

## MASS TRANSFER STUDIES IN A RECTANGULAR DUCT

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Experimental measurements have been made of mass transfer in a rectangular duct of variable aspect ratio. It has been found that the mass transfer coefficient has a maximum value at the vicinity of the inlet and is correlated by:  $Sh = 0.20 (Re)^{0.62} (Sc)^{1/3}$ . The mass transfer data in the fully developed concentration region have been correlated by:  $Sh = 0.014 (Re)^{0.86} (Sc)^{1/3}$ . The results are compared with those found in the literature.

### INTRODUCTION

A substantial number of expressions have been proposed for the prediction of heat or mass transfer rates between a solid wall and a turbulently flowing fluid in the region of fully developed concentration or temperature profiles. Except in the region of developing concentration profiles it is generally not possible to quantitatively predict mass transfer rates by recourse to the turbulent flow theory alone. The application of a mass balance to such a flow results in additional terms involving the fluctuating components of concentration and velocity [1] which may be accounted for by empirical means.

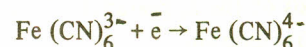
Considerable work has been done to measure the mass transfer co-efficient in a solid-liquid system under turbulent flow conditions. The majority of this work, however, have been confined to the measurement in circular ducts [2-15]. The mass transfer data in rectangular ducts, particularly at high Reynolds and Schmidt numbers are scarce, in spite of the widespread use of these ducts in various heat and mass exchanging equipments. Earlier work [16-19] has some serious drawbacks and is therefore open to doubts. This fact is also indicated by the large deviations in the results of different workers.

The purpose of the present work was to investigate the mass transfer characteristics of a variable aspect ratio rectangular duct. This work represents an improvement over the previous work in the sense that segmented cathodes that extended over the full channel instead of only part of the channel width were employed, thus minimizing edge effects.

### EXPERIMENTAL

Limiting diffusion current technique [20] was used to measure mass transfer co-efficients. The cathodic reduction

of potassium ferricyanide according to the reaction:



was the electrode reaction used throughout the current work. The solutions contained excess of potassium ferrocyanide, together with potassium hydroxide as a supporting electrolyte to prevent either the anodic reaction rate or ionic migration from affecting the cathodic current density.

Solutions of potassium ferri- and ferrocyanide are known to be photosensitive according to the reactions:



For this reason solutions were used for one week only and in addition glass sections of the flow circuit were masked and the solution stored in the dark.

**Duct design:** This was a parallel plate reactor in which the cathode consisted of a segmented row of twelve stainless steel blocks. The essential parts of the duct are shown in Fig. 1.

The cathode backing plate constructed from polypropylene had a symmetrical recess machined into one face in order to accommodate the cathode. A silicon rubber 'O' ring seal was used to prevent the leakage of electrolyte behind the working electrode. In addition, the backing plate also provided the inlet and outlet ports for flowing electrolyte as well as maintaining a constant gap between the electrodes. The anode was a simple stainless steel strip mounted flush on the perspex block. Seals were again silicon rubber 'O' rings. The duct was assembled together by thirty bolts, symmetrically arranged (Fig. 1).

**Cathode design:** In order to measure variations in mass transfer coefficients along a flow path, it is essential to

determine the values of local mass transfer coefficients at suitable points along the flow path of the electrolyte. This

The electrical circuit: A detailed diagram of the measuring circuit for the channel is shown in Fig. 2. The current

