International Journal of Engineering and Advanced Technology (IJEAT)
ISSN: 2249-8958 (Online), Volume-2 Issue-6, August 2013

Mass Transfer Study of a Single Phase Flow Accelerated Corrosion (FAC) in 90° Copper Elbow

M. A. Fouad, T. M. Zewail, N. K. Amine, Y.A. El-Taweel

Abstract – Single phase FAC of 90° copper elbow in acidified dichromate has been investigated in relation to the following parameters: acid concentration, solution velocity, temperature and elbow radius to pipe diameter ratio. The rate of FAC was expressed in terms of mass transfer coefficient. The results showed that the mass transfer coefficient increases as solution velocity increases. Whereas the mass transfer coefficient decreases as the elbow radius to pipe diameter ratio increases. The effect of the acid concentration on the mass transfer coefficient varies according to the range of acid concentration considered. Activation energy calculation revealed partial controlled reaction kinetics at high acid concentration. The present mass transfer data for flow inside 90° copper elbows has been correlated by the equations:

$$Sh = 1.2\,\mathrm{Re}^{0.44}\,Sc^{0.33}\left(\frac{r}{d}\right)^{-2} \qquad 678 < Sc < 767$$

$$Sh = 5.2\,\mathrm{Re}^{0.44}\,Sc^{0.33}\left(\frac{r}{d}\right)^{-2} \qquad Sc = 845$$

The importance of these equations in the prediction of mass transfer coefficient in 90^0 copper elbows is highlighted.

Keywords – erosion corrosion, Flow accelerated corrosion, mass transfer coefficient, stainless steel, 90° copper elbow.

I. INTRODUCTION

Flow accelerated corrosion (FAC) is the increased corrosion resulting from increased fluid turbulence intensity and mass transfer. FAC also sometimes is referred to erosion corrosion. However it should be noticed that erosion corrosion is the general term encompassing a spectrum of mechanisms from FAC to purely mechanical damage [1-3]. For most power plants oil refineries and petrochemical plants, FAC is considered as one of potential corrosion mechanism responsible for piping leakage [4]. This piping leakage can result in costly outages and expensive plant strong influence of mass transfer coefficient on the prediction of corrosion rates.

Several investigators have conducted experiments to determine the maximum mass transfer coefficient in 90° elbows and 1800 bends.

Poulson et al [6] has proposed an expression for the ratio of the maximum mass transfer coefficient for 1800 bend to the mass transfer coefficient for fully developed pipe flow (MTC). Their expression is a function of Reynolds number; they have concluded that MTC ratio increases as the Reynolds number increases. The mass transfer coefficient in elbow and bends was experimentally investigated and an equation for MTC ratio was developed as follows [7]:

$$\mathrm{MTC} = \frac{\mathrm{Sh\ outside\ radius\ of\ bend}}{\mathrm{Sh\ fully\ developed\ pipe}} \equiv 1 + 2.2\left(\frac{R}{r}\right)^{1.2}\left(\frac{L}{d}\right)^{0.75} \qquad (1)$$

Where: Sh is the Sherwood number, d pipe diameter, R is the radius of the pipe, r is the mean radius of the elbow, L is the length along the center line of the curved section of the elbow. Their correlation suggested that Re has no effect on the MTC ratio.

Local mass transfer coefficient in 450 bend with r/d of 2.72 was measured in a previous study. It has been concluded that MTC ratio in 450 and 1800 bends decreases as the flow Re number increases [7].

Some investigators have used three dimensional computational flow dynamic (CFD) modeling to obtain mass transfer correlation in elbows. Wang et el [8] have obtained a correlation for predicating the maximum mass transfer coefficient in elbow based on CFD and mass transfer predications. Their correlation is a function of Re, Sc and elbow radius to pipe diameter ratio (r/d) as follows:

MTC ratio = 0.68 + (1.2 – 0.044 lnRe) e-0.065(r/d) + (0.58/ ln(Sc+2.5) (2)

The discrepancy between the authors on the effect of Re number on the MTC ratio can be ascribed to that all investigations determined maximum local mass transfer coefficient which depends on many factors such as the hydrodynamic conditions the chemistry of corrosive environment and the metallurgical effects [9]. Therefore, a more detailed study of mass transfer coefficient in 90^0 elbows is needed to increase the understanding of mass transfer process in elbows and to predict corrosion in 900 elbows.

