in acidified chromate which has been developed by Madden and Nelson [14], and Gregory and Riddiford [15]. The technique has been used widely to study liquid–solid mass transfer.

Besides, the present work aims at testing the possibility of using drag reducing polymers as inhibitors for the diffusion controlled corrosion of rotating impellers. These polymers proved to be effective in reducing mass transfer and diffusion controlled corrosion in pipelines [16,17]. Drag reducing polymers have the potential of being used in agitated vessels to reduce power consumption by virtue of the ability of polymer molecules to damp the small scale high frequency eddies which prevail in the hydrodynamic boundary layer at the impeller, shaft and the wall of the agitated vessel. Mashelkar et al. [18], and Quraishi et al. [19] who investigated the influence of drag reducing agents on power consumption in agitated vessels found that polymer addition reduce the torque by a maximum of 59% whereas polymer addition reduce the torque in aerated tanks by a maximum of 77%. The mechanism of drag reduction is mentioned elsewhere [20,21]. In a recent development, Little et al. [22] recommended using drag reducing polymers in the form of a slurry instead of polymer solution in view of the fact that polymer slurries are more resistant to mechanical degradation than polymer solutions. Hydrodynamic studies of agitated vessels [23] have revealed the fact that the flow is laminar in the tank for $Re < 10$, turbulent for $Re > 1000$ and for the range between 10 and 10 000 the flow is transitional being turbulent at the impeller and laminar in remote parts of the vessel.

2. Experimental technique

A baffled and an unbaffled vessel were used in the present study, each a 3 l cylindrical container made of plexiglass with an inside diameter of 13.5 cm. A copper impeller was centrally mounted on an epoxy coated copper shaft of 1 cm diameter connected to 0.3 hp variable speed motor. The rotational speed of the motor was controlled by a variac and measured by an optical tachometer. The impeller speed was varied from 100 to 600 rpm. The motor was held firmly in position to avoid vibration and eccentric motion. Three types of impellers were used, namely four blade 45° pitched turbine, four blade flat turbine and six blade disc turbine. In all cases impeller diameter ranged from 0.3 to 0.65 of the vessel diameter. The baffled vessel contained four 90° plexiglass baffles each baffle had 1.2 cm width and 0.2 cm thickness.

Before each run 2000 cm^3 of acidified chromate was placed in the vessel, the solution depth was approximately equal to the tank diameter. The impeller was located centrally at a distance equal to the impeller diameter from the vessel bottom. The above dimensions correspond to the standard dimensions used in the design and operation of agitated vessels [23]. Three different solutions were used namely, 0.003 M $K_2Cr_2O_7$+0.5 M H_2SO_4, 0.003 M $K_2Cr_2O_7$ +1 M H_2SO_4, 0.003 M $K_2Cr_2O_7$ +2 M H_2SO_4. The rate of impeller dissolution was followed by withdrawing samples of 2 cm^3 from the agitated vessel at 10 min intervals for chromate analysis by titrating against standard solution of ferrous ammonium sulphate using diphenylamine sulphonate as indicator [24]. All chemicals used in the present work were AR grade, distilled water was used in preparing all solutions. Experiments were carried out at temperatures ranging from 22°C to 30°C. Each experiment was repeated once or twice. Solution density and viscosity used to correlate the data were determined by a density bottle and Ostwald viscometer [25].

Diffusivity of chromate was taken from the literature [15]. To test the effect of suspended solids on the rate of diffusion controlled corrosion of the impeller, porcelain particles were used. Particle size ranged from 0.3 to 0.7 mm while particle concentration ranged from 1% to 3% by volume. In order to test the effect of drag reducing polymers on the rate of diffusion controlled corrosion of the impeller, polyethylene oxide (polyox WSR-301) a product of Union Carbide was used in the form of suspension at concentrations of 200, 200, 400 and 500 ppm. The solid polymer powder has a density of 1.15–1.26 g/cm^3, particle size ranged from less than 38 μm to larger than 500 μm. The polymer was used as received and no attempt was made to

Table 1
Physical properties of the solutions used at 22°C

Solution composition	ρ (g/cm^3)	μ (Poise)	$D\times10^4$ (cm^2/S)
0.3 M $K_2Cr_2O_7$ + 0.5 M H_2SO_4	1.0274	0.01	9.657
0.003 M $K_2Cr_2O_7$ + 1.0 M H_2SO_4	1.06178	0.0112	8.6094
0.003 M $K_2CR_2O_7$ + 2.0 M H_2SO_4	1.1195	0.0125	7.694

separate different sizes. The chemical stability of the polymer in acidified chromate was tested in separate experiments by adding polyox to acidified chromate solution (blank) for 1 h after which chromate concentration was determined, no change in chromate concentration was found to take place, i.e polyox is chemically stable in the solutions used in the present study. Rheological measurements showed that all polymer containing solutions were Newtonian; polymer addition in the form of solid particles to the blank solution was found to have a negligible effect on the physical properties of the solutions. Table 1 shows the physical properties of the solutions.