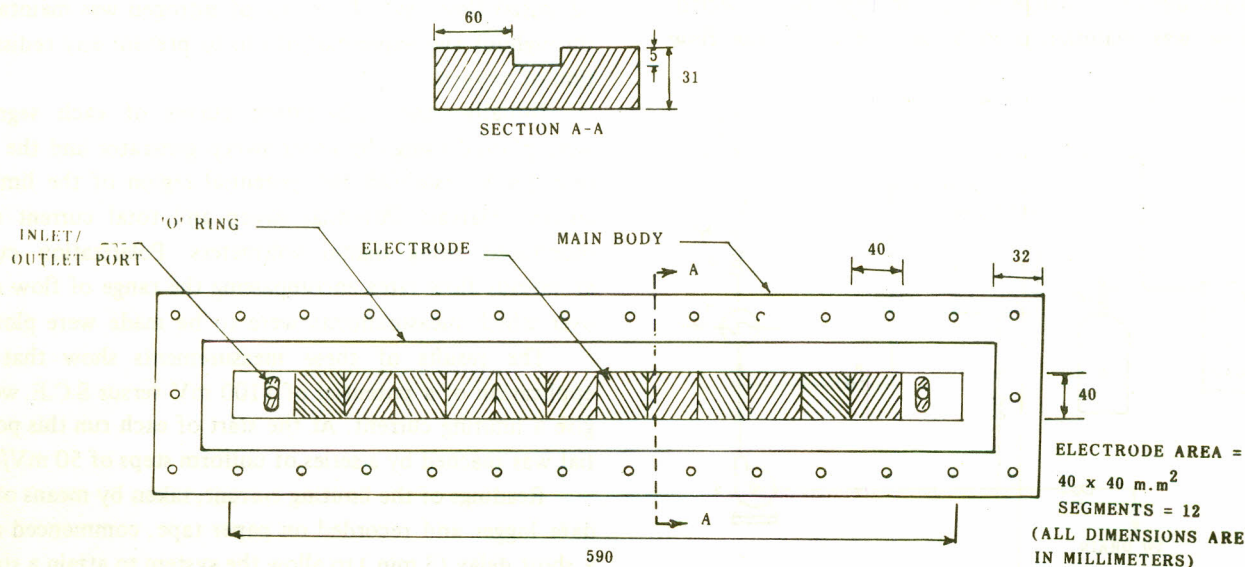


Fig. 1. Parallel plate channel reactor showing arrangement of cathode in backing plate (not to scale).

was achieved by the use of segmented cathodes. Individual segments were machined from blocks of stainless steel and then cemented together using the Araldite epoxy resin adhesive, which also provided insulation between segments, effective up to 60 V. The area of the individual segments was chosen so as to be small enough to describe local conditions, while remaining large enough to give a meaningful average mass transfer relationship of the local flow conditions. In addition a segmented electrode makes it easier to ensure that all parts of the electrode function under limiting current conditions. This is particularly true was the cell size increase.

Potential measurements at the cathode were carried out using a saturated calomel reference electrode and stainless steel lugging capillary probes. The lugging capillary probes were insulated from the segments by means of Araldite epoxy resin adhesive.

**Instrumentation:** The following measuring, recording and control equipment was used throughout.

- 1) Potentiostat: A.H.B. Thomson precision mini-potentiostat, model (251) (28 Volts and 1.25 amp) was used in most experiments.
- 2) Sinclair Digital Multimeters, DM3 and DM4 as voltmeters and ammeters.
- 3) A.J. Dawson Sweep generator.
- 4) A Bryans X-Y recorder model 25000.
- 5) A data logging package (Solartron Schlumberger).
- 6) A J.M. 1860 (Solartron) time domain analyser.

to the individual segments was measured as a potential drop across the resistor,  $R$  ( $1\Omega \pm 2\%$ ). Recording of the currents being achieved by use of a 12 pole 11 way switch to the x-y recorder.

