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Natural convection mass transfer inside cylindrical cavities of different orientation

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Rates of free convection mass transfer inside cylindrical cavities were studied by measuring the limiting current for the cathodic deposition of copper from acidified copper sulphate solution using a cylindrical anode placed inside the cavity. Variables studied were cavity orientation (vertical with upward facing opening, vertical with downward facing opening and horizontal), physical properties of the solution and cavity dimensions (diameter and depth). For vertical cavities with upward facing openings the data were correlated by the equation

$$Sh = 0.257\,(Sc \times Gr)^{0.33}$$

For horizontal cavities the data were correlated by the equation

$$Sh = 0.139\,(Sc \times Gr)^{0.33}$$

For vertical cavities with downward facing openings the data were correlated by the equation

$$Sh = 0.187\,(Sc \times Gr)^{0.297}$$

A comparison between the present data and the data obtained from other cavity geometries was made to shed light on the role of cavity geometry in thermosyphon design.

List of symbols

- a, b constants
- A cavity area
- C copper sulphate bulk concentration
- C_p specific heat
- D diffusivity
- d cavity diameter
- F Faraday constant
- g acceleration due to gravity
- h heat transfer coefficient
- I_L limiting current
- k thermal conductivity
- K mass transfer coefficient
- L cavity depth
- L_c characteristic length calculated from Equation 3
- Z number of electrons involved in the reaction
- Gr Grashof number $(gL_c^3\Delta\rho/\nu^2/\rho_i)$
- Nu Nusselt number (hL_c/k)
- Pr Prandtl number $(C_p\mu/k)$
- Sc Schmidt number (ν/D)
- Sh Sherwood number (KL_c/D)
- Ra Rayleigh number $(Sc \times Gr)$ or $(Pr \times Gr)$

Greek letters

- μ dynamic viscosity of the electrolyte
- ν kinematic viscosity of the electrolyte
- ρ density of the electrolyte
- ρ_i interfacial density
- $\Delta\rho$ density difference between the bulk solution and interfacial solution

1. Introduction

Previous studies [1–6] on natural convection heat and mass transfer at surfaces of complex geometry have revealed the fact that the rate of heat or mass transfer at the complex surface cannot, in most cases, be obtained by summing the rate of heat or mass transfer at the individual surfaces of which the surface is composed, owing to hydrodynamic interaction between different faces. Accordingly, experimental study is necessary to delineate the natural convection mass transfer behaviour of such surfaces. The objective of the present work is to study the free convection mass transfer behaviour of cylindrical cavities in three different positions, namely, vertical cavities with an upward facing opening, vertical cavities with a downward facing opening and horizontal cavities. Cylindrical cavities are encountered frequently in practice, for example, cavities filled with liquids are used in cooling

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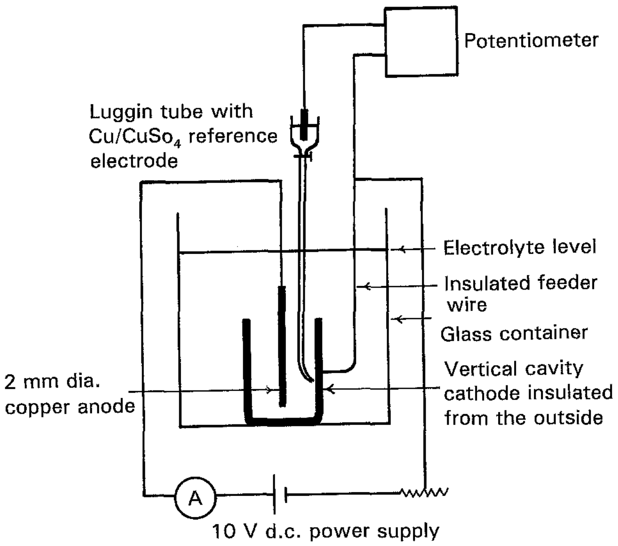

Fig. 1. Experimental apparatus.