3. Results and discussion

Assuming that the solution is perfectly mixed in the agitated vessel, the mass transfer coefficient of the diffusion controlled dissolution of the copper impeller in acidified chromate was obtained under different conditions from the chromate concentration–time data which are related by the equation

$$-Q\frac{dC}{dt} = KAC \qquad (5)$$

which on integration yields

$$\ln C_o/C = KAt/Q \qquad (6)$$

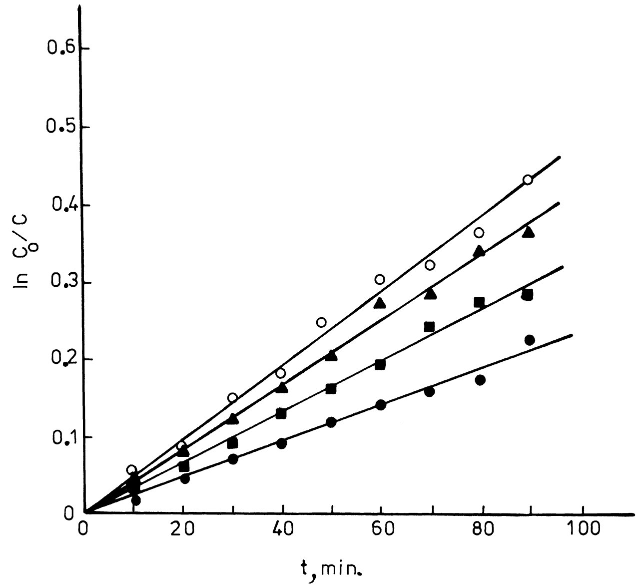

Fig. 1. Typical Ln C_o/C vs. t for four blade 45° pitched turbine Sc = 1095; impeller diameter = 5.3 cm; impeller rotation speed, rpm: ● – 100, ■ – 200, ▲ – 300, ○ – 400.

Fig. 1 shows typical ln C_o/C vs. t plot; the mass transfer coefficient was calculated from the slope of ln C_o/C vs. t line. Mass transfer coefficient were determined for the three different impellers under different rotation speeds, different solution physical properties and different impeller diameters. Fig. 2 shows that impeller diameter has a negligible effect on the mass transfer coefficient. The data were correlated for the three impellers in terms of the groups Sh, Sc and Re. Fig. 3 shows that the data for the four blade flat turbine under the conditions: 3350 < Re <33 500; 1050 < Sc < 1510; 0.3 < d/d_T <0.6, fit the equation

$$Sh = 1.727Sc^{0.33}Re^{0.55} \qquad (7)$$

with an average deviation of ±13%.

