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Electrochemical mass transfer studies in open cavities

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Experimental measurements on free convection mass transfer in open cavities are described. The electrochemical deposition of copper at the inner surface of a cathodically polarized copper cylinder, open at one end and immersed in acidified copper sulphate was used to make the measurements. The effects on the rate of mass transfer of the concentration of the copper sulphate, the viscosity of the solution, the angle of orientation, and the dimensions of the cylinder were investigated. The data are presented as an empirical relation between the Sherwood number, the Rayleigh number, the Schmidt number, the angle of orientation and the ratio of the diameter to the depth of the cylinder. Comparison of the results with the available heat transfer data was not entirely satisfactory for a number of reasons that are discussed in the paper.

Nomenclature

C_b	bulk concentration of Cu^{++} ($mol\,cm^{-3}$)
C_b'	bulk concentration of H_2SO_4 ($mol\,cm^{-3}$)
C_o	concentration of Cu^{++} at cathode ($mol\,cm^{-3}$)
C_o'	concentration of H_2SO_4 at cathode ($mol\,cm^{-3}$)
D	cavity diameter (cm)
$\mathscr{D}$	diffusivity of $CuSO_4$ ($cm^2\,s^{-1}$)
$\mathscr{D}'$	diffusivity of H_2SO_4 ($cm^2\,s^{-1}$)
Gr	Grashof number [dimensionless] ($= Ra/Sc$)
g	acceleration due to gravity ($= 981\,cm\,s^{-2}$)
H	cavity depth (cm)
h	coefficient of heat transfer ($W\,m^{-2}\,K^{-1}$)
i_L	limiting current density ($mA\,cm^{-2}$)
K	mass transfer coefficient ($cm\,s^{-1}$)
K_1, K_2	parameters in Equation 1 depending on the angle of orientation (θ) of the cavity (see Table 3 for values) [dimensionless]
k	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
L^*	characteristic dimension of the system (= D for cylindrical cavity) (cm)
m	exponent on the Rayleigh number in Equation 1 (see Table 3 for values) [dimensionless]
Nu	Nusselt number ($= hL^*k^{-1}$) [dimensionless]
n	exponent on the Schmidt number in Equation 1 (see Table 3 for values) [dimensionless]
Pr	Prandtl number ($= \nu/\kappa$) [dimensionless]
Ra	Rayleigh number (defined in Equation 2) [dimensionless]
Sc	Schmidt number ($= \nu/\mathscr{D}$) [dimensionless]
Sh	Sherwood number ($= KD/\mathscr{D}$) [dimensionless]
t_{H^+}	transference number for H^+ [dimensionless]
$t_{Cu^{++}}$	transference number for Cu^{++} [dimensionless]
α	specific densification coefficient for $CuSO_4$ $[(1/\rho)\partial\rho/\partial C]$ ($cm^3\,mol^{-1}$)
α'	specific densification coefficient for H_2SO_4 $[(1/\rho)\partial\rho/\partial C]$ ($cm^3\,mol^{-1}$)
κ	thermal diffusivity ($cm^2\,s^{-1}$)
μ	dynamic viscosity of the electrolyte ($g\,cm^{-1}\,s^{-1}$)
ν	kinematic viscosity of the electrolyte ($= \mu/\rho$) ($cm^2\,s^{-1}$)
ρ	density of the electrolyte ($g\,cm^{-3}$)
θ	angle of orientation of the cavity measured between the axis of the cavity and gravitational vector (see Fig. 1) [degrees]
ξ'	parameter of Hasegawa *et al.* [4] ($= (2H/D)^{5/4}Pr^{-1/2}$) [dimensionless]

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Subscripts

r	fluid property evaluated at the reference condition, which was the film concentration $C_f = (C_b + C_o)/2$
D	indicates $L^* = D$ in Gr, Nu, Ra, Sh

1. Introduction

This paper is concerned with the application of the electrochemical mass transfer technique to the study of transport processes in an open, cylindrical cavity of the type shown in Fig. 1. Previous studies in the open cavity have been restricted to the measurement of heat transfer. However, the electrochemical technique is attractive for the investigation of transport processes because the measurements are simpler, cheaper and speedier.