Table 1. Cavity dimensions

Cavity depth, L /cm	*Cavity diameter, d* /cm	*Aspect ratio* L/d
0.5	1.72	0.29
1	1.72	0.58
1.5	1.72	0.87
2	1.72	1.16
2.5	1.72	1.45
3	1.72	1.74
2	2	1
2	2.96	0.68
2	3.18	0.63
2	4.1	0.49

equipment such as nuclear reactors, transformer cores, turbine blades and internal combustion engines under the term thermosyphon [7]. Fabrication or surface finishing of such cavities may be carried out through a diffusion controlled process such as electrochemical machining, electroforming, electroplating, electroless plating, etching and electropolishing. The study of natural convection mass transfer inside cylindrical cavities makes it possible to predict the rate of these processes under natural convection or under the combined natural and weak forced convection where natural convection is dominating [8]. In a previous study Somerscales and Kassemi [9] studied the natural convection mass transfer behaviour of inclined cylindrical cavities (between the horizontal position and the vertical position with the cavity mouth facing upward) by measuring the limiting current of the cathodic deposition of copper from acidified copper sulphate solution using a cell whose anode was placed outside the cavity. Under such condition potential distribution was not uniform inside the cavity, this affects the current distribution inside the cavity. Visual observation of the cavities by the authors revealed that the deposits of copper were greatest in the vicinity of the opening while the interior portions were usually only very lightly plated, if at all. Somerscales and Kassemi correlated their data with the equation:

$$Sh = a(d/L)^b Sc^{0.056} Ra^{0.28} \quad (1)$$

The value of a and b depends on the angle of inclination of the cavity. Cavity diameter was used as a characteristic length. Previous theoretical and experimental studies on plating through holes in printed circuit boards using external anodes have shown that under natural convection conditions current distribution is not uniform on the walls of the hole, the nonuniformity in current distribution increases with increasing current density and aspect ratio [10–12].

The present study was carried out using a cylindrical anode placed inside the cavity to improve current distribution.

2. Experimental technique

The apparatus (Fig. 1) consisted of the cell and electrical circuit. The cell consisted of a 250 cm^3 glass beaker filled with 200 cm^3 of electrolyte. Cavities of the dimensions shown in Table 1 were used as cathodes; cavity diameter ranged from 1.72 to 4.1 cm while cavity depth ranged from 0.5 to 2 cm. All cavities were made of pure copper; each cavity was brazed to a 2 mm copper wire which acted as cathode holder and current feeder. A 2 mm diameter copper wire placed inside the cavity at its centre acted

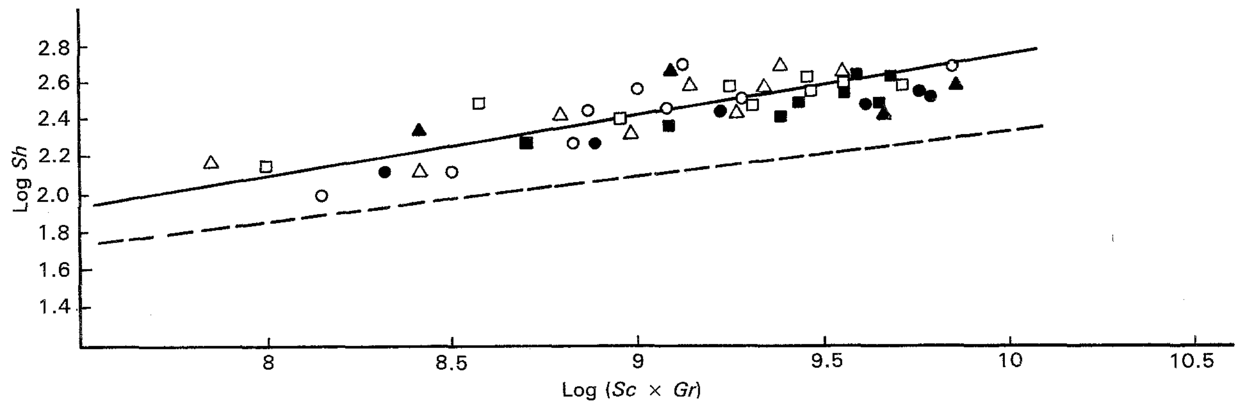

Fig. 2. Overall mass transfer correlation at vertical upward facing cavity. $CuSO_4$ concentration: (○) 0.027, (△) 0.05, (□) 0.075, (■) 0.1, (●) 0.131, and (▲) 0.189 M. (– – –) Data of Somerscales and Kassemi [9].