The main objective of the present work is to investigate mass transfer of single phase FAC in 900 copper elbows in acidified dichromate. The system was chosen for its accuracy and simplicity [10-11].

Manuscript published on 30 August 2013.
***** Correspondence Author (s)

M. A. Fouad, Chemical Engineering Department, Faculty of Engineering, Alexandria University, P. O. Box 21544 Alexandria, Egypt

Dr. T. M. Zewail, Chemical Engineering Department, Faculty of Engineering, Alexandria University, P. O. Box 21544 Alexandria, Egypt

Dr. N. K. Amine, Chemical Engineering Department, Faculty of Engineering, Alexandria University, P. O. Box 21544Alexandria, Egypt

Dr. Y.A. El-Tawail, Chemical Engineering Department, Faculty of Engineering, Alexandria University, P. O. Box 21544Alexandria, Egypt

To this end the effect of the following parameters on the rate of mass transfer has been investigated:(i) acid concentration, (ii) solution velocity,(iii) temperature and (iv) elbow radius to pipe diameter ratio, An attempt to correlate the present mass transfer data using dimensionless analysis has been envisaged. The mass transfer correlation can be used in predication of corrosion rate in 900 elbows.

II. MATERIALS AND METHOD:

II.1 Material:

The experimental apparatus used in the present work is shown schematically in Fig. (1). It consists mainly of a PVC piping system of 0.0127 m diameter, stainless steel centrifugal pump (0.9 HP) (Flottec, made in china), a plexi glass storage tank of (0.3x0.3x0.3) m and a 900 active copper elbow section was used to connect the down stream pipeline to the upstream pipeline. A flexible plastic joint was connected between down stream pipe outlet and the elbows inlet to allow using different elbow with different diameters. Precaution was taken that the upstream pipe length to be in the range 50-60% of inlet pipe diameter to avoid the effect of entrance length. The flow rate of solution was adjusted by the main valve and/ or the bypass valve.

A. II.2 Method:

The rate of mass transfer was determined using the diffusion controlled corrosion of copper elbow in acidified dichromate solution. Before each run 10 liters of freshly prepared acidified dichromate solution were placed in the storage tank. Samples of 5 mls were withdrawn from the discharge line every 5 minutes intervals for dichromate analysis by titrating against standard solution of ferrous ammonium sulphate using diphenylamine barium salt as indicator [12]. In preparing all solutions A.R grade chemicals and distilled water were used. All experiments were carried out at temperature 24˚C ± 2˚C. The solution density (ρ) and solution viscosity (μ) were measured by hydrometer and viscometer respectively. The diffusivity of dichromate ion (D) was taken from literature [13].

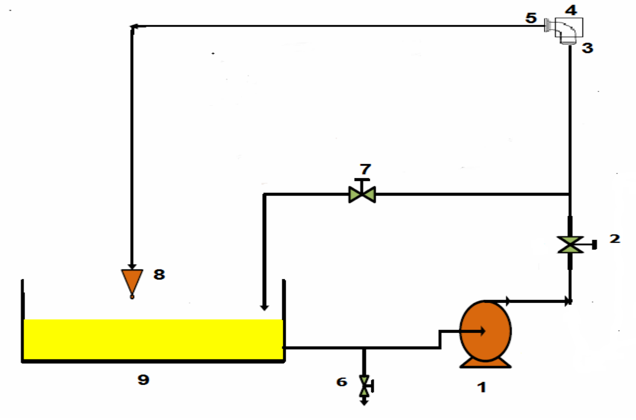


Fig (1) Experimental apparatus

1- Plastic pump.
2- Main valve.
3,5- flexible joint.
4- Copper elbow.
6- Drain valve.
7- By-pass valve.
8- Return valve.
9- plexi glass storage tank.

III. RESULT AND DISCUSSION

The rate of diffusion controlled corrosion of 90^0 copper elbow in acidified dichromate solution can be expressed in terms of the rate of active dichromate ion disappearance according to the following equation [14]:

$$-Q\frac{dC}{dt} = kAC \qquad (6)$$

Which upon integration using the following conditions:
at t =0 , $C = C_o$ and at t = t, $C_t = C$

$$\ln\frac{C_o}{C} = \left(\frac{kA}{Q}\right)t \qquad (7)$$

Where: (k) is the mass transfer coefficient, (A) is the active area of copper elbow, (Q) is the solution volume, (C_o) is the initial dichromate ions concentration, (C) is the dichromate ions concentration in the system at time t.