The objective of the research was to provide a practical correlating equation for the experimental data that could be used to predict mass transfer and heat transfer in open cavities. Tests were therefore carried out using cavities of various diameter-to-depth ratios (D/H) with the opening upward ($\theta = 180°$), the opening horizontal ($\theta = 90°$) and at a number of angles (θ) between these two extremes. A subsidiary objective was to evaluate the proposed correlation by comparing it with available heat transfer data.

2. Previous investigations

Previous research on transport processes in cavities of the type shown in Fig. 1 (also known as an open thermosyphon in the heat transfer literature) has been restricted to measurements of heat transfer. The relevant literature has been carefully reviewed by Japikse [1] [see also Japikse and Winter [2]]. This suggests that heat and mass transfer in an open cavity depend on the following dimensionless groups: the Rayleigh number (Ra_D), the Prandtl number (Pr), in the case of heat transfer, or the Schmidt number (Sc) in the case of mass transfer, the ratio D/H, and the angle of orientation (θ) in the gravitational field. The Rayleigh number, which is a dimensionless temperature or concentration difference, defines various flow regimes, and in the vertical thermosyphon ($\theta = 180°$) for $Ra_D \geqslant 4 \times 10^6$ the flow is usually taken to be turbulent. Since the minimum Rayleigh number in these experiments was 1×10^8, the flow was considered to be turbulent. For this reason the review of previous research will concentrate on experimental and theoretical investigations of transport processes under turbulent flow conditions. In particular the review will give special attention to those situations where Ra_D exceeds 1×10^8, which lies in what Martin [3] calls the fully mixed turbulent flow regime; this terminology is used to differentiate it from the so-called turbulent boundary layer regime with $4 \times 10^6 < Ra_D < 8 \times 10^7$.

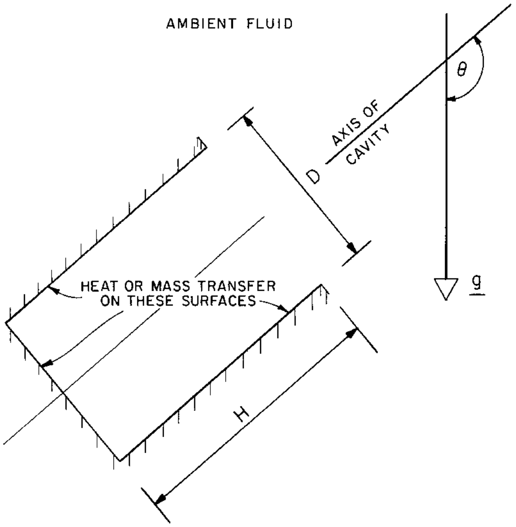

Fig. 1. Open cavity. D = diameter of the cavity, H = depth of the cavity, θ = angle of orientation of the cavity relative to the gravitational vector g.

2.1. *Vertical open cavity ($\theta = 180°$)*

Investigations of the heat transfer in vertical open cavities using fluids of different Pradtl numbers and D/H ratios have been reported by Martin [3], Hasegawa *et al.* [4], and Lockwood and Martin [5] for Rayleigh numbers between 2.56×10^4 and 5.02×10^9. Martin did not commit himself to a correlation of his experimental data, and Hasegawa *et al.* used a rather complicated functional relation involving the ratio D/H, the Prandtl number and the Rayleigh number. Simpler correlations involving products of powers of these dimensionless groups were employed by Lockwood and Martin, and by Japikse and Winter [2] in their review paper.

2.2. *Horizontal open cavity ($\theta = 90°$)*

The only measurements on transport processes in a horizontal cavity ($\theta = 90°$) are the heat transfer values by LeQuere *et al.* [6], for natural convection in a cubical cavity (all dimensions equal) with one vertical face open. The experimental fluid was air ($Pr = 0.7$) and the Rayleigh number range was from 7×10^6 to 7×10^9. The data were correlated by a simple dimensionless equation involving the Grashof number ($Gr = Ra/Pr$).