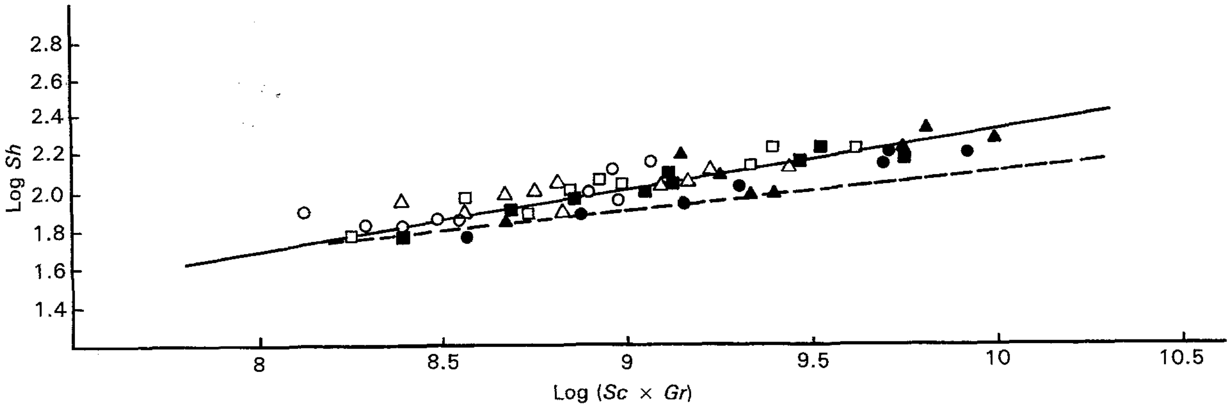

Fig. 3. Overall mass transfer correlation at horizontal cavity. $CuSO_4$ concentration: (○) 0.027, (△) 0.05, (□) 0.075, (■) 0.1, (●) 0.131, and (▲) 0.189 M. (– – –) Data of Somerscales and Kassemi [9].

as the cell anode. The electrical circuit consisted of 10 V d.c. power supply with a voltage regulator and a multirange ammeter connected in series with the cell. The outer surface of the cavity, as well as the current feeder, was isolated with epoxy resin. Before each run the inner surface of the cavity was treated as mentioned elsewhere [13]. Polarization curves, from which the limiting current was determined, were plotted by increasing the current stepwise and measuring the steady state cathode potential against a reference $Cu/CuSO_4$ electrode using a high impedance voltmeter. The reference electrode was placed in the cup of a thin luggin tube filled with the cell solution, the tip of the luggin tube was positioned half way between the top and bottom of the cavity. Preliminary experiments showed that the position of the luggin tube inside the cavity has a negligible effect on the limiting current. The solution consisted of copper sulphate dissolved in 1.5 M H_2SO_4; the copper sulphate concentration ranged from 0.027 to 0.189 M; higher concentrations were avoided because they were found to passivate the anode owing to the high anode current density resulting from the small anode area. Anodic polarization curves for the $CuSO_4$ concentration range 0.027–0.189 M using the 2 mm wire anode did not exhibit any anodic limiting current or passivity even at currents higher than the cathodic limiting current of copper deposition at the cavity wall. All solutions were prepared from AR grade chemicals and distilled water. Temperature ranged from 18 to 25 °C; the exact temperature was measured in each experiment and the physical properties of the solution were evaluated accordingly. Each experiment was carried out twice.

3. Results and discussions

Polarization curves with well defined limiting current plateaux were obtained under different conditions, the limiting current was determined from these curves and used to calculate the mass transfer coefficient according to the equation

$$k = I_L/ZFAC \qquad (2)$$

The mass transfer coefficient was correlated to other variables using the dimensionless groups *Sh*, *Sc* and *Gr*. The physical properties of the solution used to calculate these groups were taken from the literature [13, 14]. The characteristic length L_c used in calculating *Sh* and *Gr* was calculated from the equation [15]

$$L_c = \frac{\text{Internal cavity area}}{\text{Perimeter projected onto horizontal plane}} \qquad (3)$$