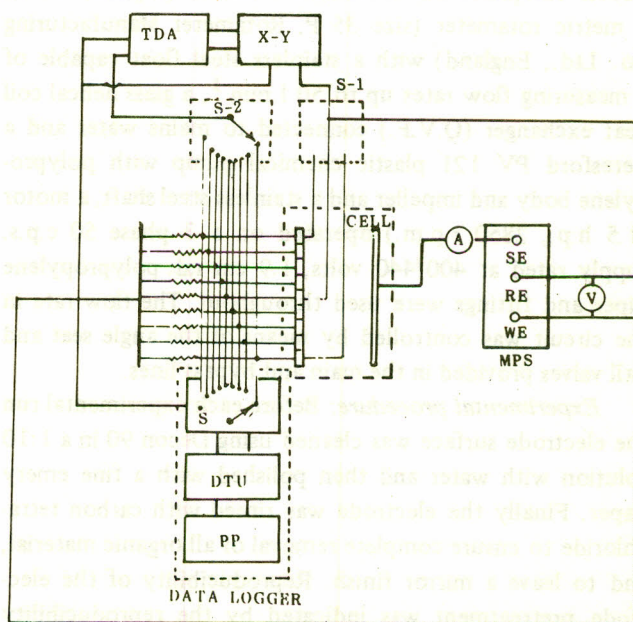


Fig. 2. Measuring and recording circuit diagram; A - Digital multimeter (current); DTU - Data transfer unit; MPS - Mini-potentiostat; RE - Reference electrode; S - Scanner; S1 - 4 pole 3 way switch; S2 - 10 pole 9 way switch; TDA - Time domain analyser; X-Y - X-Y recorder; WE - Working electrode; PP - Paper tape punch; V - Digital multimeter; (potential).

**The flow circuit:** The arrangement of the flow circuit is shown in Fig. 3. As the overall composition of the electrolyte does not change during the experiment electrolyte flow was maintained in a close d loop. The flow

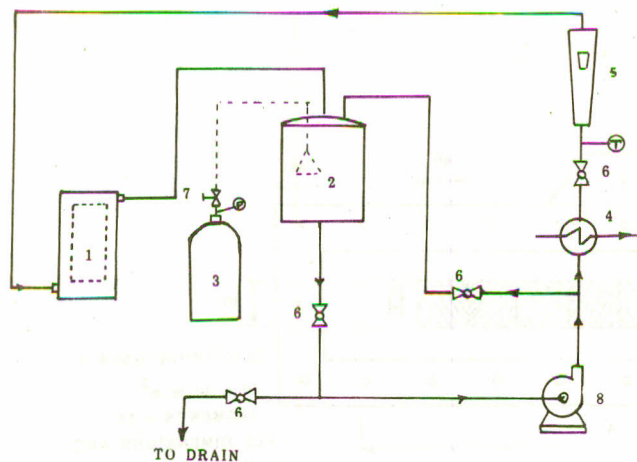


Fig. 3. Layout of experimental set-up. (1) Electrolytic reactor; (2) Reservoir; (3) Nitrogen gas cylinder; (4) Heat exchanger; (5) Rotameter; (6) Valves; (7) Gas regulator; (8) Pump; (T) Thermomter; (P) Pressure gauge.

circuit comprises an electrolyte reservoir (capacity 16 l), a metric rotameter (size 35 P, Rotameter Manufacturing Co. Ltd., England) with a stainless steel float capable of a measuring flow rates up to  $50 \text{ l min}^{-1}$ , a glass helical coil heat exchanger (Q.V.F.) connected to mains water and a Beresford PV 121 plastic chemical pump with polypropylene body and impeller and a stainless steel shaft, a motor (1.5 h.p., 2850 r.p.m.) operated on a 3 phase 50 c.p.s. supply rated at 400/440 volts, 1.9 cm i.d. polypropylene pipes and fittings were used throughout. The flow rate in the circuit was controlled by means of the angle seat and ball valves provided in the main and bypass lines.

**Experimental procedure:** Before each experimental run the electrode surface was cleaned using Decon 90 in a 1:10 solution with water and then polished with a fine emery paper. Finally the electrode was rinsed with carbon tetrachloride to ensure complete removal of all organic material, and to leave a mirror finish. Reproducibility of the electrode pretreatment was indicated by the reproducibility of the polarization curve plotted at the start of each run, which consisted of the measurement of limiting current densities at a fixed potential over a range of flow rates.

Prepared solutions in doubly distilled water were then added to the reservoir and were deoxygenated by passing oxygen-free nitrogen through the solution. During this

period the solution was pumped round the flow circuit to establish a solution temperature ( $20 \pm 0.5^\circ$ ) and the required initial flow rate. The flow of nitrogen was maintained throughout the experimental run to prevent any redissolution of oxygen.