2.3. *Open cavity at an angle*

Martin and Cresswell [7] and Martin [8] have reported measurements for $4.5 \times 10^6 \leqslant Ra_D \leqslant 4.5 \times 10^8$ of the effects on the heat transfer of inclining a cavity at an angle ($\theta < 180°$) to the gravitational vector. Results were given for water, ethylene glycol, glycerine, and rape seed oil, although fully mixed turbulent flow, the regime of interest here, was only observed with water ($2 \leqslant Pr \leqslant 7.5$). No functional relation between the Nusselt, Rayleigh and Prandtl numbers was given in either of the papers under discussion.

Substantial increases (varying from 40 percent to 100 percent), compared to the value at $\theta = 180°$, in the Nusselt number for water were observed for orientation angles (θ) between 180° (vertical) and 145°. A weak dependence on angle was found for angles less than 145°.

3. Apparatus

In the experiments described here the mass transfer of copper to a cathodically polarized model of the open cavity was used as the experimental system. The electrolyte was copper sulphate (0.05 and 0.1 M) with sulphuric acid (1.5 M) added as the supporting electrolyte. In some of the tests the solution included glycerol (3 M) in order to increase the viscosity and, thereby, allow the effect of the Schmidt number on the mass transfer to be investigated. More extensive discussions of the electrochemical method of investigating mass transfer will be found in the comprehensive reviews of Mizushina [9], and Selman and Tobias [10].

Nine cavities having diameter-to-depth (D/H) ratios of 0.5, 1 and 2 were used (see Table 1 for dimensions). The cavities were oriented at angles (θ) of 180°, 150°, 135°, 120° and 90°. It will be noted that these angles are confined to the upper half plane. When the cavity was oriented with its opening in the lower half plane the time for the mass transfer process to attain steady conditions was very long because mass transfer was dominated by diffusion rather than convection, consequently, excessive plating occurred on the interior surfaces of the cavity. This plating changed both the surface area of the electrode and the physical form (see also the discussion in Section 5).

Table 1. Dimensions of cavities

Depth, H (cm)	*Diameter, D (cm)*	*D/H*
0.635, 1.27, 2.54	1.27	2, 1, 0.5
1.27, 2.54, 5.08	2.54	2, 1, 0.5
1.905, 3.81, 7.62	3.81	2, 1, 0.5

A schematic diagram of the apparatus and the electric circuit is shown in Fig. 2. The test chamber was a 114 l tank of length 88.9 cm, width 43.2 cm, and height 30.5 cm, and contained about 70 l of copper sulphate solution. The tank was thermally insulated on all surfaces with a 2.54 cm thickness of expanded polystyrene, in order to minimize the effects of ambient temperature variations. A heavy steel plate mounted on levelling screws and anti-vibration mountings carried the tank. Evaporative loss from the electrolyte was minimized by always keeping the tank covered and by adding water to the solution as necessary. In this way the copper concentration was maintained to within ± 1%. The copper concentration was measured both before and after an experiment using the EDTA titration method with 'Snazoxs' as the indicator (Guerrin *et al.* [11]).

The electrolytic reaction was limited to the interior surfaces of the cavity by cementing the model into an open ended acrylic plastic cylinder (see Fig. 3). The closed end of the copper–plastic cylinder was attached to a circular acrylic plastic disc of larger diameter than the cylinder. This served as a mounting flange whereby the test cylinder was held in its support. In this way one support served the nine different models that were used. The current lead to the cathode passed

