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# *A parameter characterizing the geometry of expanded metal. II. Natural convection mass transfer at expanded metal electrodes*

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Free convective mass transfer rates at vertical electrodes of expanded metal were measured by the electrochemical method. Electrode height and electrolyte concentration were varied and the dependence of the expanded metal on the geometry and on the mesh orientation with respect to the vertical direction was investigated. A single equation was developed to correlate all the results. Besides the generalized dimensionless groups for natural convection the correlation includes a parameter characterizing the geometry of the expanded metal. The correlation also represents free convective mass transfer results obtained by other investigators with vertical mesh electrodes.

**Nomenclature**

| | |
|---|---|
| $a$ | width of narrow space |
| $A$ | mean mesh aperture |
| $c_0$ | bulk concentration |
| $d$ | cavity diameter |
| $d_p$ | particle diameter |
| $D$ | diffusivity |
| $g$ | acceleration due to gravity |
| $Gr$ | Grashof number $= g\Delta\varrho h^3/\varrho\nu^2$ |
| $h$ | electrode height |
| $H$ | cavity depth |
| $k$ | mass transfer coefficient |
| LD | long dimension of expanded metal |
| $R_h$ | hydraulic radius |
| $Sc$ | Schmidt number $= \nu/D$ |
| SD | small dimension of expanded metal |
| $Sh$ | Sherwood number $= kh/D$ |
| $\varepsilon$ | void fraction |
| $\nu$ | kinematic viscosity |
| $\varrho$ | density |
| $\phi$ | electrode area per unit volume |
| $\psi$ | electrode area per unit net area |

## 1. Introduction

Expanded metal has become an interesting material for manufacturing electrodes for electrolysis conducted with dilute solutions or low current densities, with gas evolution or the requirement of high residence times of the electrolyte. The efficiency of the expanded metal in these cases is attributable to its geometrical configuration which leads to high surface areas per unit volume, an increase in local fluid velocity, high mass transfer coefficients and deflection of gas bubbles.

The design of electrochemical reactors incorporating expanded metal electrodes requires knowledge of the mass transfer characteristics of these electrodes and their dependence on hydrodynamic and geometric factors. In Part I [1] experimental data for forced convection mass transfer obtained by other authors with flow-by electrodes of expanded metal were correlated in dimensionless form, making it necessary to introduce a geometric factor in the correlation. This factor was also found to apply to wire gauzes.

In this second part an experimental study of natural convection mass transfer to expanded metal electrodes is reported. In addition to the

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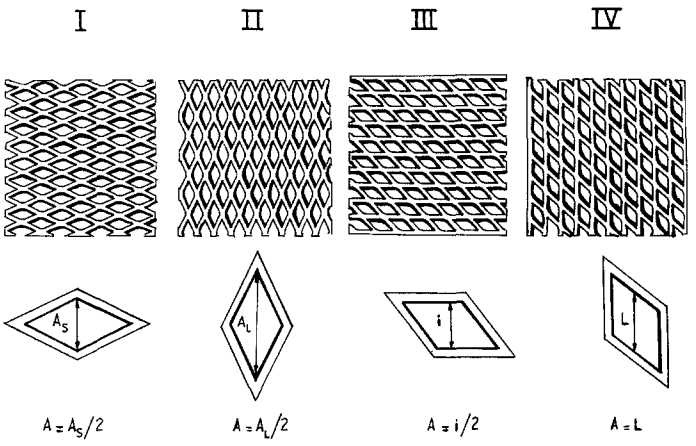


Fig. 1. Mesh orientations investigated.

concentration of the reacting species and the electrode height, the geometric characteristics of the expanded metal and the mesh orientation with respect to the vertical direction have been varied.

## 2. Experimental details

Mass transfer coefficients were determined by the well-known electrochemical method: limiting currents were measured for the cathodic reduction of ferricyanide from aqueous solutions equimolar in potassium ferricyanide and ferrocyanide, all containing 2 M sodium hydroxide. Four concentrations of the redox couple were investigated: 0.025 M, 0.1 M, 0.15 M and 0.2 M. The electrolyte was maintained at a temperature of 25 $\pm$ 0.1° C in order to minimize thermal effects.