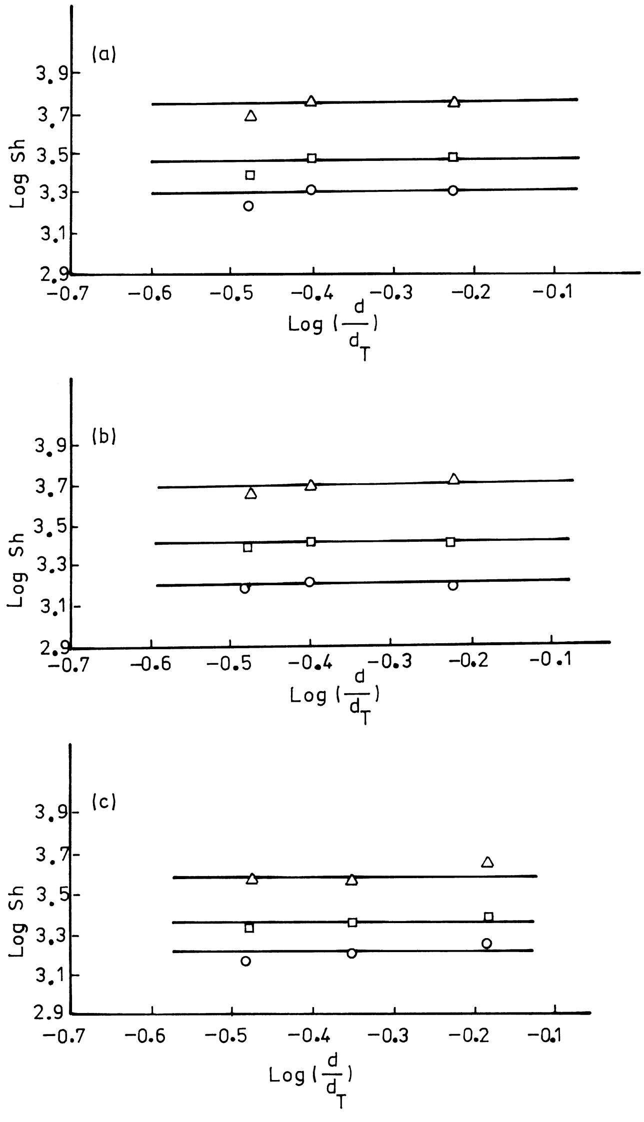

Fig. 2. Effect of impeller diameter on Sh. (a) four blade flat turbine; (b) four blade 45° pitched turbine; (c) six blade disc turbine. Sc = 1095; Re = ○ – 5000, □ – 10 000, △ – 30 000.

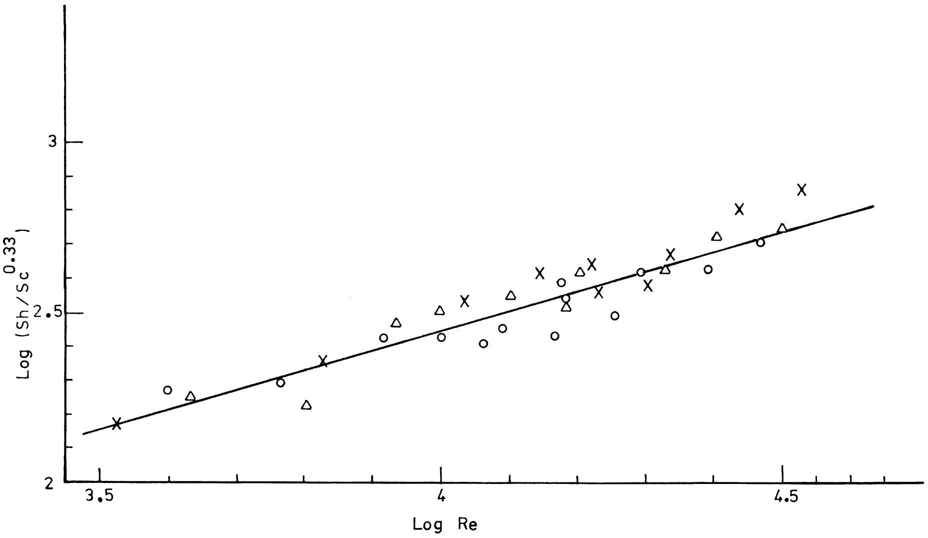

Fig. 3. Overall mass transfer correlation for four blade flat turbine. Sc: ○ – 937, □ – 1095, △ – 1353.

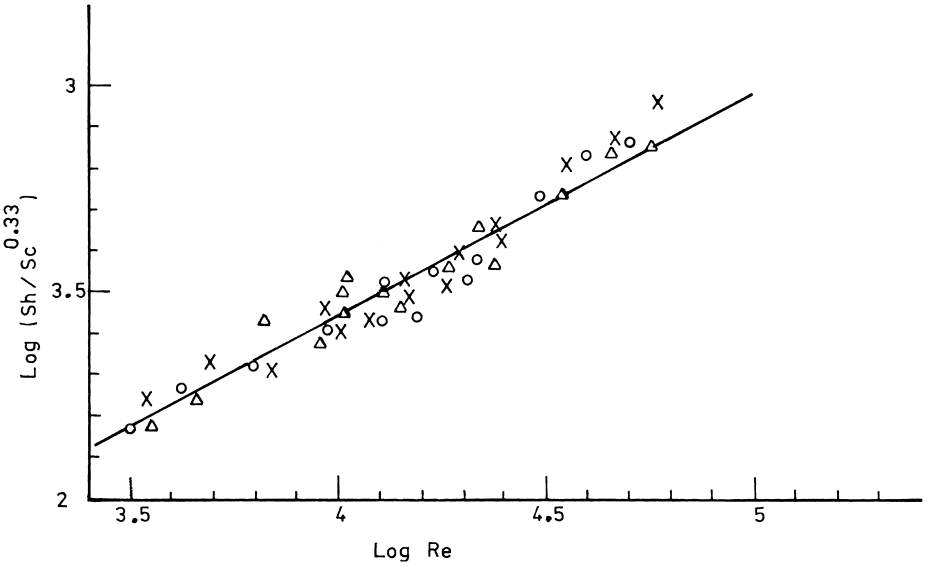

Fig. 4. Overall mass transfer correlation for four blade 45° pitched turbine. Sc: ○ – 937, □ – 1095, △ – 1353.

