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Mass transfer between a liquid and an array of discs in a cylindrical container. Part I: Pumped flow or rotation alone

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Abstract

This paper deals with average mass transfer between a liquid and both sides of discs arranged as baffles in a cylindrical container. The case of pumped flow alone through the stationary arrangement is first considered; the radial flow between the pairs of stationary discs is divergent and convergent successively. In other experiments, there is no pumped flow, but the discs are rotated between the stationary annular discs. The mass transfer coefficients are measured electrochemically for different geometrical and hydrodynamic conditions and the results are empirically correlated. The behaviour of corresponding surfaces involving a convergent or a divergent radial flow is discussed.

List of symbols

D	molecular diffusion coefficient ($m^2\,s^{-1}$)
e	hydraulic radius (m)
h	half-distance between two discs (m)
H	distance between two discs ($H = 2h$) (m)
$\bar{k}_d$	mean mass transfer coefficient ($m\,s^{-1}$)
N	speed of rotation (rpm)
Q_V	volumetric flowrate ($m^3\,s^{-1}$)
R_0	radius of the full disc (m)
R_1	inner radius of the annular disc (m)
R_2	inner radius of the cell (m)
Re_C	channel Reynolds number ($= Q_V/(H\nu)$)
Re_H	rotation Reynolds number based on $H (= \omega H^2/\nu)$
Re_m	channel Reynolds number ($= Q_V/(2\pi H\nu)$)
Re_R	rotation Reynolds number based on $R_2 (= \omega R_2^2/\nu)$
Ro	Rossby number ($= Re_C/Re_R$)
Sc	Schmidt number ($= \nu/D$)
$\overline{Sh}$	mean Sherwood number ($= 2h\bar{k}_d/D$)
Y	dimensionless term, Expression 1

Greek letters

β	exponent
ν	kinematic viscosity ($m^2\,s^{-1}$)
ρ	density ($kg\,m^{-3}$)
ω	angular velocity (s^{-1})

1. Introduction

A steady forced fluid flow through an assembly of annular and full discs in the cylindrical cell of Figure 1, undergoes an alternating succession of expansions and contractions. In other words, the radial flow between each pair of discs (one annular, the other full) is successively divergent (outflow) and convergent (inflow). If the fluid is a liquid, such a baffled system may find application as an electrochemical reactor and/or a heat exchanger. This paper first considers mass transfer between a flowing liquid and the different discs, maintained in a stationary configuration (Figure 1). The situation in which the liquid is not pumped, but the full discs are rotated, is also interesting for comparing the results with mass transfer correlations proposed for discs rotating in an infinite medium, or in a confined system.

The present electrochemical mass transfer study is the continuation of previous work [1, 2]. The case of two parallel discs, one rotating, the other stationary, located in a closed cylinder, has been previously investigated [1]. More recently, the case of the radial divergent liquid flow between two opposite parallel discs was considered [2]. These two situations, which were examined with cells having only two discs, can be seen as