The electrodes were 2 and 3 cm high and presented different geometry or mesh orientation. They were constructed from sheets of expanded stainless steel, nickel-plated by autocatalytic deposition. Only the vertical position of the electrodes was investigated. The current lead passed through a thin plastic rod which served as support for the cathodes. Two anodes, made of porous nickel, were placed at both sides of the cathode, 5 cm apart.

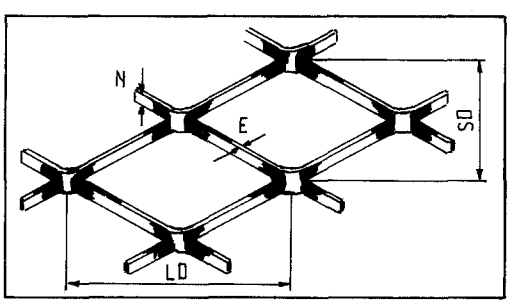


Fig. 2. Characteristic parameters of expanded metal.

Fig. 1 shows the different mesh orientations with respect to the vertical direction. This is taken as the reference because of the fact that the buoyancy forces, originated by the density differences in the solution and giving rise to the hydrodynamic flow, act in this direction. The same figure also indicates the magnitude taken as a measure of the mean aperture, $A$, of the mesh.

As can be seen from Fig. 1, narrow horizontal, vertical or diagonal areas will be present, depending on the mesh orientation; in every case these show a slight deviation with respect to the vertical plane and face alternately upward and downward. However, the inclination angle and the length of these transferring areas are small, so that the boundary layer remains attached to them but separates from the transferring surface in each opening. The frequency of this flow separation and the interaction of neighbouring boundary layers depends strongly on the electrode geometry and mesh orientation. These are summarized in Table 1 for all the electrodes tested. Fig. 2 explains the meaning of the different dimensions. Table 1 also includes the characteristics of mesh electrodes used by other investigators [2, 3].

Two planar electrodes having the same net areas and heights as the expanded metal electrodes were also used with each electrolyte con-

*Table 1. Electrode characteristics*

| *Expanded metal LD–N–E** | *Mesh orientation* | *Height (mm)* | *LD (mm)* | *SD (mm)* | *A (mm)* | $\varepsilon$ | $\phi$ ($cm^{-1}$) | $R_h$ (mm) | $\psi$ | *Symbol* |
|---|---|---|---|---|---|---|---|---|---|---|
| 10–1.3–0.6 | I | 20, 30 | 10 | 5.1 | 2.45 | 0.863 | 8.33 | 1.04 | 1.50 | ◇ |
| 10–1.3–0.6 | II | 20, 30 | 10 | 5.1 | 3.55 | 0.863 | 8.33 | 1.04 | 1.50 | ◇ |
| 10–1.3–0.6 | III | 20, 30 | 10 | 5.1 | 2.40 | 0.863 | 8.33 | 1.04 | 1.50 | ▱ |
| 10–1.3–0.6 | IV | 20, 30 | 10 | 5.1 | 3.90 | 0.863 | 8.33 | 1.04 | 1.50 | ▱ |
| 10–0.95–0.4 | I | 30 | 10 | 4.55 | 1.60 | 0.872 | 10.88 | 0.80 | 1.30 | ◆ |
| 6–0.7–0.6 | I | 20, 30 | 6 | 3.8 | 1.30 | 0.833 | 10.50 | 0.79 | 1.26 | ◆ |
| 6–0.7–0.6 | II | 20, 30 | 6 | 3.8 | 2.15 | 0.833 | 10.50 | 0.79 | 1.26 | ◆ |
| 6–0.7–0.6 | III | 20, 30 | 6 | 3.8 | 1.23 | 0.833 | 10.50 | 0.79 | 1.26 | ◥ |
| 12–0.95–0.4 | I | 30 | 12 | 5.55 | 2.10 | 0.909 | 9.63 | 0.94 | 1.15 | ◆ |
| Electroformed mesh† | – | 1.5–58.3 | – | – | 0.38 | 0.360 | 12.25 | 0.029 | 1.86 | ○ |
| Metal screen‡ | – | 13.5–110 | – | – | 0.886 | 0.750 | 30.00 | 0.25 | 2.25 | ● |

* Commercial denotation; † from reference [2]; ‡ from reference [3].