For the four blade 45° pitched turbine under the conditions: $3000 < Re < 60\,000$; $1075 < Sc < 1510$; $0.3 < d/d_T < 0.6$, Fig. 4 shows that the data fit the equation:

$$Sh = Sc^{0.33}Re^{0.6} \tag{8}$$

with an average deviation of ±9%.

For the six blade disc turbine under the conditions: $3350 < Re < 37\,600$; $1075 < Sc < 1510$; $0.3 < d/d_T < 0.65$, Fig. 5 shows that the data fit the equation:

$$Sh = 0.22Sc^{0.33}Re^{0.75} \tag{9}$$

with an average deviation of ±15%.

Fig. 6 shows that the four blade pitched turbine dissolves at a higher rate than the four blade flat turbine and the six blade disc turbine under the same conditions. It seems that the rate of diffusion controlled impeller dissolution is not only affected by the turbulence generated at the impeller but also by the overall flow pattern in the agitated vessel. The higher rate of dissolution of the four blade pitched turbine may be attributed to its higher ability to induce axial flow along with radial and swirl flow [25]. Axial flow improves the mixing conditions and reduce stagnant pockets i.e increase the rate of mass transfer by convection and decrease the contribution of slow diffusion. On the other hand the strong swirl motion induced by the four blade flat turbine and the six blade disc turbine reduces the slip velocity between the rotating impeller and the rotating solution with a consequent decrease in the rate of mass transfer.

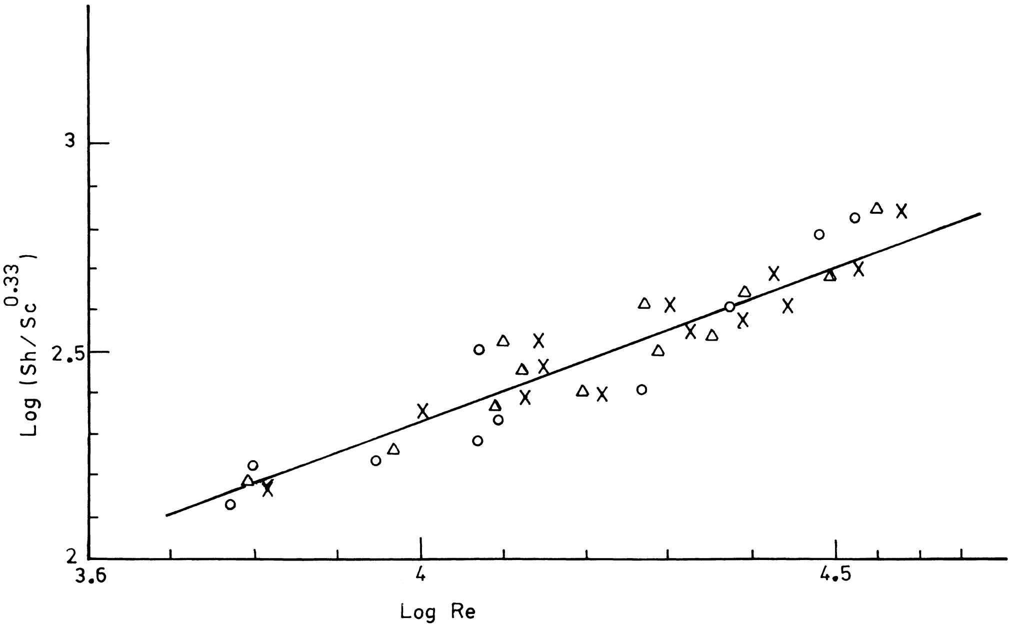

Fig. 5. Overall mass transfer correlation for six blade disc turbine. Sc: ○ – 937, □ – 1095, △ – 1353.