Fig. (2) Shows a typical plot of ln C_o/C versus time at different solution velocities. It has been seen that during the first 5 minutes a high change in active dichromate ions concentration has occurred, followed by a stepwise change (slower rate regime) in the dichromate ions concentration with time up to the end of the experiment.
The initial high change in dichromate ions concentration indicates high corrosion rate. The high corrosion rate at the beginning may be due to the high driving force (ΔC), in addition to the high degree of turbulence. However with time, the dichromate ions concentration decreases with a slight decline in the mass transfer rate.
As the slower rate regime is the rate determining regime, the slope (kA/Q) of this regime will be used in calculating the mass transfer coefficient at different conditions.

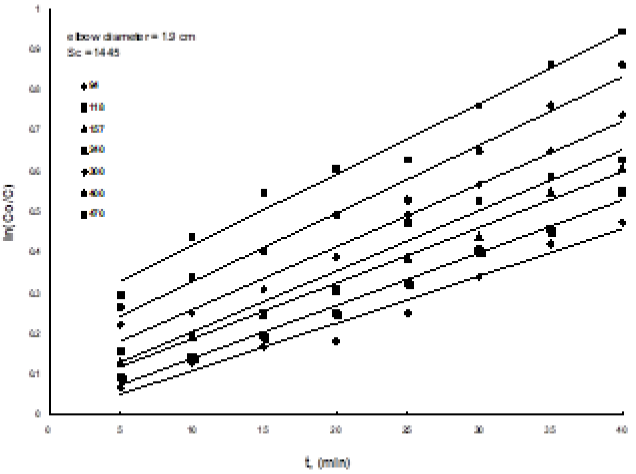


Fig. (2) ln C_o/C versus time at different solution velocities

3.1. Effect of solution velocity

Fig. (3) Shows the effect of solution velocity on the mass transfer coefficient at different acid concentrations expressed as Sc. It has been noticed that as the solution velocity increases the mass transfer coefficient increases.

Published By:
Blue Eyes Intelligence Engineering
and Sciences Publication (BEIESP)

The mass transfer coefficient can be related to the solution velocity by the following equations:

$k \alpha v^{0.44}$ for Sc from 678 to 845 (8)

$k \alpha v^{0.3}$ for Sc from 1040 to 1445 (9)

The increase in mass transfer coefficient with solution velocity may be ascribed to that the flow inside 90^0 elbows is subject to severe changes in the flow direction. These changes give rise to the development of secondary flows and/or flow separation. The secondary flow induces a pressure drop along the elbow, which can significantly increase the wall shear stresses and the turbulence intensity close to the wall. The higher the velocity the higher the intensity of secondary flow; which in turn enhances rate of mass transfer [15]. In addition, as the solution velocity increases the thickness of the hydrodynamic boundary layer decreases, as a consequence the thickness of the diffusion layer at the wall of copper elbow decreases as well. That decrease in diffusion layer thickness enhances the rate of mass transfer over the entire copper elbow [16]. It should be noticed that the power of Re (0.44) is in a fair agreement with the value obtained from the hydrodynamic boundary layer theory i.e (0.5). The low power of Re (0.3) for high Sc may be due to changes in reaction kinetic.

3.2. *Effect of the acid concentration*

Fig. (3) Shows also the effect of initial H_2SO_4 concentration, expressed as Sc on the mass transfer coefficient. The mass transfer coefficient increases with the increase of Sc in the range from 678 to 845. However the mass transfer coefficient decreases with the increase of Sc in the range from 1040 to 1445. The increase of mass transfer coefficient with Sc in the low Sc range can be attributed to the increase of driving force of mass transfer. While the observed decrease in the mass transfer coefficient in high Sc range, may be due to the decrease of dichromate diffusivity (D) owing to the increase in solution viscosity (μ) according to Stock's – Einstien equation.

$$D\mu / T = Const \quad (10)$$

In addition, inter-ionic forces between ions increase with the increase of acid concentration with a consequent decrease in dichromate ion mobility and decrease of its diffusivity [17].