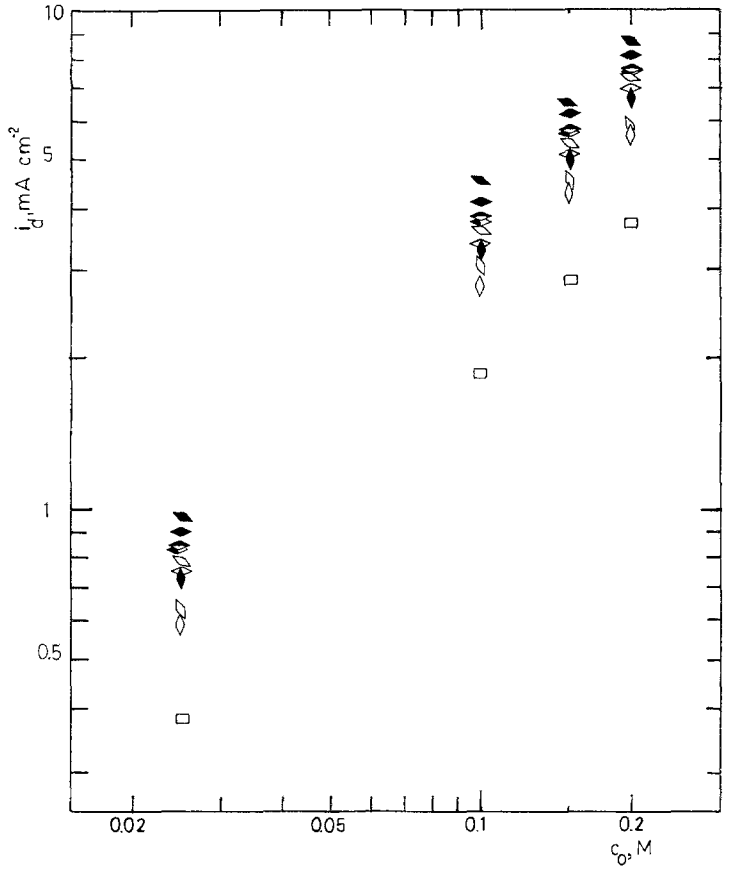


Fig. 3. Natural convection mass transfer results for vertical expanded metal electrodes and a planar electrode ($h$ = 2 cm). Symbols as listed in Table 1.

centration in order to check the validity of the experimental technique.

## 3. Results and discussion

The mass transfer results obtained with the planar electrodes were compared with the values calculated from the correlation for natural convection at vertical plates

$$Sh = 0.67(Sc\,Gr)^{0.25} \quad (1)$$

The difference between the measured and calculated values of the limiting current density did not exceed 4%, indicating a satisfactory agreement.

The experimental data for the limiting current density measured with all the electrodes, including the planar ones, were plotted on logarithmic coordinates as a function of the bulk concentration of the electrolyte (Figs 3, 4). As expected, the higher the concentration of the reacting species and the smaller the electrode height, the higher is the limiting current density.

As clearly shown, the values obtained with expanded metal are higher than those corresponding to the flat plate and they depend on the geometry of the expanded metal and on the mesh orientation. For the same electrode material and height and for the same concentration, differences of about 20–30% and more are achieved by changing the mesh orientation; it is seen that orientation III is always the most effective in mass transport.

At first sight it would appear that no practical correlating equation for the experimental data can be derived, because no definite trend is observed. The usual manner of representing natural convection mass transfer data by a relation between the Sherwood number and the product of the Schmidt number and the Grashof number, yields:

$$Sh = 0.84(Sc\,Gr)^{0.27} \quad (2)$$

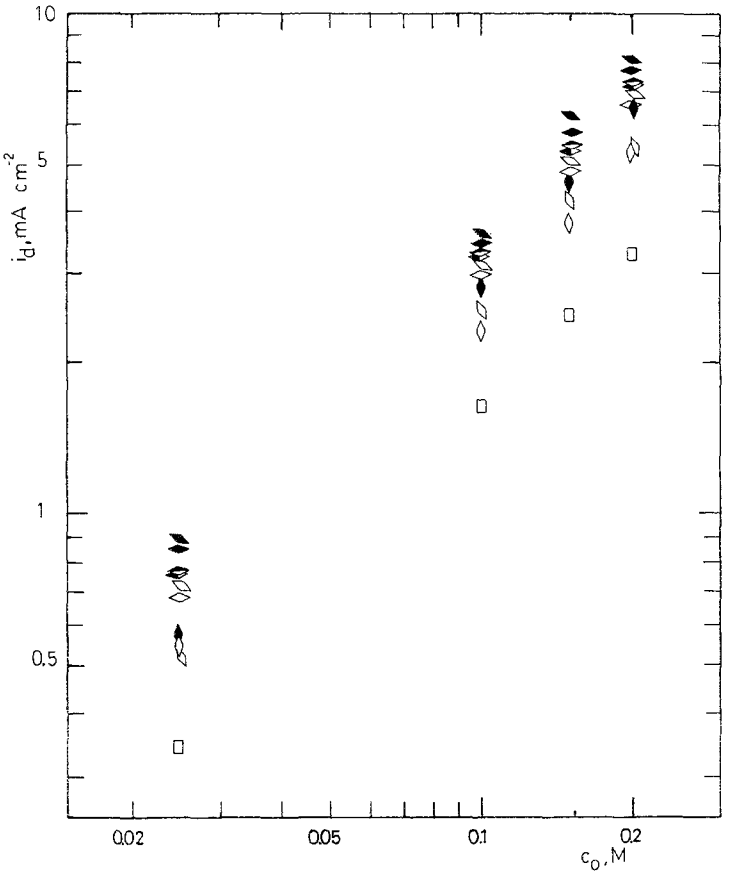


Fig. 4. Natural convection mass transfer results for vertical expanded metal electrodes and a planar electrode ($h$ = 3 cm). Symbols as listed in Table 1.

but the mean deviation of 16.9% indicates that such a representation is inadequate.

It is known that geometric parameters were repeatedly found to be useful for deriving general empirical correlations that could be used to predict natural convection mass transfer. For instance, the relation

$$Sh = 0.0225(Sc\,Gr)^{0.85}(a/h)^2 \quad (3)$$

holds for the case of natural convection taking place in narrow spaces [4];

$$Sh = 0.228(Sc\,Gr)^{0.32}(R_h/d_p)^{0.22} \quad (4)$$

describes free convective mass transfer in packed beds of spheres and screens [5]; and

$$Sh = 0.232(Sc\,Gr)^{0.28}Sc^{0.056}(d/H)^{0.191} \quad (5)$$

and

$$Sh = 0.215(Sc\,Gr)^{0.215}Sc^{0.056}(d/H)^{0.073} \quad (6)$$

are the correlating equations for the data obtained for mass transfer in vertical and horizontal open cavities, respectively [6].

In Part I [1] a dimensionless parameter characterizing the geometry of expanded metal was presented which allowed the correlation of forced convection mass transfer data. This parameter is the ratio of the hydraulic radius of the three-dimensional electrode to the mean aperture of the mesh in the flow direction; it takes into account the discontinuity of the transferring area which causes successive interruptions of the boundary layer. When this parameter is used together with the dimensionless groups $Sh$ and $(Sc\,Gr)$ the findings of the present work can be well correlated. The following empirical relation is established:

$$Sh = 1.29(Sc\,Gr)^{0.27}(R_h/A)^{0.46} \quad (7)$$

with a mean deviation of 5.34%.