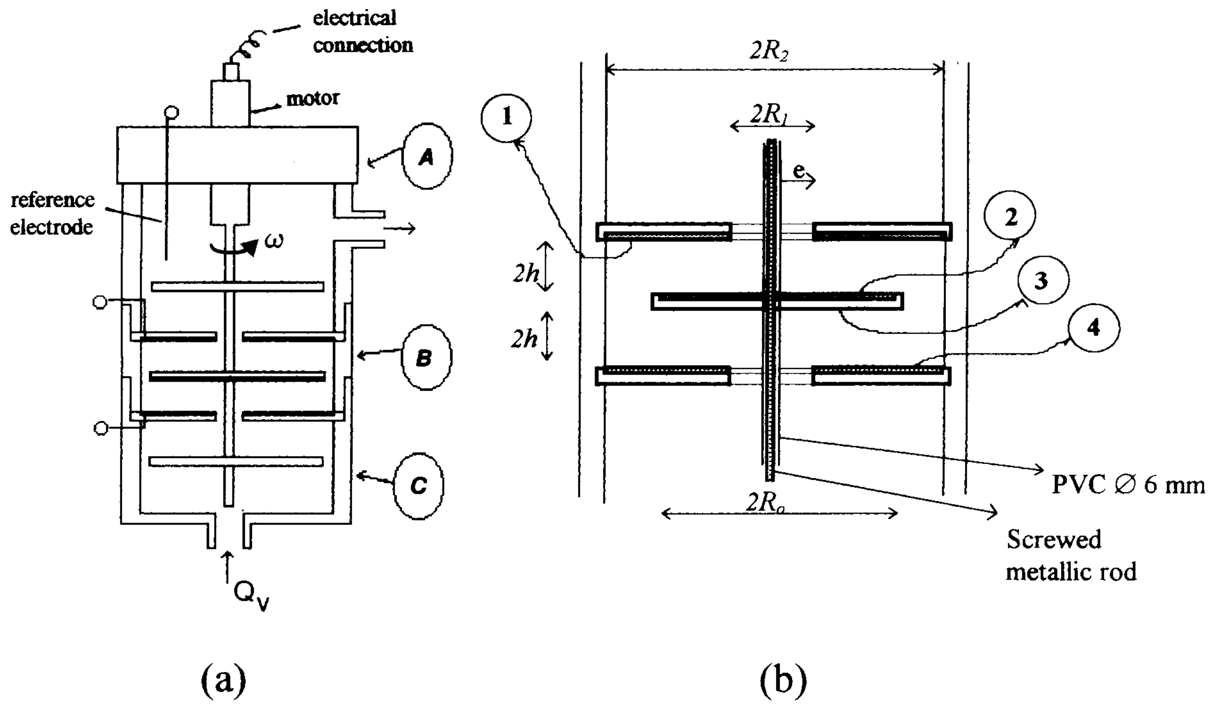


Fig. 1. Experimental cell: (a) general view; (b) view of the four surfaces in the modulus. Parameters: $2R_0 = 50$, 54 and 56 mm; $2R_1 = 12$, 16 and 20 mm; $2R_2 = 60$ mm; $2h = 2$, 4, 6 and 8 mm; $e = 3$, 5 and 7 mm.

limiting cases of the current problem (pumped flow through a stationary arrangement; no pumping but rotation of one class of discs). In view of the development of the '*pump cell*', Jansson et al. [3–6] carried out a few experiments without any disc rotation but with forced (convergent or divergent) radial flow. Although mass transfer between the liquid and the stator (an annular disc) was measured, the results were not correlated.

2. Experimental details

The cell (Figure 1) was made of Altuglas. It was assembled by screwing together the three main cylindrical (inner diameter $2R_2 = 60$ mm) parts A, B and C (Figure 1(a)). Three full discs of diameter $2R_0$ (50; 54 or 56 mm), 3 mm thick, were screwed around a metallic rod; they were made equidistant by small PVC cylindrical tubes (outer diameter 6 mm), the role of which was also to protect the metallic axis from any contact with the liquid. The distance $H = 2h$ between successive discs was 2, 4, 6 or 8 mm, while changing part B allowed variation of the distance between the annular discs.

A nickel disc inserted in one face of the PVC median full disc was then electrically connected with the metallic axis, thus allowing the latter to act as a current feeder to the nickel surface. This median disc (diameter $2R_0$) was set up with the nickel surface upwards or downwards, thus defining the transfer surface **2** or **3**, respectively (Figure 1(b)).

The diameter of the central hole in the annular disc was $2R_1$ (12; 16 or 20 mm) and the hydraulic diameter of the annular space defined between the disc and the cylindrical axial support was $2e$ (6; 10 or 14 mm). The nickel surfaces **1** and **4** were inserted in the annular discs which were maintained in place by screwing part B between parts A and C. The bottom of part C acted as an annular disc.

The mass transfer study was focussed on the modulus included between surfaces **1** and **4**. The liquid flow entering into this modulus through **4** is successively radial divergent between **3** and **4**, and radial convergent between **2** and **1**. The wall to liquid mass transfer coefficients, $\bar{k}_d$, were determined by the electrochemical method based on the reduction of ferricyanide ions in an alkaline medium [7].

When one of the surfaces **1** to **4** was used as the working electrode (cathode), the opposite nickel disc was the counter-electrode (anode); the SCE reference electrode was introduced through the top cover of part A. The nickel surfaces **1** to **4** were mechanically polished down to 0.25 μm. Before each category of experiments, they were activated by a short immersion (30 s) in a dilute (50 wt %) aqueous solution of HCl.

The electrolyte was a mixture of 0.005 M $Fe(CN)_6K_3$ and 0.05 M $Fe(CN)_6$ K_4 in aqueous 0.5 M NaOH, the physical properties of which are known from previous work. At 30 °C the kinematic viscosity and density are, respectively, $\nu = 0.94 \times 10^{-6}$ m^2 s^{-1} and $\rho = 1050$ kg m^{-3}, and the molecular diffusion coefficient of ferricyanide ions is $D = 8.8 \times 10^{-10}$m^2 s^{-1}; thus the Schmidt number was $Sc = \nu/D = 1070$.