It would be of interest to compare the present results with the results of the single study conducted by save et al. [27] on mass transfer at impellers in agitated vessels. The authors measured the rate of mass transfer using two different systems namely, the dissolution of turbine impellers coated with benzoic acid in water and the dissolution of copper turbine in acidified chromate. The majority of the data were obtained using the dissolution of benzoic acid. The following turbine impellers were used in the study: (i) four-and six-blade disc turbines; (ii) four-and six-blade 45° pitched turbines; (iii) four-and six blade curved turbines. The authors found that the rate of impeller dissolution was

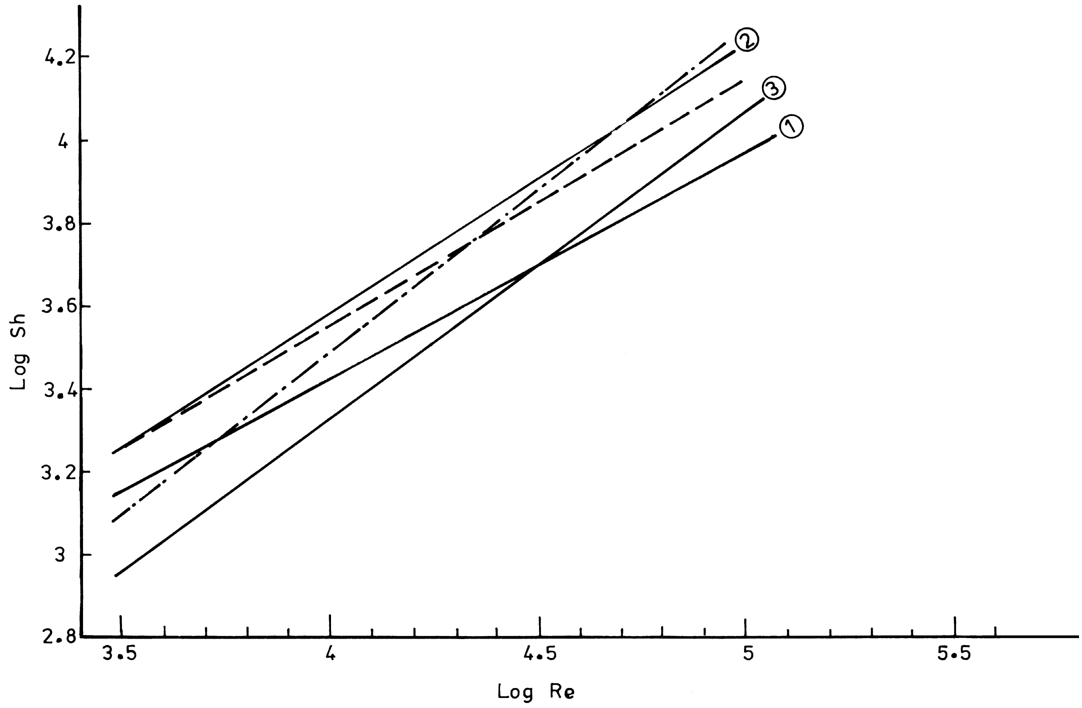

Fig. 6. Comparison between the present data and the data of Save et al. (1) Present data for the four blade flat turbine; (2) Present data for the four blade pitched turbine; (3) Present data for the six blade disc turbine. - · - the data of Save et al. for the four blade turbine. - - - the data of Save et al. for the four blade turbine.

not sensitive to the turbine geometry but depends among other things on the number of turbine blades. The authors correlated their data for the conditions: $5000 < Re < 90\,000$ and $1025 < Sc < 37876$ by the equations:

$$\text{For six blade turbine,} \quad Sh = 2 + 1.176Re^{0.569}.Sc^{0.677} \tag{10}$$

$$\text{For four blade turbine,} \; Sh = 2 + 1.176Re^{0.779}.Sc^{0.765} \tag{11}$$

Fig. 6 shows that the data of Save et al. are at variance with the present data. The discrepancy may be attributed to: (i) the difference in the range of experimental conditions especially the range of Sc; (ii) the benzoic acid technique used to obtain the majority of the data of Save et al. suffers from the shortcoming that surface roughness develops during benzoic acid dissolution with a subsequent change in the active area and the hydrodynamic conditions at the dissolving impeller. Despite this discrepancy, the rates of impeller dissolution reported by Save et al. under different conditions lie within the range of the rate of impeller dissolution recorded in the present work at different Re as shown in Fig. 6.