Although mass transfer enhancement of about 70% and more occurs when compared

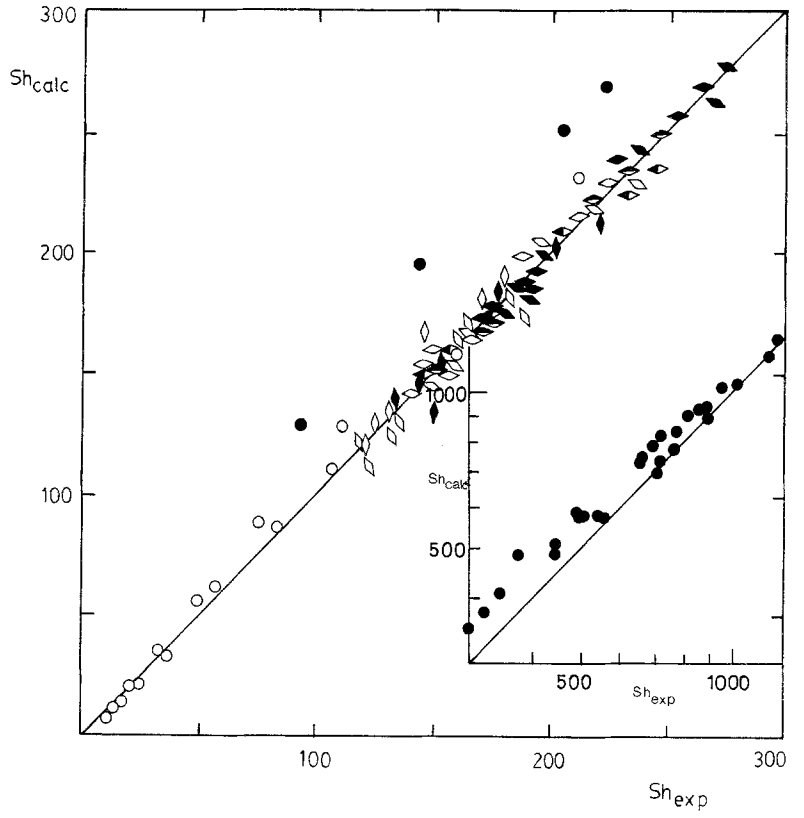


Fig. 5. Comparison between calculated and experimental values of Sherwood numbers for expanded metal and wire cloth.

with the results obtained with planar electrodes, the exponent of $(Sc\,Gr)$, differing only slightly from the value which applies for laminar flow, indicates that turbulent conditions were not attained. The exponent of the ratio $(R_h/A)$ is relatively high, which means that the effect of the geometric characteristics is an important factor in determining the convection behaviour.

The Sherwood numbers deduced from Equation 7 are compared to the experimental values in Fig. 5. The small deviation of the points around the diagonal suggests that the correlation is satisfactory.

Since it was found in Part I that the geometric parameter $(R_h/A)$ may also be applied in the case of forced convection mass transfer at screen electrodes, it was felt of interest to determine the applicability of Equation 7 when vertical screen electrodes are working in natural convection conditions. Although some work has been carried out on natural convection at horizontal screens and screen beds [5, 7], apparently only two investigations dealing with vertical screens have been reported [2, 3], which also provide the necessary information about the geometry of the mesh electrodes. Table 1 gives the characteristics of the electrodes employed in these investigations. From the measurements made by Wragg [2] with vertical nickel mesh electrodes, Sherwood numbers were obtained taking into account the corrections recommended in [8]. The work by Sedahmed and Shemilt [3] was limited to a vertical cathode (4 cm × 12 cm) of stainless steel screen insulated from the edges by a plastic lacquer in order to vary the electrode height. As shown in Table 1 the geometric characteristics of both woven screens differ considerably, which becomes reflected in the mass transfer rates. For similar values of $(Sc\,Gr)$ the Sherwood numbers obtained by Sedahmed and Shemilt are twice the values obtained by Wragg. However, when the experimental Sherwood numbers of both investigations are compared to those calculated by Equation 7, which accounts for the geometry, a quite satisfactory agreement is found (Fig. 5). In the case of Wragg's data the difference from the

calculated value exceeds 20% only for one result and it is less than 10% for two-thirds of the experimental points. The differences of the correlation values from the Sedahmed–Shemilt data increase systematically from 0.2% up to 30% as the electrode height is reduced; the experimental Sherwood numbers fall more and more below Equation 7. This can be attributed to the varying working conditions in the investigation by Sedahmed and Shemilt: entrance effects get more pronounced for smaller electrode heights since skin friction at the insulated surface of the screen hinders the free convective flow thus lowering the mass transfer rate. Nevertheless, only 6 out of 34 results differ more than 20% from the calculated values. It seems that Equation 7 derived for expanded metal is also applicable to vertical mesh electrodes.

## 4. Concluding remarks

The experimental study of free convective mass transfer at vertical electrodes of expanded metal showed that mass transfer coefficients are about 70% higher than those obtained with planar electrodes in the same conditions.

The dimensions of the geometric parameters of the expanded metal are seen to influence mass transfer and, for a given material, variations of 20–30% are found, depending on the orientation of the rhomboidal opening with respect to the vertical. Nevertheless, all the results are well correlated by a single equation when the parameter characterizing the geometry of the expanded metal ($R_h/A$) is included.

The correlation also applies to free convective mass transfer results obtained with vertical mesh electrodes.

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