The limiting diffusion current, I_L, corresponding to the maximum flux of the ferricyanide ions reacting at the cathode, and from which the mean mass transfer coefficient $\bar{k}_d$ was calculated, was determined with a three-electrode potentiostatic circuit using a Tacussel PRT 20-2 potenstiostat, a Tacussel Pilovit-NUM pilot unit and a Sefram-Servotrace register. The ferricyanide concentration was determined by amperometric titration with a cobalt salt, using a platinum rotating disc electrode.

The hydraulic circuit included the cell, a magnetic pump, rotameters and a stirred reservoir in which the liquid was maintained at 30 °C under a nitrogen atmosphere. In experiments with pumped flow, the liquid entered the cell at its bottom and left it laterally at the top; the volumetric flowrate, Q_v, was varied between 10 and 135 $dm^3 h^{-1}$. For the measurements with rotation only, the cell was first filled with liquid at 30 °C; then the discs were rotated and the limiting diffusion current was measured. The filling operation was frequently repeated; thus, the liquid temperature in the cell was kept at 30 °C. The speed of rotation $N = \omega/(2\pi)$ was varied from 50 to 100 rpm.

3. Results

3.1. *Pumped flow only*

Figure 2 shows, for given geometrical conditions, the variations of $\bar{k}_d$ with Q_v for surfaces **1** to **4**. Surfaces **1** and **2** (convergent flow) and surface **4** (divergent flow) show approximately the same behaviour, while the mass transfer is higher at surface **3** which receives the entering annular jet (Figure 2(d)). When $H = 2h$ is reduced from 8 mm to 2 mm (Figure 2(a) and (b)), all the other para- meters being constant, the pairs of surfaces **3/4** and **1/2** behave differently; surface **4** exhibits the smaller values of $\bar{k}_d$. On the other hand, when the hydraulic diameter $2e$ decreases from 14 mm to 6 mm (Figure 2(b) and (c)), the values of $\bar{k}_d$ at surface **3** are higher, as a consequence of a higher mean