For vertical cavities,

$$L_c = \frac{\pi dL + \pi d^2/4}{\pi d} \qquad (4)$$

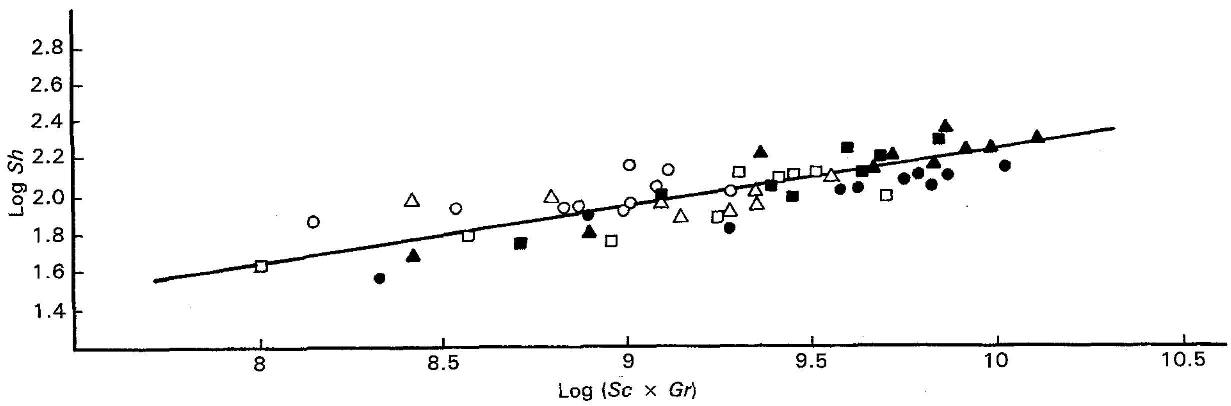

Fig. 4. Overall mass transfer correlation at vertical downward facing cavity. $CuSO_4$ concentration: (○) 0.027, (△) 0.05, (□) 0.075, (■) 0.1, (●) 0.131, and (▲) 0.189 M.

For horizontal cavities,

$$L_c = \frac{\pi dL + \pi d^2/4}{2(d+L)} \quad (5)$$

Figure 2 shows that the data at vertical cavities with an upward facing opening for the conditions $7 \times 10^7 < Sc \times Gr < 6.9 \times 10^9$ fit the equation

$$Sh = 0.257\,(Sc \times Gr)^{0.33} \quad (6)$$

with an average deviation of $\pm 5.8\%$.

The rate of mass transfer given by Equation 6 is the outcome of flow interaction between the upward facing cavity bottom and the vertical cavity wall. When considered separately, the flow at the cavity bottom is turbulent under the present conditions ($Sc \times Gr > 3 \times 10^7$) [16] while the flow at the cavity wall is laminar as found by Sedahmed and Shemilt [17] who studied free convection mass transfer at the outer surface of vertical annuli. Optical study of flow ascending from vertical open cavities (sides and base active) revealed the presence of oscillatory flow at the limiting current in the solution bulk [18]. It is probable that this oscillatory flow enhances the rate of mass transfer at the cavity wall. Previous heat transfer studies in vertical cylindrical open cavities [9] have shown that turbulent flow develops inside the cavity when *Ra* (based on cavity diameter) exceeds 4×10^6. Under the present conditions where *Ra* ranges from 2.55×10^8 to 2.34×10^{10} (based on cavity diameter), the turbulent nature of the flow as might be indicated by the exponent 0.33 of Equation 6, is consistent with previous heat transfer studies. Heat transfer data in vertical relatively short cylindrical cavities under turbulent flow conditions were correlated by the equation [7, 19].

$$Nu = 0.1\,Ra^{0.33} \quad (7)$$

The above equation was obtained for $60 > Pr > 200$ and $L/d = 7.5$, 11, 25; cavity radius was used as a characteristic length.

Figure 3 shows that the mass transfer data inside horizontal cavities for the conditions $1.3 \times 10^8 < Sc \times Gr < 1 \times 10^{10}$ fit the equation

$$Sh = 0.139\,(Sc \times Gr)^{0.33} \quad (8)$$

with an average deviation of $\pm 3.7\%$.

The exponent 0.33 in Equation 8, which may denote a turbulent flow mechanism inside the cavity, is consistent with the finding of Sedahmed and Shemilt [20] who studied free convection mass transfer inside a horizontal annulus. They correlated their data in

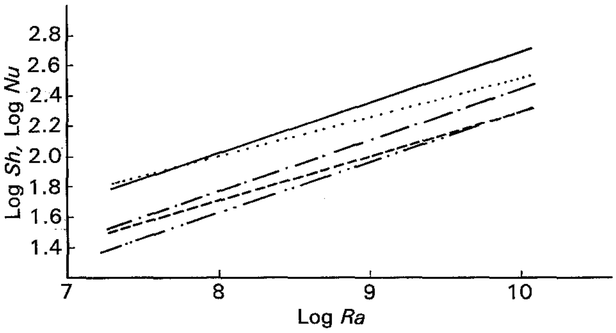

Fig. 5. Comparison between heat (HT) and mass transfer (MT) data in upward facing cavities of different geometry. (——) MT in vertical upward facing cylindrical cavity (present work). (·····) MT in vertical slender conical cavity [23]. (–·–·–) MT in upward facing hemispherical cavity [22]. (– – –) MT in upward facing cubical cavity [6]. (–··–··–) HT in upward facing cylindrical cavity [19].