Initially, the polarization curves of each segment were plotted using the linear sweep generator and the X-Y recorder to establish the potential region of the limiting current plateau. Potential sweep and total current were monitored using digital voltmeters. Polarization curves at various flow rates encompassing the range of flow rates over which measurements were to be made were plotted.

The results of these measurements show that the application of a potential of 1100 mV versus S.C.E. would give a limiting current. At the start of each run this potential was reached by a series of uniform steps of 50 mV/min.

Readings of the limiting current, taken by means of the data logger and recorded on paper tape, commenced after a short delay (3 min.) to allow the system to attain a steady state. The averaging facility of the time domain analyser was used to average signals over a five minute period to allow comparison between this average and that attained from the results recorded on the paper tape.

The flow rate was then increased to the next required value and the process repeated. In all ten values of the limiting current at each segment were recorded at 20 second intervals for each flow rate.

A series of measurements were carried out with the duct in various positions and the current density values for each cell positions were averaged to give the final results.

## RESULTS AND DISCUSSION

The experimental measurements of current density, overall current density and current density at individual segments were used to calculate the average mass transfer coefficient,  $K_L$ , and the local mass transfer coefficients,  $k_L$ , respectively.

The data from each segment were used to produce a correlation of the form:

$$\text{Sh} = a (\text{Re})^b (\text{Sc})^{1/3},$$

where Sh and Re are based on the equivalent diameter,  $D_e$ , which in the present context is defined as:

$D_e = \frac{2 \times W \times S}{W + S}$ , where W is the width of the duct (M) and S is the height (M), using a least squares curve fitting programme, as implemented on the IBM 370/168 computer running under the Michigan terminal system. Segments

having a similar correlation, i.e. those that have similar mass transfer characteristics, are grouped together.

The mass transfer data for each of the twelve segments are shown in Fig. 4. It is apparent that the first segment exhibits a markedly different behaviour from that displayed by the others. A regression analysis of the data for the remaining segments produces correlation (1.b). The correlation for the first segment is given by equation (1.a).

$$Sh = 0.20 (Re)^{0.62} (Sc)^{1/3} \quad (1.a)$$

$$Sh = 0.014 (Re)^{0.86} (Sc)^{1/3} \quad (1.b)$$

As expected, the mass transfer co-efficient is observed to have its highest value at the segment adjacent to the inlet port and then decreases rapidly as the flow develops. A comparison of results from the present work with findings in the literature (Fig. 5) shows good agreement on the whole. The exceptions are the correlations by Dawson and Trass [19] and that of Landan and Tobias [21], the latter having been derived from experiments conducted at relatively high Reynolds number (up to 125,000), and predicts Sherwood, Number even higher than those obtained by the

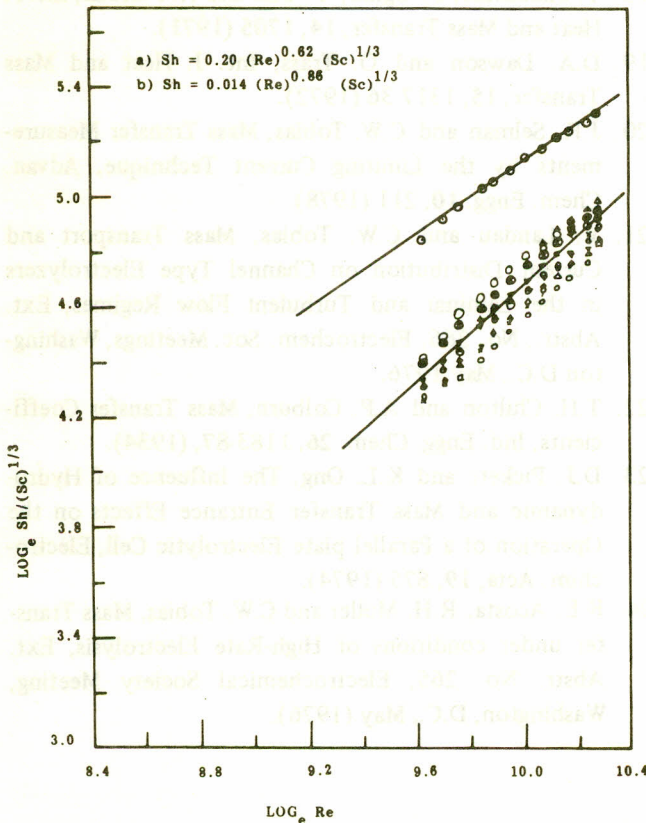


Fig. 4. Regression analysis plot for the channel reactor: (a) Entry region (first segment), (b) Fully developed region.