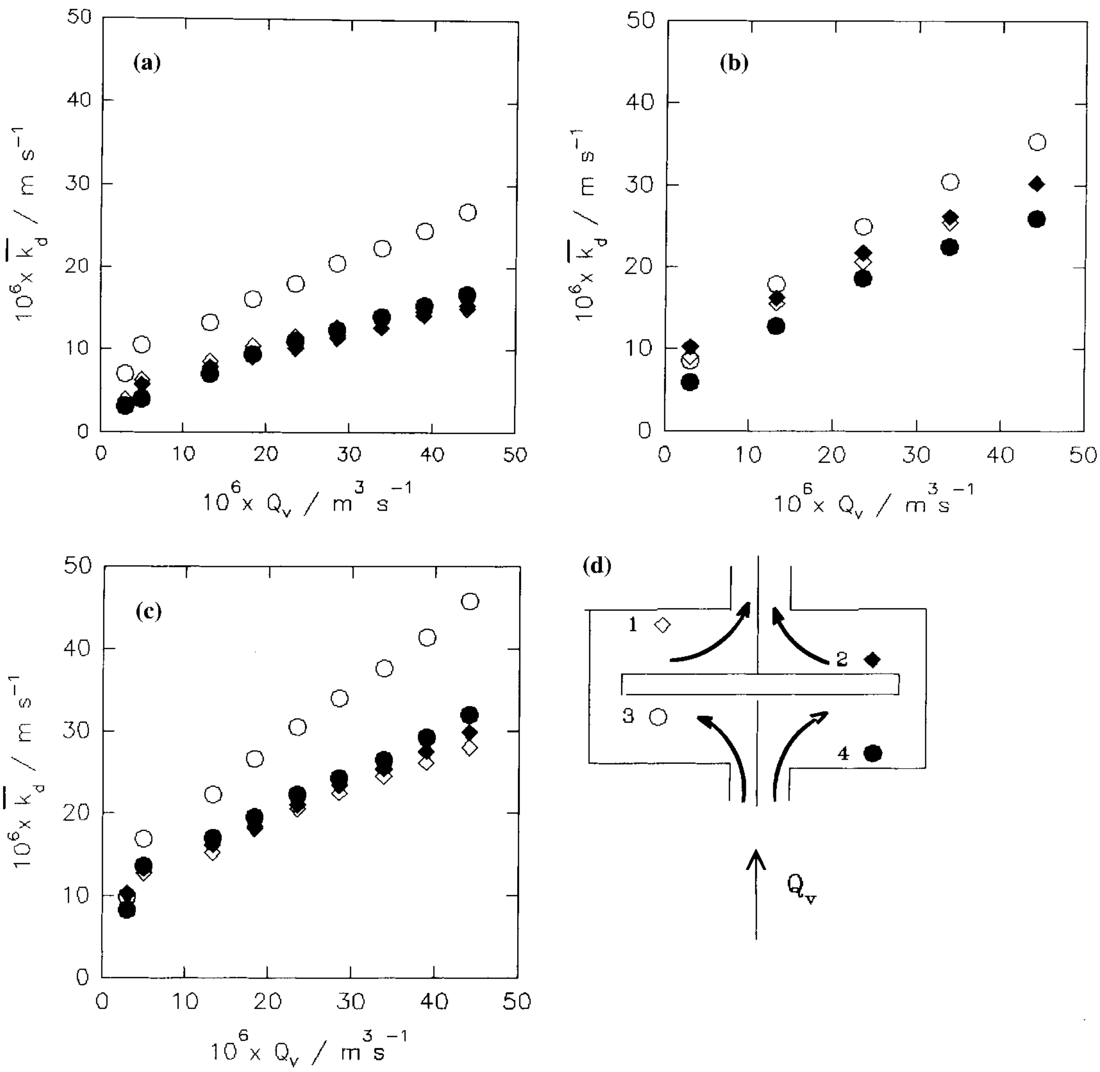


Fig. 2. Variations of $\bar{k}_d$ with Q_v for each surface. Influence of $2h$ and e. (a) $2h = 8$ mm, $2e = 14$ mm; (b) $2h = 2$ mm, $2e = 14$ mm; (c) $2h = 2$ mm, $2e = 6$ mm.

entrance jet velocity and, probably, owing to a modification of the flow over surface **3**.

3.1.1. *Divergent flow (surfaces **3** and **4**)*
Apart from a few differences (lateral confinement; presence of the supporting axial rod; ascending flow), the channel defined between surfaces **3** and **4** in the cell of Figure 1 is comparable with the cell of [8–12]. The experiments reveal that, at a given channel Reynolds number, Re_m, mass transfer at surfaces **3** and **4** is smaller than at discs D_I (lower, analogous to **3**) and D_S (upper, analogous to **4**) of [2], respectively; this could be due to the lateral wall effect and to the cylindrical supporting rod, which can both generate recirculating flows.

Figure 3 summarizes the method of obtaining the empirical mass transfer correlations. The mean Sherwood number, $\overline{Sh}$, varies as $Re_C^{0.5}$ (Figure 3(a)), where Re_C is a channel Reynolds number different from Re_m by a factor 2π, as verified in Figure 3(b) for surface **4**, at least for values of Re_C higher than those corresponding to the vertical dotted lines. On the other hand, $\overline{Sh}/Re_C^{0.5}$ varies as $[H^2/(R_2^2 - R_1^2)]^{\beta}$ with $\beta = 0.5$ for surface **4** (see Figure 3(c)) and $\beta = 0.67$ for surface **3** [13]. If it is accepted that the influence of Re_C is Re_C^{β}, the two dimensionless numbers Re_m and $H^2/(R_2^2 - R_1^2)$ can be joined by the following dimensionless parameter:

$$Y = \frac{2Re_m(2h)^2}{R_2^2 - R_1^2} \tag{1}$$

which was considered previously [2] for the empirical correlation of results. Kreith [11, 12] established and used the product $Y \times Sc$, thus attributing to Sc an influence different from $Sc^{1/3}$, contrary to boundary layer concepts and to [2] where the results were empirically correlated in the form $\overline{Sh} \times Sc^{1/3}$ against a power function of Y. The empirical correlations established for surfaces **3** and **4** are shown in Figure 4(a) and (b), respectively.

3.1.2. *Convergent flow (surfaces **1** and **2**)*
There is an annular distribution of the liquid in the space defined between surfaces **1** and **2**, with a normal impingement on surface **1**; then, the liquid converges towards the exit around the supporting axial rod. The empirical correlations describing the mass transfer results at surfaces **1** and **2** are shown in Figure 4(c) and (d), respectively. It appears that the influence of the term Y is as $Y^{0.5}$ for the two surfaces.

The empirical correlations established for the average mass transfer to surfaces **1** to **4** are summarized in Table 1, together with their respective domains of validity.