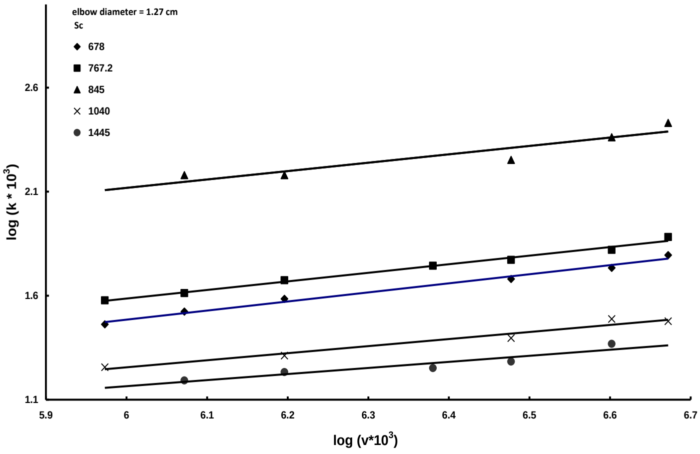


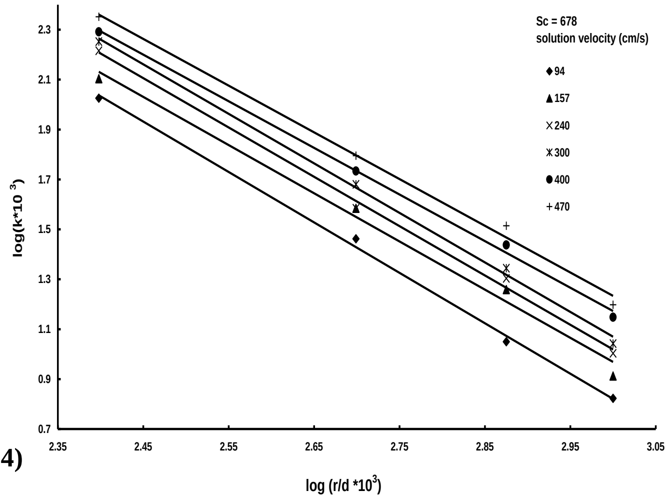
Fig (3) Effect of solution velocity on the mass transfer coefficient at different Sc

3.3 *Effect of elbow radius/pipe diameter ratio*

Fig. (4) Shows the effect of elbow radius to pipe diameter ratio (r/d) on mass transfer coefficient. It has been seen that as the (r/d) ratio decreases the mass transfer coefficient increases. The mass transfer coefficient can be related to the (r/d) ratio by the following equation:

$$k \alpha \left(\frac{r}{d} \right)^{-2} \quad (11)$$

The increase of mass transfer coefficient with the decrease of (r/d) ratio can be attributed to as a radius of elbow decreases at constant pipe diameter, the inlet velocity increases with a consequence increase of a secondary flow intensity; which in turn enhances rate of mass transfer. Sedahmed et al [18] have found that mass transfer inside pipe increases as the inlet pipe nozzle diameter to pipe diameter ratio increases which in agreement with the present result. Poulson [19] has found that the ratio of maximum mass transfer coefficient downstream of an orifice to mass transfer coefficient inside pipe increases with the decrease of orifice diameter to pipe diameter ratio.



(4)

Fig (4) Effect of (r/d) on the mass transfer coefficient at different solution velocities

4.4. *Effect of temperature*

To confirm the diffusion controlled characteristic of the copper elbow corrosion in acidified dichromate under the present hydrodynamic conditions, the effect of temperature on mass transfer coefficient was investigated.

Fig. (5) Shows a plot of ln (C_o/C) versus time at different temperatures. It is obvious that as temperature increases, the mass transfer coefficient increases. This behavior may be explained by the fact that as temperature increases the viscosity of solution decreases and diffusivity increases according to Stock's Einstein equation.

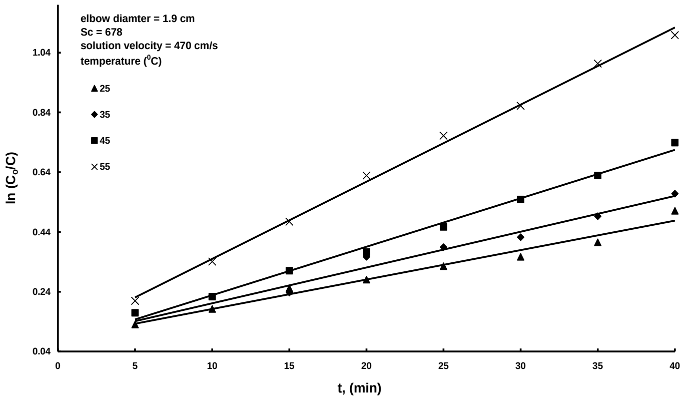


Fig (5) ln (Co/C) versus time at different solution temperatures

Figures (6&7) depict a plot of ln k versus 1/T at various solution velocities. It is clear that the data fit the Arrhenius equation type according to the following:

$$\ln k = \ln A^{'} - \left(\frac{E}{R}\right)\frac{1}{T} \qquad (12)$$

Where: (E) is the activation energy of the reaction, (R) is the gas constant, ($A^{'}$) is frequency factor and (T) is solution absolute temperature.