dissolution technique, which itself results in exaggerated mass transfer co-efficients. The values obtained in channel flow are generally lower than those observed for flow in a pipe. For example, the discrepancy between the results of Hanratty *et al.* for pipe flow, and that of the Chilton-Colburn equation [22] varies from 17 to 34 % at Reynolds numbers 5,000 and 50,000 respectively.

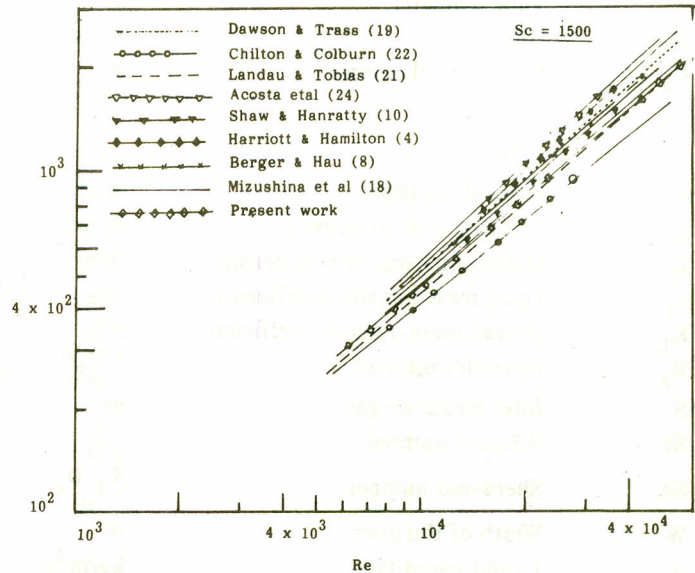


Fig. 5. Mass transfer in rectangular duct: Comparison of previously available correlations with what obtained from the present study.

The difference in the results between pipe and channel flow are more obvious at Schmidt number lower than 3,000 and are particularly pronounced in the correlations of Hanratty and Vanshaw [9], when compared with the experimental data of Pickett and Ong [23].

It is interesting to note that correlation for the entry effect of the duct ( $De/L = 0.45$ ), namely  $Sh = 0.20 (Re)^{0.62} (Sc)^{1/3}$  agrees very well with the equation derived by Van Shaw *et al.* [10] for entry into a pipe which for the same  $De/L$  value predicts a relationship of  $Sh = 0.21 (Re)^{0.58} (Sc)^{1/3}$ .

### CONCLUSION

The mass transfer behaviour of a channel has been investigated and the results correlated. The behaviour of such a duct can be fully predicted by two equations; equation (1.a) relates the data in the developing concentration and hydrodynamics boundary layers whereas the fully developed mass transfer region has been represented by equation (1.b), and the results agree well with the findings in the literature.

## NOMENCLATURE

Symbol	Description	Units
a	Correlation constant	
A	Flow cross-sectional area	m <sup>2</sup>
b	Correlation constant	
d	Tube diameter	m
D	Diffusivity	m <sup>2</sup> /s
D <sub>e</sub>	Equivalent diameter	m
	$= \frac{2WS}{W+S}$	
i	Current density	A/m <sup>2</sup>
i <sub>L</sub>	Limiting current density	A/m <sup>2</sup>
I <sub>L</sub>	Overall limiting current density	A/m <sup>2</sup>
k <sub>L</sub>	Local mass transfer coefficient	m/s
K <sub>L</sub>	Overall mass transfer coefficient	m/s
R <sub>e</sub>	Reynolds number	$\frac{u D \rho}{\mu_m}$
S	Inter electrode gap	m
Sc	Schmidt number	$\frac{\mu}{\rho D}$
Sh	Sherwood number	$\frac{K_L D_e}{D}$
W	Width of the duct	m
μ	Liquid viscosity	kg/m <sup>2</sup> s
ν	Kinematic viscosity	m <sup>2</sup> /s
ρ	Liquid density	kg/m <sup>3</sup>