Fig. 7 shows the effect of using four baffles fixed to the wall of the agitated vessel on Sh, the presence of baffles increases the rate of mass transfer by about 80% in case of four blade 45° pitched turbine, and by an amount ranging from 60% to 90% in case of four blade flat turbine, while in case of the six blade disc turbine the increase ranges from 50% to 115%. The enhancing effect of baffles is attributed to the breakdown of the swirl motion of the solution in favour of axial and radial motion [23,26] which lead to better mixing conditions in the vessel. Figs. 8 and 9 show the effect of suspended solid particles on the rate of mass transfer. The mass transfer coefficient increases by an amount ranging from 7% to 70% depending on impeller type, particle size, solid particle concentration and Re. For a given set of conditions, Fig. 8 shows that the increase in the rate of diffusion controlled corrosion of the six blade disc turbine is far less than that of the four blade 45° pitched turbine and the four blade flat turbine. This may be explained by the high degree of turbulence prevailing at the six blade disc turbine as revealed by the Re exponent 0.75 in Eq. (5); under such conditions the turbulence generated by the solid particles contributes little to enhancing the rate of mass transfer. Figs. 8 and 9 show that generally the rate of impeller dissolution increases with increasing solid particle concentration and Re, the smaller the particle size the higher the rate of impeller dissolution. The increase in the rate of impeller dissolution in the presence of solid

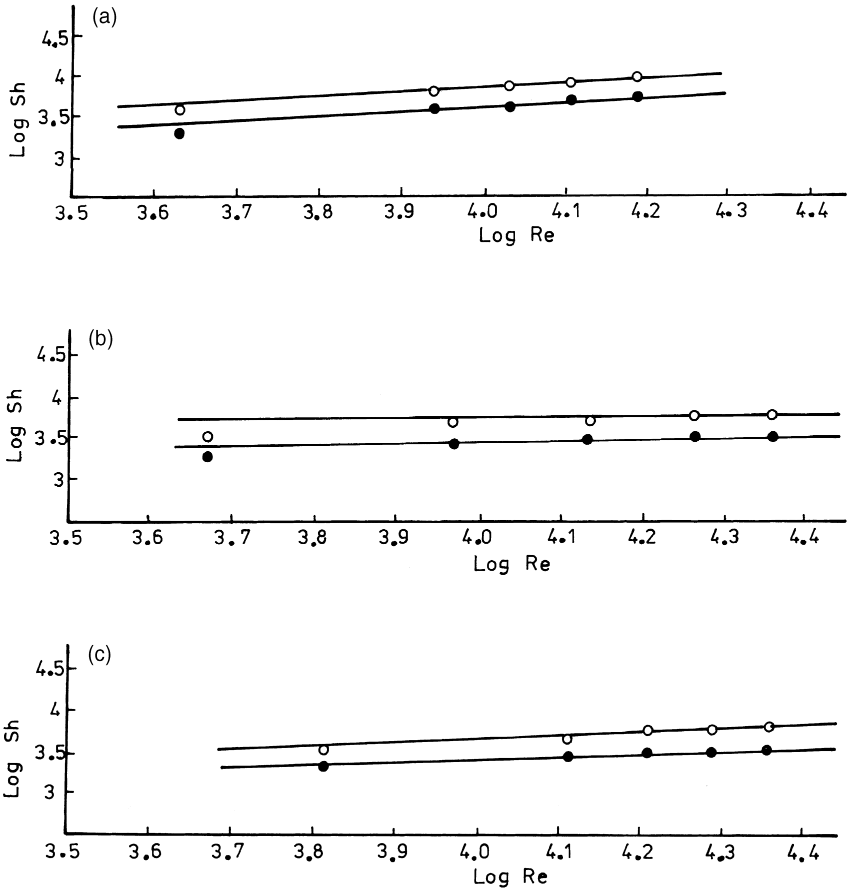

Fig. 7. Effect of baffles on Sh. (a) four blade flat turbine; (b) four blade 45° pitched turbine; (c) six blade disc turbine. ○ – with baffles, ● – without baffles.