Estimation of activation energy revealed value of 8.96 kCal/mol and 11.5 kCal/mol for the Sc 678 and 1040 respectively these results confirm that under the present hydrodynamic conditions the reaction is partial controlled reaction at high Sc.

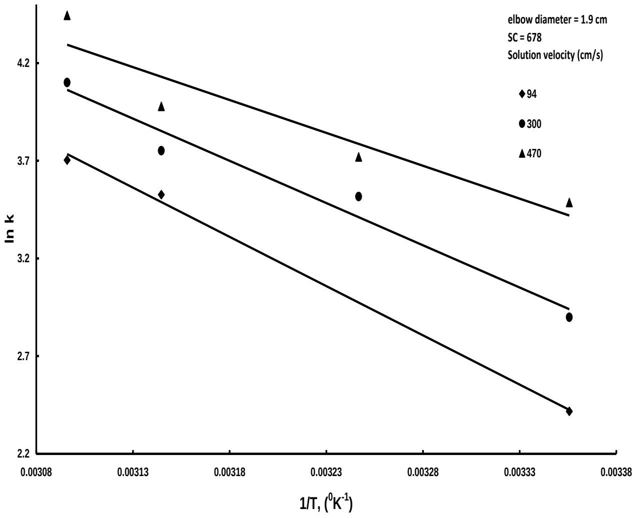


Fig (6) plot of ln k versus (1/T) at different velocities

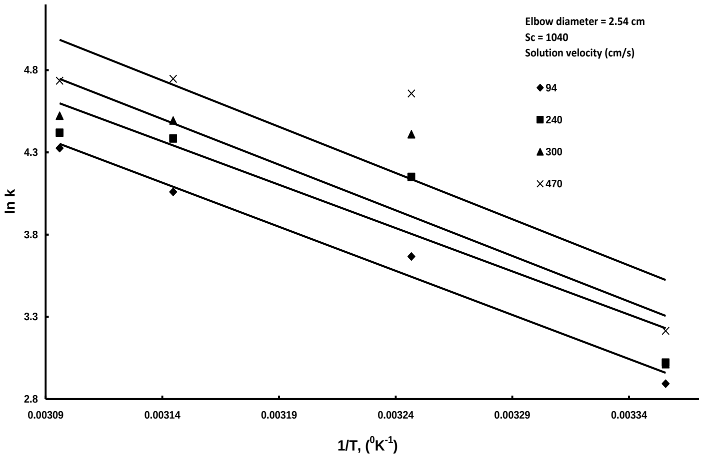


Fig (7) Plot of ln k versus 1/T at different velocities

3.5. Mass transfer data correlation

In view of the complex geometry and turbulent nature of the flow through 90^0 elbow mathematical modeling of the present mass transfer data is difficult. The present mass transfer data were correlated by the method of dimensionless analysis. An overall mass transfer correlation was envisaged using the method of dimensional analysis. The mass transfer dependence on different parameters can be expressed by the following

$$k = F(\rho, \mu, D, v, d, r) \qquad (13)$$

$$k\left(\frac{d}{D}\right) = a\left(\frac{\rho v d}{\mu}\right)^{\alpha}\left(\frac{\mu}{\rho D}\right)^{\beta}\left(\frac{r}{d}\right)^{\gamma} \qquad (14)$$

Where: (ρ) is the solution density, (μ) is the solution viscosity, (D) is the diffusivity of dichromate ions, (v) is the solution velocity, (d) is the pipe diameter, (r) is the radius of copper elbow.
i. e.

$$Sh = a\,\mathrm{Re}^{\alpha}\ Sc^{\beta}\left(\frac{r}{d}\right)^{\gamma} \qquad (15)$$