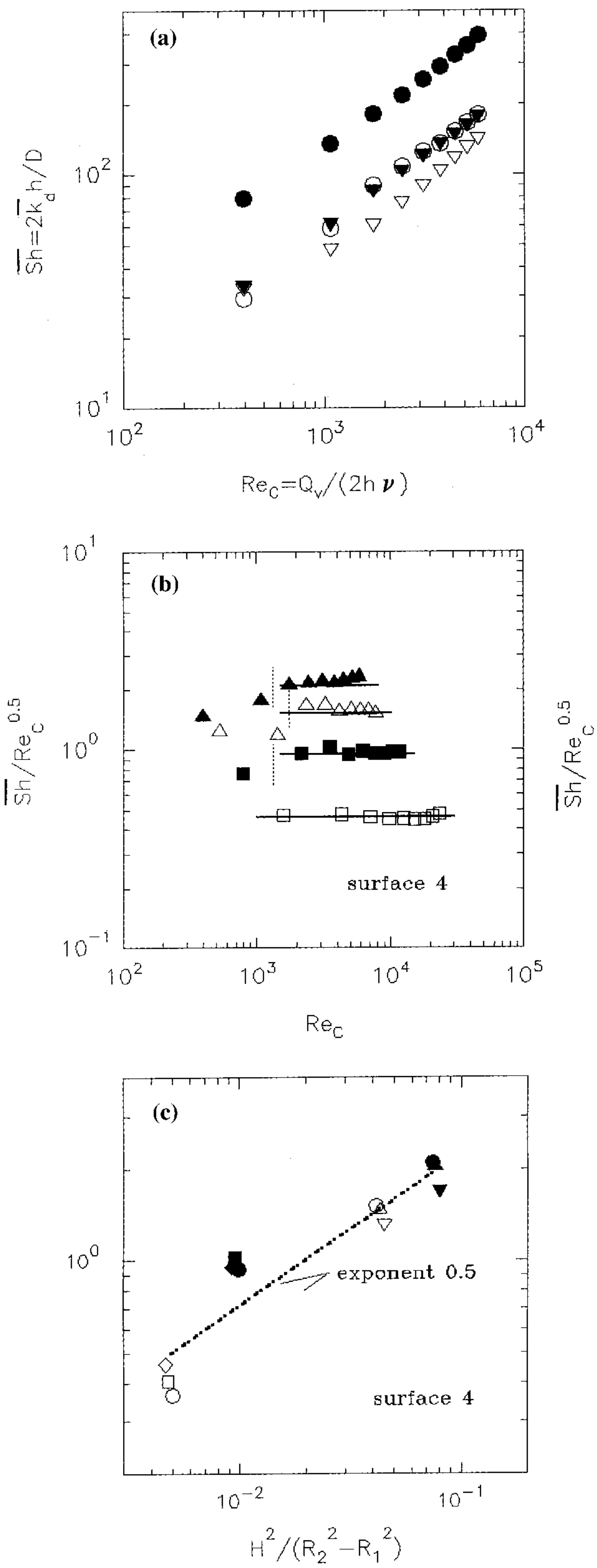


Fig. 3. Empirical analysis of results ($Q_v \neq 0$; $\omega = 0$): (a) for the four surfaces and $2h = 8$ mm; (b) for $R_2 = 27$ mm and $R_1 = 6$ mm. Surfaces in (a): (▼) **1**, (▽) **2**, (●) **3** and (○) **4**. Value of $2h$ in (b): (□) 2, (■) 4, (△) 6 and (▲) 8 mm.

3.2. *Rotation only*

In [1], empirical correlations were proposed for mass transfer at the surfaces of two opposite discs, one rotating, in a closed cylinder, particularly for the case where the two discs had approximately the same diameter. Mass transfer experiments were undertaken in order to see if the influence on mass transfer of the disc rotation alone in the cell of Figure 1 could be