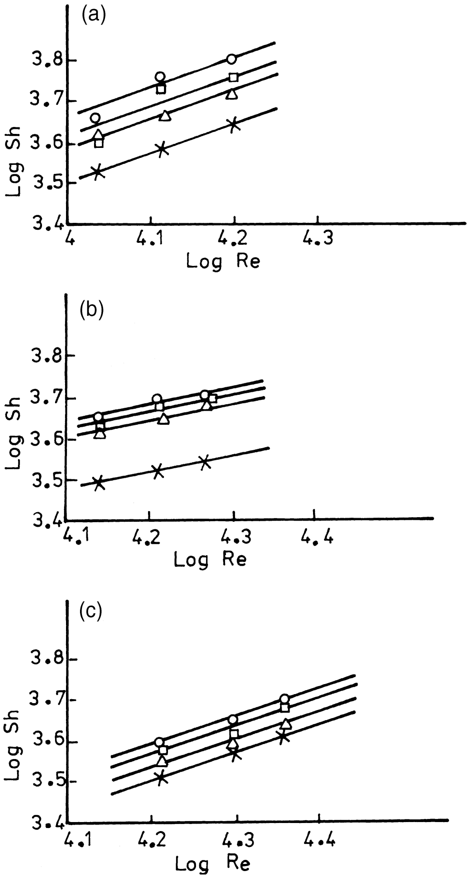

Fig. 8. Effect of suspended solid particles on Sh. (a) four blade flat turbine; (b) four blade 45° pitched turbine; (c) six blade disc turbine. Particle concentration = 1% (by volume). Particle size: × – blank, △ – 0.7 mm, □ – 0.5 mm, ○ – 0.3 mm.

particles may be attributed to the following effects: (i) collision of the solid particles with the rotating impeller disturbs the laminar sublayer and the diffusing layer; (ii) as a result of the relative motion between the particles and the solution at the impeller surface, turbulence generation may take place in the wake of the moving particles; (iii) particles present in the laminar sublayer tend to rotate under the influence of velocity gradient, particle rotation generates local turbulence (microconvection) in the laminar sublayer with a consequent increase in the rate of mass transfer; (iv) it is also possible that solid particles which penetrate the diffusion layer at the impeller surface drag with them fresh solution from the bulk; since the amount of entrained solution increases with increasing particles surface area, it follows that the rate of mass transfer should increase with decreasing particle size as revealed by Fig. 5. The increase in the rate of mass transfer due to suspended solids is consistent with the results obtained by previous studies on mass transfer at rotating discs [28–32]

Fig. 10 shows the effect of polyox WSR-301 drag reducing polymer on the rate of mass transfer. The rate of mass transfer decreases by an amount ranging from 5% to 39% depending on impeller geometry, polymer concentration and Re. The percentage reduction in the mass transfer coefficient for the six blade disc turbine is less that in case of the four blade impellers probably because of the higher degree of polymer degradation caused by the high shear stress induced by the highly turbulent flow generated by the six blade disc turbine as indicated before. The present finding along with the finding that drag reducing polymers reduce the rate of diffusion controlled corrosion at the wall of the agitated vessel [9,10] calls for using drag reducing polymers as corrosion inhibitors in agitated vessels. However drag reducing polymers should be used with caution if the agitated vessel involves heat transfer between the contents of the vessel and a cooling coil or a cooling jacket. In that case the presence of drag reducing polymer would reduce the rate of heat transfer by virtue of damping the small scale high frequency eddies at the heat transfer surface. Also caution should be exercised with using drag reducing polymers in agitated vessels where liquid mixing is important owing to the fact that polymers increase the mixing time [33]. In view of the study of Quraishi et al. [33], and Desai [34], drag reducing polymers can find application without reservation in agitated vessels used in processes involving suspended solid particles, eg., mineral washing, ore leaching, solid dissolution, crystallization and sewage treatment. Quraishi et al. found that the presence of drag reducing polymer has no effect on the critical rotation speed at which complete suspension of solid particles occurs, while Desai found that the rate of mass transfer between the suspended particles and the liquid was not affected by the presence of the drag reducing polymer. In conclusion the use of drag reducing polymers in agitated vessels involving suspended solids would lead to decreasing the operating and capital costs of the process through decreasing power consumption and prolongation of the life time of the vessel via decreasing its rate of corrosion.

4. List of Symbols

A	impeller area
C	chromate concentration at time t
C_o	initial chromate concentration
C_s, C_1, C_2	saturation solubility of oxygen, concentration of oxygen at the liquid–film interface and concentration of oxygen at the metal surface respectively
D	chromate diffusivity
d	impeller diameter
d_T	vessel diameter
K_1, K_2, K_3	liquid phase mass transfer coefficient, solid film mass transfer coefficient and reaction rate constant respectively
K	mass transfer coefficient
n	rotation speed of the impeller (rps)
N	dissolved oxygen flux