Where: (Sh) Sherwood number, (Re) Reynolds number and (Sc) Schmidt number. (α, γ, β) are constants which were determined using the present experimental data. Following previous experimental and theoretical mass transfer studies, the value of β was fixed at 0.33 [20]. Since at high Sc (1040- 1445) the reaction kinetics become partially-controlled, correlation of the present data will consider only low Sc (678-845).
Fig. (8) Shows the effect of the (r/d) ratio on Sh. The present data fit the equation:

$$Sh\alpha\left(\frac{r}{d}\right)^{-2} \qquad (16)$$

Published By:
Blue Eyes Intelligence Engineering
and Sciences Publication (BEIESP)

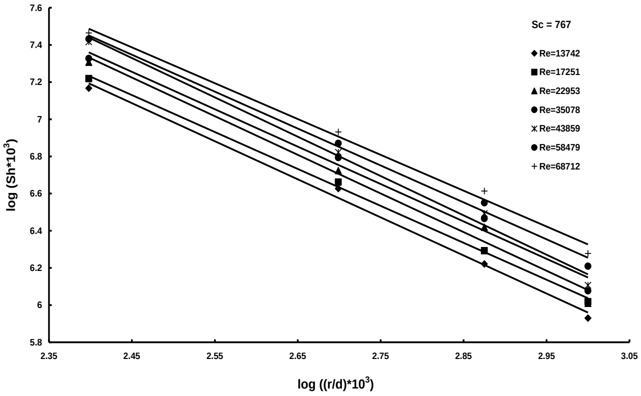


Fig (8) log Sh versus log (r/d) at different Re

Fig. (9 & 10) Show the relation between log Sh versus log Re at different Sc , the present data fit the equation:

$$Sh \alpha \mathrm{Re}^{0.44} \qquad (17)$$

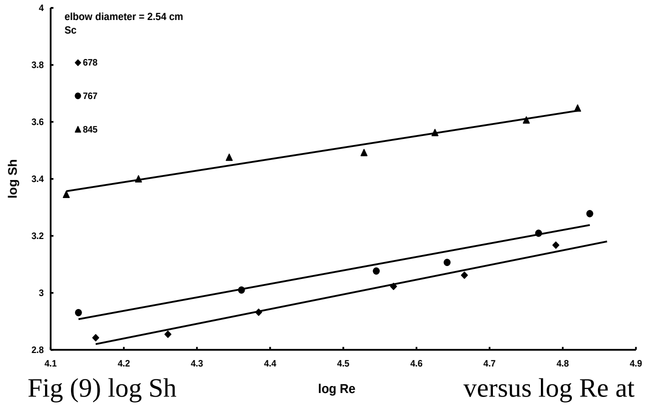


Fig (9) log Sh versus log Re at different Sc

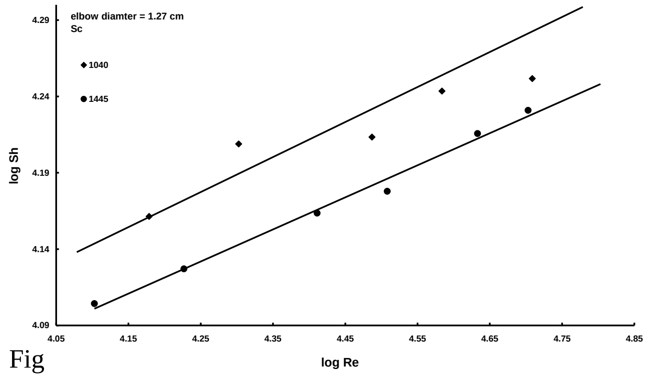


Fig (10) log Sh versus log Re at different Sc

Fig. (11) Shows that the present data for conditions 678 <Sc < 767 , 13742 < Re < 72534 and 0.25< r/d< 1 fit the following overall correlation:

$$Sh = 1.2\,\mathrm{Re}^{0.44}\,Sc^{0.33}\left(\frac{r}{d}\right)^{-2} \qquad (18)$$