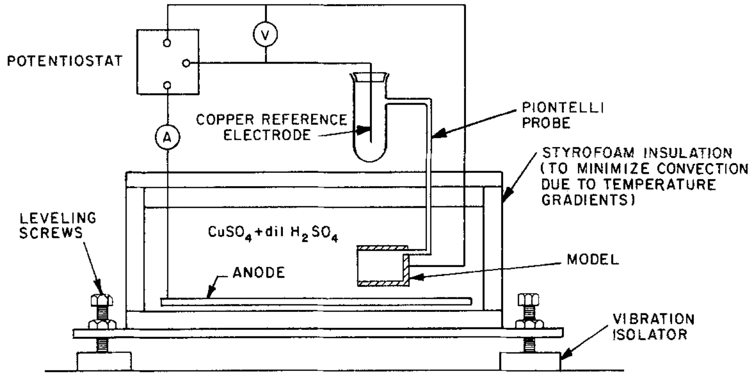

Fig. 2. Schematic arrangement of the apparatus.

through a compression fitting on the mounting disc and, therefore, did not interfere with the fluid flow in the vicinity of the model.

The inside surfaces of the cavity were machined to a fine finish and then further polished to a mirror finish with emery papers of decreasing fineness, concluding with 'Selvyt' cloth wetted with 'Brasso'. The specimens were always returned to a mirror finish and then carefully washed with distilled water and alcohol before a test run was commenced.

The test cylinder support was suspended by two 1.27 cm diameter acrylic plastic rods from a 0.95 cm thick aluminium plate.

The copper–copper sulphate reference electrode, which defines the potential at the cathode, was located outside the test chamber. It was connected to the electrolyte in the vicinity of the test model by a salt-bridge in the form of a small diameter, flexible plastic tube, filled with the electrolyte in the tank, that entered the closed end of the cylinder (Fig. 2).

The potential at the cathode was controlled by a potentiostat (Eco Inc., type 549) which was driven by the automatic programmer (Eco Inc., type 567). The Y-input to the recorder was the potential drop across a standard resistor located in the current lead to the cathode. The recorder then provided a continuous record of the current–potential relation at the cathode from which the limiting current could be read.

4. Experimental procedure

The cleaned and polished cylinder was mounted in the test specimen support and was aligned relative to the gravitational vector. The aligned cylinder was lowered into the electrolyte which had just previously been vigorously agitated with two electric stirrers to ensure a uniform concentration.

In carrying out a run the cathode potential (measured relative to the reference electrode) was

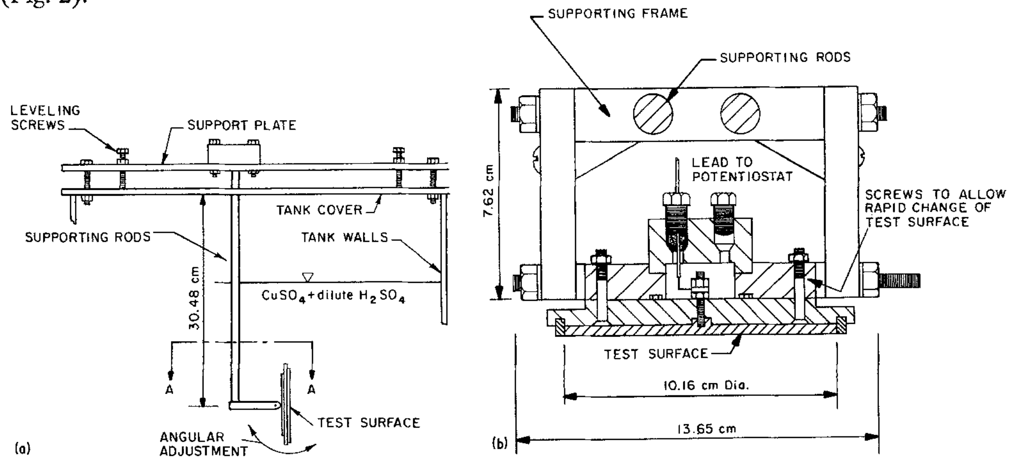

Fig. 3. (a) Overall view of model support system. Note: A flat plate test surface, used in preliminary tests to check the validity of the measurements (see section 5), is shown. (b) Detail of the model support system. Note: A flat plate test surface, used in preliminary tests to check the validity of the measurements (see section 5), is shown.

varied at a constant rate (usually 1 mV s^{-1}, but where time dependent effects (see section 5) were important rates of 0.5 mV s^{-1} were used) from zero to −0.75 V. The current–potential relation was continually recorded by the *XY*-recorder At the conclusion of the run the cylinder was removed from the electrolyte and its interior surface was examined. A sketch was made of the pattern of plating in order to assist in interpreting the limiting current measurements.