the range $5 \times 10^7 < Sc \times Gr < 2.8 \times 10^{10}$ at the outer tube of the annulus by the equation

$$Sh = 0.1275\,(Sc \times Gr)^{0.33} \quad (9)$$

Annulus equivalent diameter was used as a characteristic length. Flow visualization by Liu *et al.* [21], who studied free convection heat transfer in horizontal annuli using silicone oil ($Pr > 2000$), found that at high $Pr \times Gr$ ($> 10^6$) oscillatory flow sets in, whose frequency and amplitude increases with *Gr*. The 0.33 exponent of Equation 8 shows that the turbulent flow inside the cavity overshadows the laminar flow effect at the vertical disc base [4]. Figure 4 shows that the mass transfer data inside vertical cavities with a downward facing mouth in the range $1 \times 10^8 < Sc \times Gr < 1.3 \times 10^{10}$ fit the equation

$$Sh = 0.187\,(Sc \times Gr)^{0.297} \quad (10)$$

with an average deviation of $\pm 5\%$.

The exponent 0.297 in Equation 10 may denote unstable flow inside the cavity. At first sight this seems surprising in view of the fact that the flow at the vertical cavity wall is supposed to be laminar and the radial flow at the downward facing disc (cavity top) is weakly laminar [3]. It seems that by virtue of continuity, the upward flow at the cavity wall is reflected downward at the cavity centre when it strikes the cavity top; this downward flow is augmented by the downward flow resulting from anode dissolution at the cavity centre. The presence of two opposing streams inside the cavity induces the formation of eddies which enhances the rate of mass transfer at the cavity wall. Also, it is probable that eddies are generated at the cavity top when the upward flow changes its direction to the horizontal direction and downward. The above speculation about the flow

Table 2. Previous mass transfer equations obtained for upward facing cavities of different geometries

Cavity geometry and reference	*Characteristic length*	*Equation*	Ra *range*
Hemispherical [22]	cavity diameter	$Sh = 0.143\,Ra^{0.33}$	6.5×10^7–1×10^{10}
Slender conical [23]	slant height	$Sh = 0.89\,Ra^{0.25}$	1.46×10^{10}–8.3×10^{11}
Cubical [6]	side length	$Sh = 0.259\,Ra^{0.3}$	1.37×10^9–6×10^{10}
Cylindrical (present work)	L_c [Equation 3]	$Sh = 0.257\,Ra^{0.33}$	7×10^7–6.9×10^9

field inside the cavity needs to be confirmed by optical techniques.

Figures 2 and 3 show that the data obtained by Somerscales and Kassemi lie below the present data, the difference increases with increasing $Sc \times Gr$. This discrepancy may be attributed mainly to the fact that Somerscales and Kassemi used an external anode while the present study uses an internal anode. Previous studies [10–12] on plating through holes under natural convection have shown that placing the anode outside the hole leads to non-uniformity in current distribution inside the hole; the current decreases along the hole as the distance from the hole mouth increases. In the case of cavities, it is probable that with an external anode the limiting current is reached only in the cavity mouth region, while the rest of the cavity is below the limiting current. On the other hand, placing the anode inside the cavity leads to a better potential distribution and, accordingly, to a better limiting current distribution and higher mass transfer coefficient than observed by Somerscales and Kassemi. Besides, placing the anode inside the cavity alters the hydrodynamic situation inside the cavity by virtue of the interaction between the cathodic convection and the anodic convection.

In view of the importance of cavities in the design of thermosyphons and the analogy between heat and mass transfer, it would be of interest to compare the present data with those obtained using other cavity geometries to shed light on the possible role played by cavity geometry on the rate of heat or mass transfer. Table 2 summarizes the results of previous studies on different upward facing cavity geometries. In order to compare the mass and heat transfer data of different geometries, the data were correlated using a characteristic length given by Equation 3. Figure 5 shows that (i) vertical upward facing cylindrical cavities give the highest rate of mass transfer followed by conical, hemispherical and cubical cavities, respectively. To explain the effect of cavity geometry on the rate of mass, a basic study on flow visualization in different cavities is needed. (ii) Fig. 5 also shows that for cylindrical cavities, the rate of mass transfer predicted from Equation 6 is higher than the rate of heat transfer predicted from Equation 7. The discrepancy may be attributed in part to the differences in Pr used in heat transfer and Sc used in mass transfer; heat transfer data were also obtained using deeper cavities. Previous heat transfer studies in vertical cylindrical cavities [7] have shown that the range of Pr and cavity aspect ratio crucially affect the nature of the flow inside the cavity and, hence, the rate of heat transfer.

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