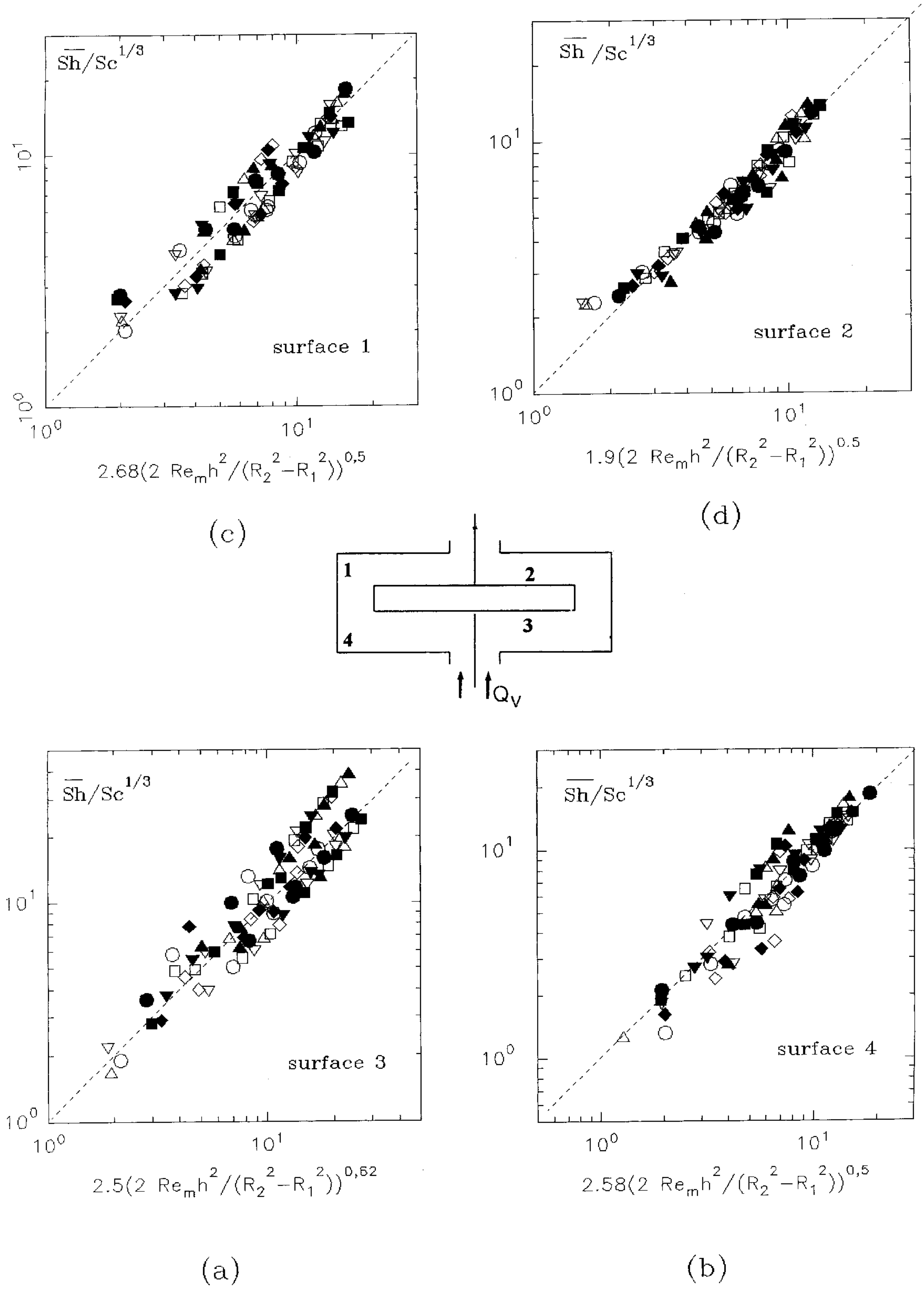
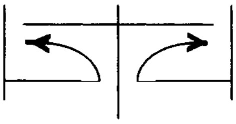
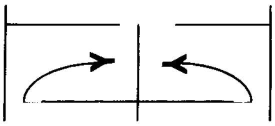


Fig. 4. Empirical correlations for the four surfaces (pumped flow only).

different than that in [1], owing to a few geometrical details (annular fixed disc; rotating cylindrical rod). The experimental parameters were varied as follows: R_2 (from 0.0025 to 0.028 m), $H = 2h$ (from 4 to 8 mm), then $2h/R_2$ (from 0.14 to 0.32), and the speed of rotation N (from 50 to 1000 rpm). The final empirical correlations are given graphically (Figure 5) together with their domains of validity. In these correlations, Re_R is a rotation Reynolds number.