5. Error considerations and uncertainty of the data

This section deals with a number of possible error sources and an estimate of the uncertainty of the quantities appearing in the correlating equation (Equation 5).

5.1. *Comparison with flat plate measurements*

In order to check the validity of the experimental technique a few measurements were made with mass transfer at an upward facing horizontal plate. The results were compared with the data reported in the literature by Fenech and Tobias [12], and by Wragg and Loomba [13]. The difference between the measured and reported values of the limiting current density did not exceed two percent of the measured value which is in reasonable agreement with the estimated uncertainty (± 1%) of the measurement.

5.2. *Time dependent effects*

Selman and Tobias have drawn attention to the need, when carrying our limiting current measurements in the study of mass transfer, for the rate of change of potential to be sufficiently slow to ensure that the process corresponds to steady state conditions. In the experiments reported here we observed tht at low concentrations of copper sulphase (0.05 M and smaller) the current–potential plot would have a 'camel back' shape, as previously noted by Selman and Tobias, if the potential sweep rate was too high to ensure quasi-steady conditions in the mass transfer system. Reduction of the sweep rate eliminated the unwanted 'hump'. However, this led to an increase in the amount of copper plated onto the interior surface of the cavity because the overall duration of the sweep was longer. For sweeps of very long duration the build-up of copper was sufficent to change the shape of the cavity. This problem was especially acute with 0.01 M $CuSO_4$ solutions, and eventually tests under these conditions had to be abandoned. With 0.1 M and 0.05 M $CuSO_4$ solutions sweep rates between 1 and 0.5 mV s^{-1} (depending on the orientation of the cavity) were found to give current–potential curves with the classical horizontal limiting current sector, together with very light copper deposits

5.3. *Effect of variations in temperature*

The formulas given by Fenech and Tobias [12] for calculating the fluid density (ρ), the specific densification coefficients (α, α') dynamic viscosity (μ), and diffusivites ($\mathscr{D}, \mathscr{D}'$) are for fluids at a temperature of 22° C. The electrolyte in the tank was maintained at a temperature of 21.7 ± 0.5° C by means of the thermal insulation around the tank, and because the tests were carried out in a temperature controlled room. The resulting variations in the fluid properties were about ±0.02%, which is negligible compared to other contributions to the uncertainty of the measurements (see subsection 5.4).

5.4. *Uncertainty of the measurements*

To analyse the uncertainty of the final results the uncertainty of the various measurements as shown in Table 2a were used. In addition the uncertainty of the fluid properties ($\mathscr{D}$, $\mathscr{D}'$, ν, t_{H^+}, $t_{\mathrm{Cu}^{++}}$, α, α') were taken as ±0.5 on the basis of information given in the source [13] of the fluid property values. The uncertainty in the determination of the Sherwood number from the correlating Equation 5 is between 1 and 2% depending on the concentration of the copper sulphate solution (see Table 2b).

6. Data analysis and results

On the basis of the discussion in section 2, it is appropriate to represent the data by the relation

$$Sh_{\mathrm{D}} = K_1(\theta) \left(\frac{D}{H}\right)^{K_2(\theta)} Sc^n Ra_D^m \qquad (1)$$

where the quantity K_1 can be expected to depend on the flow regime, as well as the indicated dependence on the angle of orientation (θ). It is possible

Table 2a. Uncertainty of directly measured quantities

Quantity	*Nominal value*	*Uncertainty*	*Basis*
D		± 0.002 cm	half least count of micrometer.
C_b	0.0001 mol cm^{-3} 0.00005 mol cm^{-3}	± 1%	analysis of chemical procedures and consideration of variability of C_b during a run.
i_L	3 mA cm^{-2}	± 1%	half least count of Y-scale on XY-recorder and analysis of method for determining i_L.