With an average standard deviation of 17.5 %

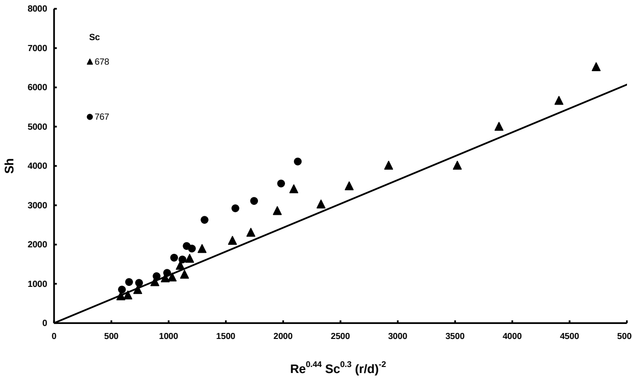


Fig (11) Overall mass transfer correlation of 90^0 copper elbow corrosion in acidified dichromate of low Sc

Fig. (12) Shows that the present data for Sc = 845 ,13221 < Re < 66108 and 0.25< r/d< 1 fit the following overall correlation:

$$Sh = 5.2\,\mathrm{Re}^{0.44}\,Sc^{0.33}\left(\frac{r}{d}\right)^{-2} \qquad (19)$$

With an average standard deviation of 17.5 %.

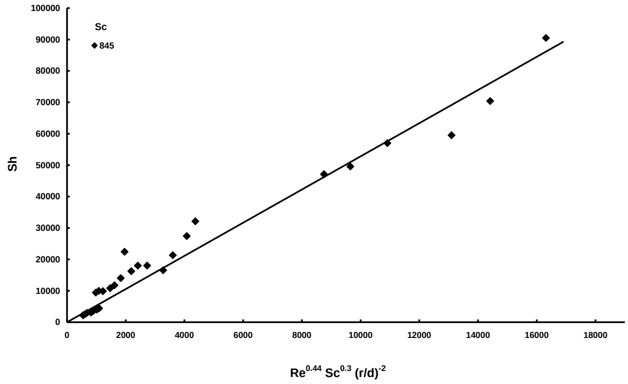


Fig (12) Overall mass transfer correlation of 90^0 copper elbow corrosion in acidified dichromate of transition Sc

Fig. (13) shows that the present data for conditions 1040 <Sc < 1445 and 10094 < Re < 60086 fit the following overall correlation:

$$Sh = 16\,\mathrm{Re}^{0.3}\,Sc^{0.33}\left(\frac{r}{d}\right)^{-2}$$

(20)

With an standard deviation of 5 %.

Published By:
Blue Eyes Intelligence Engineering
and Sciences Publication (BEIESP)

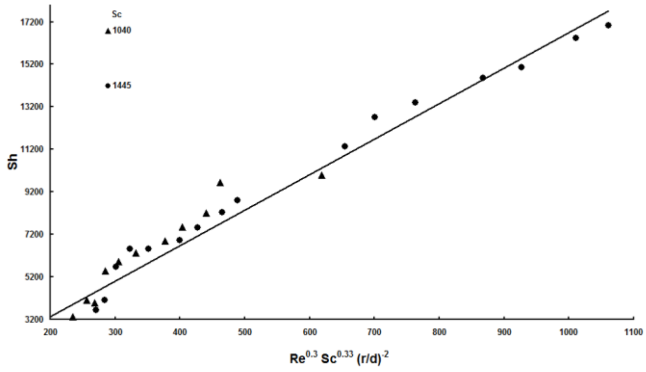


Fig (13) Overall mass transfer correlation of 90^0 copper elbow corrosion in acidified dichromate of high Sc

IV. CONCLUSIONS

Single phase FAC of 90° copper elbow has been investigated in relation to different parameters. Rate of corrosion was expressed in terms of mass transfer coefficient. The following conclusions have been withdrawn:

- Mass transfer coefficient increases as solution velocity increases and decreases as r/d increases.
- The mass transfer coefficient increases as the acid concentration increases at low Sc, whereas it decreases as the acid concentration increases at high Sc.
- Activation energy calculation reveals a value of 8.96 kCal/mol and 11.5 Kcal/mol for low range of Sc and high range of Sc respectively.
- Mass transfer data at low Sc have been correlated using dimensionless analysis.
- These dimensionless equations may be useful for the predication of corrosion rate in 90^0 elbows.
- Flow inside 90^0 elbows enhances the rate of mass transfer by a factor ranges from 1.65 to 26.2 which is a strong function of elbow diameter.

REFERENCES

[1] M. G. Fontana," Corrosion Engineering", second ed., McGraw Hill, N. Y, 1988.