It can be observed that: (i) for surfaces **1** and **4**, $\overline{Sh}$ is proportional to $\omega^{1/2}$, or approximately so, as it was observed in [1] for the stationary disc; and (ii) $\overline{Sh}$ is

Table 1. Empirical correlations obtained for surfaces **1** to **4** in the presence of pumped flow only

Type of flow	Surface	Correlation	Domain of validity
	3	$\frac{\overline{Sh}}{Sc^{1/3}} = 2.5\left(\frac{2Re_m h^2}{R_2^2 - R_1^2}\right)^{0.62}$ $r^2 = 0.98$	$63.32 \le Re_m \le 3.7 \times 10^3$ $0.0717 \le 2h/R_2 \le 0.319$
divergent (outflow)	4	$\frac{\overline{Sh}}{Sc^{1/3}} = 2.58\left(\frac{2Re_m h^2}{R_2^2 - R_1^2}\right)^{0.5}$ $r^2 = 0.98$	$63.32 \le Re_m \le 3.7 \times 10^3$ $0.066 \le 2h/R_2 \le 0.266$
	1	$\frac{\overline{Sh}}{Sc^{1/3}} = 2.68\left(\frac{2Re_m h^2}{R_2^2 - R_1^2}\right)^{0.5}$ $r^2 = 0.98$	$63.32 \le Re_m \le 3.7 \times 10^3$ $0.066 \le 2h/R_2 \le 0.266$
convergent (inflow)	2	$\frac{\overline{Sh}}{Sc^{1/3}} = 1.9\left(\frac{2Re_m h^2}{R_2^2 - R_1^2}\right)^{0.5}$ $r^2 = 0.98$	$63.32 \le Re_m \le 3.7 \times 10^3$ $0.0717 \le 2h/R_2 \le 0.319$