Table 2b. Uncertainty of indirectly measured quantities

Quantity	*Uncertainty*
κ	0.1 M: ± 1% 0.05 M: ± 2%
Sh	0.1 M: ± 1% 0.05 M: ± 2%
Sc	± 0.7%
Ra	± 0.8%
H/D	± 0.2%
K_1	± 0.001
K_2	± 0.021
m	± 0.008
n	± 0.002

that a similar dependence may also apply to the exponents K_2, m and n, and the data were analysed with this is mind.

For mass transfer in the presence of two different chemical species (the situation here) together with an electrochemical reaction at the specimen surface, the definition of the Rayleigh number, which appears in Equation 1, differs from that used with a solution of a single species and it is shown by Wagner [15], and Tobias *et al.* [16] that

$$Ra = \frac{gL^{*3}\rho_r(C_b - C_o)}{\mu_r \mathscr{D}_r} \left[\alpha - \left(\frac{\mathscr{D}_r}{\mathscr{D}_r'}\right)^{0.67} \frac{t_{H^+}}{1 - t_{Cu^{++}}}\alpha'\right] \qquad (2)$$

The reference condition (indicated by subscript r in Equation 2) used to evaluate the fluid properties shown in Equation 2 was the film concentration, $C_f = (C_b + C_o)/2$, and similarly for C_f'. The possibility of using other reference conditions was explored, but the resulting differences in the dimensionless quantities was within the uncertainty of the experimental data, so it seemed simplest to use the widely accepted film value.

The fluid properties (α, ρ, μ, $\mathscr{D}$) and the transference numbers ($t_{Cu^{++}}$, t_{H^+}) depend on the composition of the electrolyte. The formulae proposed by Fenech and Tobias [12] for the density (ρ), dynamic viscosity (μ), and diffusivity ($\mathscr{D}$) of a mixture of copper sulphate, sulphuric acid, and glycerol were used. The specific densification coefficient (α) and the dynamic viscosity (μ) were computed from these formulae. Fenech and Tobias [12] give a relation for the transference numbers that was also used.

Because the determination of the dimensionless quantities involves an iterative calculation (see Equation 1), a computer program was written having as input the measured limiting current, the bulk concentration of the copper sulphate and of the sulphuric acid, and the characteristic dimension (L^*) of the cavity. This program was tested by recomputing the mass transfer data of Fenech and Tobias [12].

The constant K_1 and the exponents K_2, m and n were determined using the method described by Martin [3], and these are shown in Table 3. The characteristic dimension L^* was set equal to the diameter D of the cavity.

To check the proposed correlation for the experimental data (Equation 1), the quantities $Sh/[Sc^{0.056}(D/H)^{K_2}]$ and Ra, both computed from the experimental data were plotted on logarithmic coordinates, together with the appropriately rearranged form of Equation 1, as shown in Fig. 4. Comparison by eye of the experimental data points and the lines representing Equation 1, suggest that the correlation is satisfactory. This was confirmed

Table 3. Constants and exponents in $Sh = K_1 (D/H)^{K_2} Sc^n Ra^m$

Orientation	θ	K_1	K_2	m	n
opening upward	180°	0.232	0.191	0.280	0.056
	150°	0.233	0.169	0.280	0.056
	135°	0.235	0.126	0.280	0.056
	120°	0.228	0.089	0.280	0.056
opening horizontal	90°	0.215	0.073	0.280	0.056

by computing the sum of the squares of the residuals $y_M - y_C$, where $y = Sh/[Sc^{0.056}(D/H)^{K_2}]$ and the subscripts M and C indicate measured values and values computed from the correlation, respectively. The quantity $[\Sigma(y_M - y_C)^2/(N-2)]^{\frac{1}{2}}$ with N = number of data points, which can be interpreted as a'global' standard deviation of the measured data with respect to the correlating equation, was equal to ± 5.4. This lies within the range (± 0.1 to ± 12.6) of the estimated uncertainty of the quantity y. Thus, the 'average observed deviation' is somewhat smaller than the 'average estimated deviation'.