[2] M. El-Gammal, H. Mazhar, J.S. Cotton, C.Shefski, J. Pietralik, C.Y. Ching, The hydrodynamic effects of single-phase flow on flow accelerated corrosion in a 90-degree elbow, *International Journal of Nuclear Engineering and Design 240 (2010) 1589-1598.*

[3] B. Poulson, Complexities in predicting erosion corrosion, *International Journal of Wear 200 (1999) 479– 504.*

[4] LI. Xiao, LU. Tao, Analysis of corrosion failure of petrochemical pipe elbow, *International Journal of Nuclear Material 12 (2005) 119- 123.*

[5] W. H. Ahmed, Evaluation of the proximity effect on flow accelerated corrosion, *International Journal of Annals of Nuclear Energy 37 (2010) 598- 605.*

[6] B. Poulson, R. Robinson, The local measurement of mass transfer at 1800 bends, *International Journal of Nuclear Engineering andDesign 31 (1988) 1289- 1297.*

[7] J. Wang, Mass Transfer in Elbows, Ph.D. thesis, Tulsa University, United states, 1997.

[8] J. Wang, S. A. Shirazi, A CFD based correlation for mass transfer coefficient in elbows, *International Journal of Heat and Mass Transfer 44 (2001) 1817- 1822.*

[9] B. Poulson, Measuring and modeling mass transfer at bends in annular two phase flow, *International Journal of Corrosion Science 46(1991)1069-1082.*

[10] J. Pollert, R.H. Sellin, Drag reduction in fluid flows. *InternationalJournal of Electrochemical Science (1989), pp. 179.*

[11] A. J. Madden and D. G. Nelson, Effect of drag reducing polymer on the rate of induced corrosion of metals, A.I.Ch.E. (1964) 415- 421.

[12] A. I. Vogel , Text Book of Quantitative Analysis. Longman, London, 1961, pp. 200- 315.

[13] G.H.Jeffery, J.Bassett and R.C.Denney, Vogles, 5th ed. Longman, New York, 1989.

[14] M.H. Abdel-Aziz, I.A.S. Mansour, G.H. Sedahmed ,Study of the rate of liquid–solid mass transfer controlled processes in helical tubes under turbulent flow conditions, *International Journal of Chemical Engineering and Process. 49 (2010) 643–648.*

[15] G.H Sedahmed, M.S.E Abdo, M.Amer and G.Abdelatif, Mass transfer at a pipe inlet zone in relation to impingement corrosion, *International Journal of Heat and Mass Transfer 25 (1998) 443-451.*

[16] B. Poulson, Eelectrochemical measurements in flowing solutions Corrosion science 23(1983) 391-430.

[17] E. L. Cussler, Diffusion Mass Transfer in Fluid Systems, 2nd ed., Cambridge university press, 1997.

[18] G.H. Sedahmed, M.S.E. Abdo, M. Amer and G Abd El-Latif, effect of drag reducing polymer on the rate of mass transfer controlled corrosion in pipelines under developing flow, *International Journal of Heat and Mass Transfer* 26 *(1999)* 531- 538.

[19] B. Poulson and R. Robinson, The use of a corrosion process to obtain mass transfer data, International Journal of Corrosion science 26 (1986) 265- 280.

[20] J.R.Welty, C.E.Wicks , R.E.Wilson and G.L.Rorrer, Fundamentals of momentum, heat and mass transfer. John Wiley &sons, N.Y.2007.

[21] R. Malka and D.A. Gulino, Erosion corrosion and synergistic effects in disturbed liquid particle flow, International Journal of Wear 262(2007) 791-799.

Mr. Mohamed Ahmed Fouad
Author affiliation: Faculty of Engineering, Chemical Engineering Department, Alexandria University, Egypt.
Degree: Master of Chemical Engineering 2009.

Prof. Tagreed Mohamed Zewail
Author affiliation: Faculty of Engineering, Chemical Engineering Department, Alexandria University, Egypt.
Degree: PhD of Chemical Engineering 2005.

Prof. Nieven Kamal Amine
Author affiliation: Faculty of Engineering, Chemical Engineering Department, Alexandria University, Egypt.
Degree: PhD of Chemical Engineering 2003.

Prof. Yehia Ahmed El-taweel
Author affiliation: Faculty of Engineering, Chemical Engineering Department, Alexandria University, Egypt.
Degree: PhD of Chemical Engineering 1974.

Chemical Engineering Department, Faculty of Engineering, Alexandria University, P. O. Box 21544; tel:(+203) 5914475; fax: (+203)5921853; Alexandria, Egypt