## REFERENCES

- R.B. Bird, W.E. Stewart and E.N. Lightfoot, *Transport Phenomena* (John Wiley, New York 1960), pp. 628-29.
- W.H. Linton and T.K. Sherwood, *Chem. Engg. Progr.* **46**, 258 (1950).
- E.S.C. Meyerink and S.K. Friedlander, *Chem. Engg. Sci.*, **17**, 121 (1962).
- P. Harriott and R.M. Hamilton, *Chem. Engg. Sci.*, **20**, 1073 (1965).
- O.J. Cermak and R.B. Beekmann, *A.I.Ch.E. J.*, **15**, 250 (1969).
- C.S. Lin, E.B. Denton, H.S. Gaskill and G.L. Patmam, *Diffusion-controlled Electrode reactions*, *Ind. Eng. Chem. (Process Design Develop.* **43**, No. 9, 2136 43 (1951).
- W.L. Friend and A.B. Metznev, *A.I.Ch.E. J.*, **4**, 393 (1958).
- F.P. Berger and F.F.L. Hau, *Int. J. Heat. Mass Transfer*, **20**, 1185 (1977).
- D.A. Shaw and T.J. Hanratty, *A.I.Ch.E. J.*, **23**, 28 (1977).
- P. Van. Shaw, P.L. Reiss and T.J. Hanratty, *A.I.Ch.E. J.*, **9**, 362 (1963).
- P.L. Reiss and T.J. Hanratty, *A.I.Ch.E. J.*, **8**, 245 (1963).
- P.L. Reiss and T.J. Hanratty, *A.I.Ch.E. J.*, **9**, 154 (1963).
- P.V. Shaw and T.J. Hanratty, *A.I.Ch.E. J.*, **10**, 475 (1964).
- T.J. Hanratty, *Study of Turbulence Close to a Solid Wall*, the *Physica of Fluids Supplement*, 126-S, 134, (1967).
- D.A. Shaw and T.J. Hanratty, *A.I.Ch.E. J.*, **23**, 160 (1977).
- G. Wranglen and O. Nilsson, *Electrochim. Acta*, **7**, 121 (1962).
- D.W. Hubbard and E.N. Lightfoot, *Ind. Engg. Chem. (Fundamentals)*, **5**, 370 (1966).
- T. Mizushina, F. Ogino, Y. Oka and H. Fukuda, *Int. J. Heat and Mass Transfer*, **14**, 1705 (1971).
- D.A. Dawson and O. Trass, *Int. J. Heat and Mass Transfer*, **15**, 1317 36 (1972).
- J.R. Selman and C.W. Tobias, *Mass Transfer Measurements by the Limiting Current Technique*, *Advan. Chem. Engg.* **10**, 211 (1978).
- V. Landau and C.W. Tobias, *Mass Transport and Current Distribution on Channel Type Electrolyzers in the Laminar and Turbulent Flow Regimes*, *Ext. Abstr.*, No. 266, *Electrochem. Soc. Meetings*, Washington D.C., May 1976.
- T.H. Chilton and A.P. Colburn, *Mass Transfer Coefficients*, *Ind. Engg. Chem.* **26**, 1183-87, (1934).
- D.J. Pickett and K.L. Ong, *The Influence of Hydrodynamic and Mass Transfer Entrance Effects on the Operation of a Parallel plate Electrolytic Cell*, *Electrochim. Acta*, **19**, 875 (1974).
- R.E. Acosta, R.H. Muller and C.W. Tobias, *Mass Transfer under conditions of High-Rate Electrolysis*, *Ext. Abstr. No. 265*, *Electrochemical Society Meeting*, Washington, D.C., May (1976).