7. Discussion and conclusions

7.1. *General*

It will be noticed that K_1 is a much weaker function of the angle θ than K_2. In addition, on plotting K_2 against tan (180° − θ), which is the ratio of the normal acceleration to the axial acceleration (Martin [8]), it was found that a clear inflection appears in the graph at a point corresponding to $\theta = 135°$. This suggests that there are two different flow regimes associated with different angular orientations of the cavity. Namely for $\theta > 135°$ the flow conditions are preponderently of the type that occur in a vertical cavity ($\theta = 180°$), and for $90° \leqslant \theta \leqslant 135°$ the flow tends to be like that which occurs in a horizontal cavity ($\theta = 90°$). This is a speculative idea and more definite conclusions could be reached if simultaneous observation of the flow field, measurements of local transport variables, and fluxes of mass could be made.

The form of Equation 1 indicates that deep cavities (small D/H) are less effective in mass transport than are shallower cavities (large D/H). This is because a major part of the mass transfer is confined to a region adjacent to the cavity opening, and the extent of this region is largely independ-

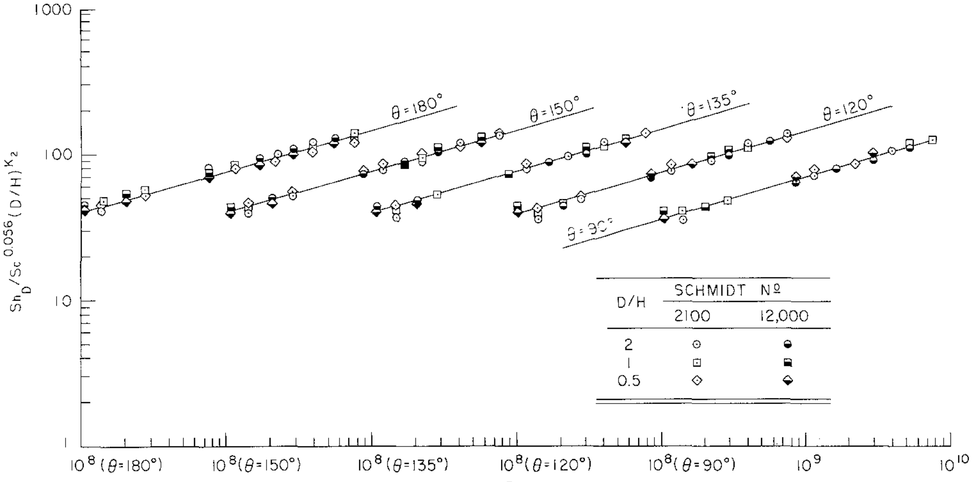

Fig. 4. Comparison of experimental data with the proposed correlation of Equation 1 and Table 3. Note: 1. A few data points have been omitted for clarity. 2. The origins of the coordinate axes are shifted one decade for each orientation, as indicated in parentheses, and the abscissa for each orientation angle covers two decades (10^8 to 10^{10}).

ent of the depth of cavity. In other words, increasing the cavity depth beyond a certain value does not lead to a significant increase in the total amount of mass transfer. This observation is confirmed by a study of the cavities after the completion of each experimental run. The deposits of copper were greatest in the vicinity of the opening and the interior portions were usually only very lightly plated, if at all.

Local heat transfer measurements by Martin [3] also indicated that the portions of the cavity in the vicinity of the entrance were much more effective in transferring heat than those parts of the interior surface remote from the entrance.