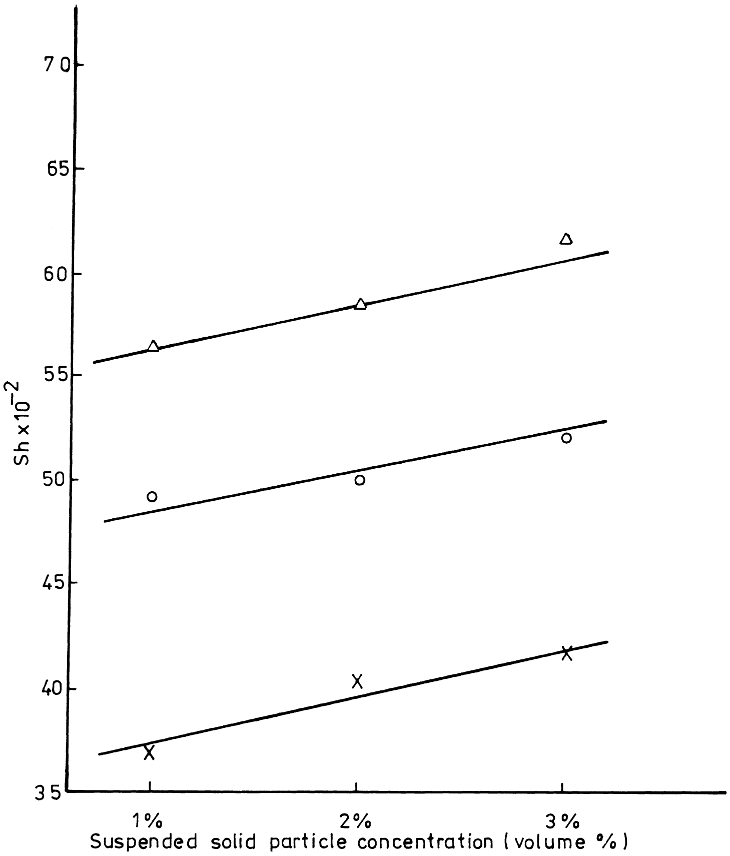

Fig. 9. Effect of suspended particle concentration on Sh. Sc = 1095; Particle size = 0.5 mm; × – six blade disc turbine; ○ – four blade 45° pitched turbine; △ – four blade flat turbine.

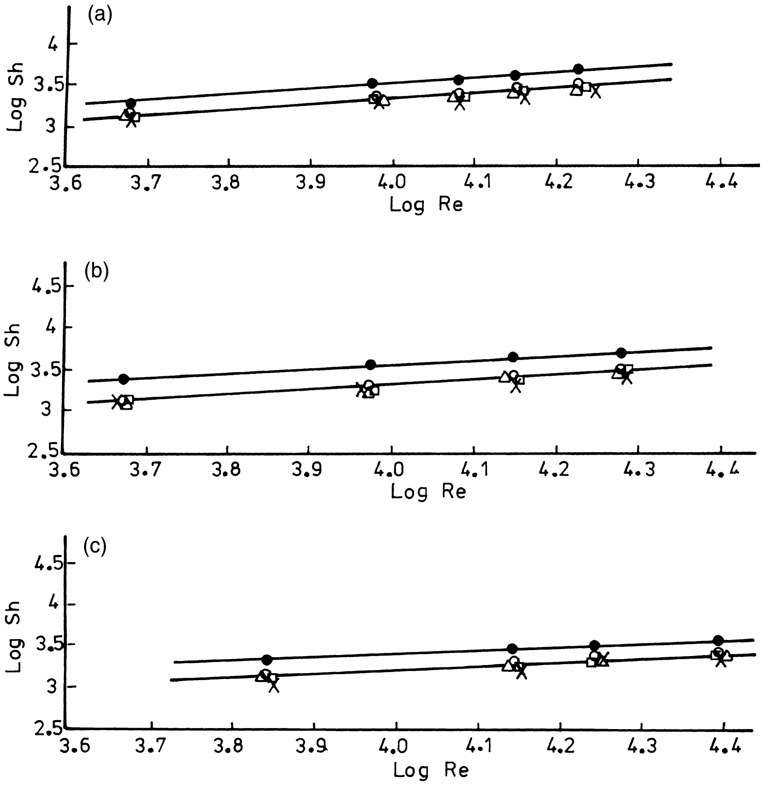

Fig. 10. Effect of polyox drag reducing polymer on Sh. (a) four blade flat turbine; (b) four blade 45° pitched turbine; (c) six blade disc turbine. Sc = 1095. Polyox concentration: ● – blank solution, ○ – 200 ppm, × – 300 ppm, △ – 400 ppm, □ – 500 ppm.

Q	volume of the solution in the agitated vessel
t	time
Re	Reynold number ($\rho n d^2/\mu$)
Sc	Schmidt number ($\mu/\rho D$)
Sh	Sherwood number (kd/D)
μ	viscosity of the solution
ρ	solution density

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