7.2. *Upward facing cavity ($\theta = 180°$)*

Japikse and Winter [2] (see also Japikse [1]) propose that the constant K_1 and the exponent K_2 in Equation 1 depend on the diameter (D) of the cavity. Our data was examined for this effect, but the results were inconclusive. This may be a consequence of the largest diameter cavity being 3.81 cm, whereas Japikse and Winter noted that significant effects of cavity diameter only started to appear when the diameter exceeded 2.54 cm.

The correlating equation (Equation 1 and Table 3) was compared with the results of the heat transfer measurements made by Martin [3], Hasegawa *et al.* [4], and by Lockwood and Martin [5]. The objective of this comparison was to ascertain the possibility of predicting heat transfer for a wide range of Prandtl numbers from mass transfer measurements. The comparison was not entirely satisfactory for three reasons:

1. There was a considerable difference in the range of values of D/H used in the various experiments. The heat transfer measurements were made with deep cavities, D/H small, whereas in the mass transfer tests the cavities were shallow (D/H large).
2. The Schmidt number of the fluids was many times greater than the Prandtl number of the fluids used in the heat transfer tests.
3. It was not certain that comparable flow regimes were being considered.

In spite of this the comparison was made and the best agreement between heat transfer and mass transfer measurements was obtained with the correlation proposed by Hasegawa *et al.* Fig. 5 shows a graphical comparison. To plot this graph values of the Rayleigh and Prandtl numbers, and the D/H ratio corresponding to these used in the mass transfer experiments were substituted into the equation proposed by Hasegawa *et al.*

7.3. *Horizontally facing cavity ($\theta = 90°$)*

Equation 1 was compared with the equation used by LeQuere *et al.* [6] to correlate their heat transfer measurements with air from a horizontal cubical cavity. This was done by introducing appropriate numerical values from Table 3 with $D/H = 1$ and $Sc = 0.7 = Pr$. The graph of the resulting formula did not agree well with a plot based on the formula of LeQuere *et al.* However, this is not surprising in view of the difference in the shape of the cavities.

7.4. *Cavities at angles of 150°, 135° and 120°*

Because of the form of the proposed correlation,

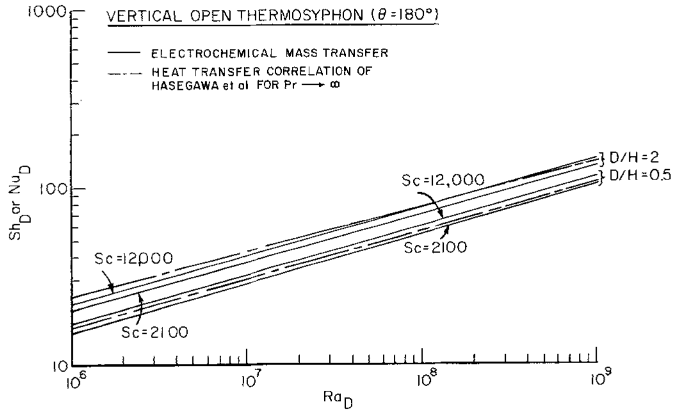

Fig. 5. Comparison of the proposed correlation (solid line) of the electrochemical mass transfer measurements in a vertical open thermosyphon with the heat transfer correlation of Hasegawa *et al.* [4] (chain dotted line) for large Prandtl numbers.

Equation 1, the effect of variations of the orientation angle (θ) for fixed D/H are shown by changes in the constant K_1 and the exponent K_2. The effect of these on the Sherwood number is quite weak. Typically, the change in Sherwood number from one angle to the other is about 10%. This is a much smaller effect than was observed by Martin [3] in his heat transfer experiments, however, the comparison is complicated by the lack of data in our experiments for angles between 180° and 150°, which is just the range of values in which Martin observed the greatest variation in Nusselt number.

6. Conclusions

A correlating equation for experimental measurements of mass transfer in an open cavity oriented at various angles with respect to the gravitational vector has been obtained. Comparison of this equation with results from heat transfer measurements is encouraging, but substantial differences in the experimental conditions prevailing in the two types of experiments makes it desirable to repeat the experiments with different parameters, and, if possible, flow visualization.

Acknowledgements

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