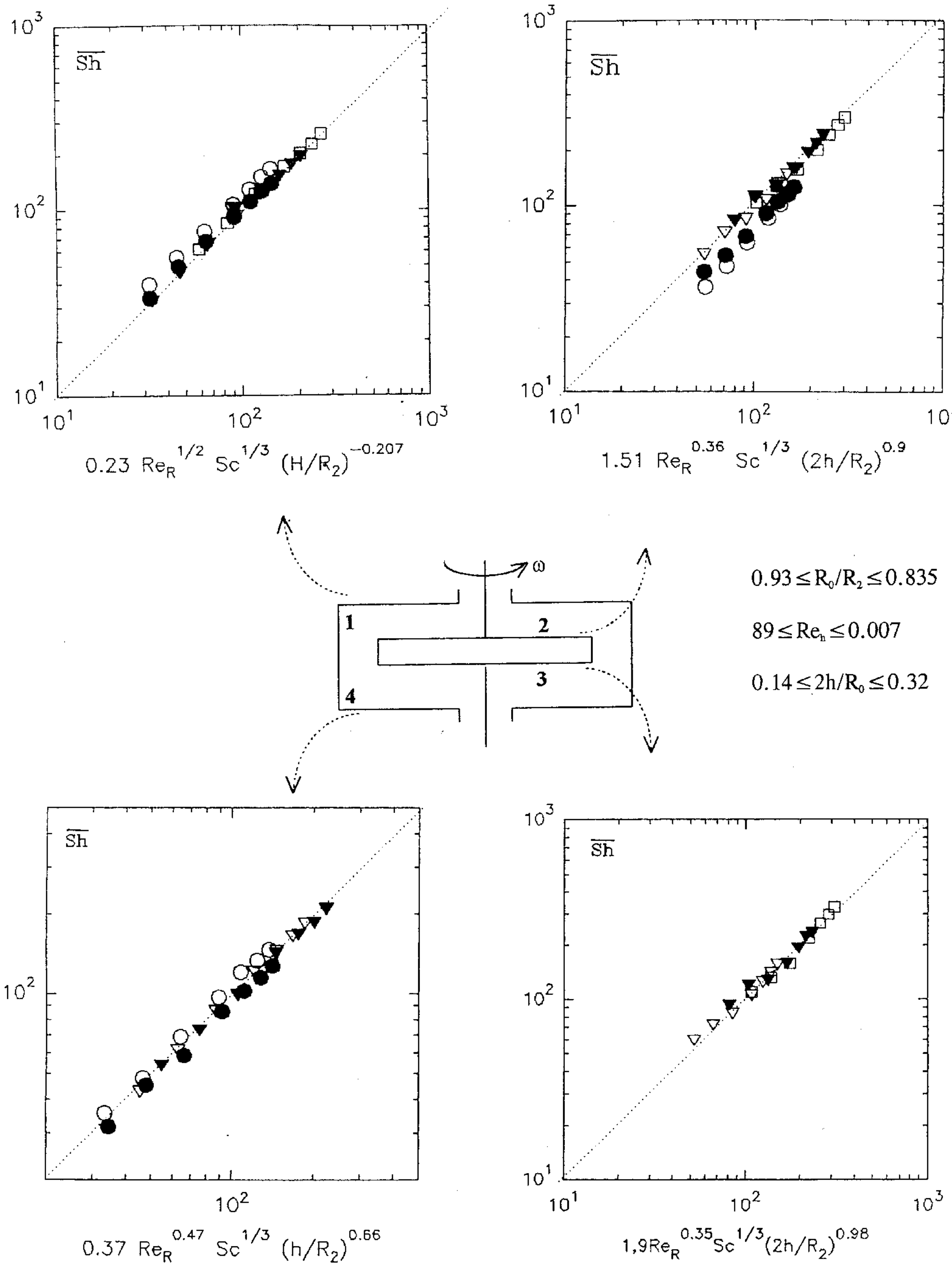


Fig. 5. Empirical correlations of the mass transfer results at the four surfaces (rotation only).

proportional to $\omega^{0.35}$ for the two sides of the rotating disc (surfaces **2** and **3**), instead of $\omega^{1/2}$ for a disc rotating in a cylinder [1], or in an infinite medium [14]. This difference is probably due to the presence of the supporting cylindrical rod, the rotation of which generates rotation of the liquid and modifies the velocity component normal to the rotating disc.

4. Discussion of the results

4.1. *Pumped flow only*

The results corresponding to the outflow channel have been compared: (i) for surface **3**, with the theoretical and/or empirical correlations of Kreith [9–11] (Fig-

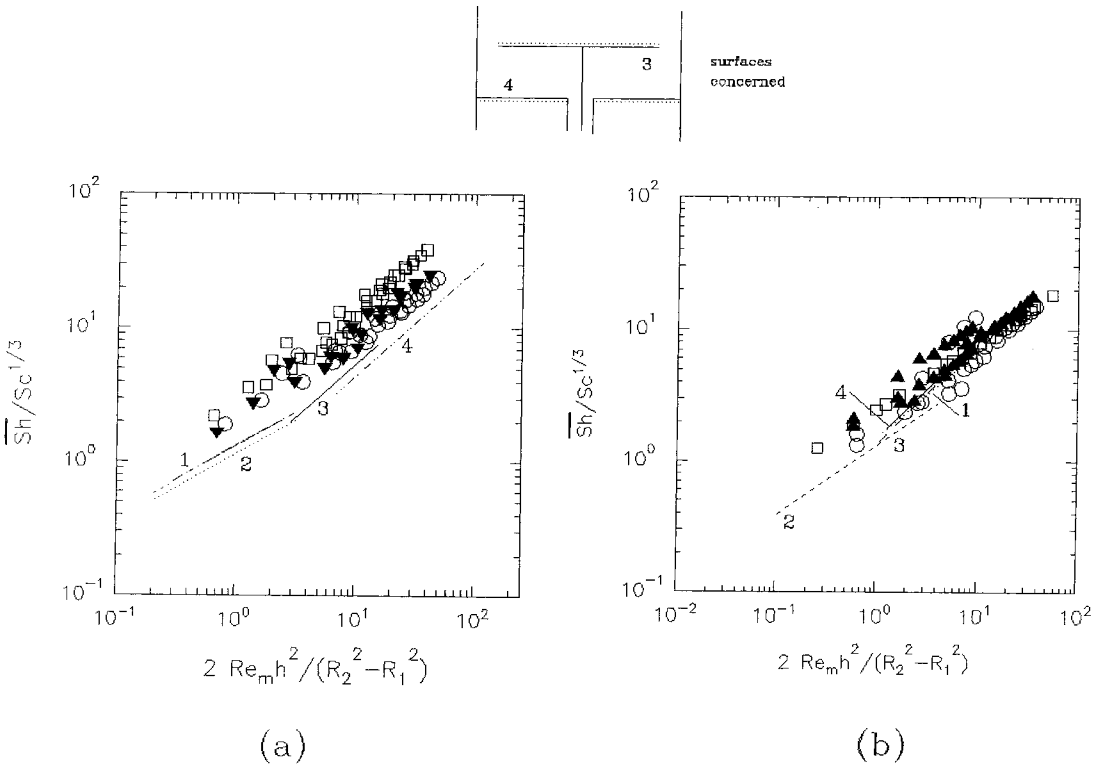


Fig. 6. Comparison with the literature for surfaces in the divergent flow (pumped flow alone): (a) surface **3**; (b) surface **4**. Lines in (a): (1) Kreith, theoretical [9]; (2) Kreith, experimental (laminar) [11]; (3) Kreith, experimental (turbulent) [11]; Kreith [10]. Lines in (b): (1) Jansson [5]; (2) Ashworth [3]; (3) Groroghchian [4]; (4) Ashworth [3].

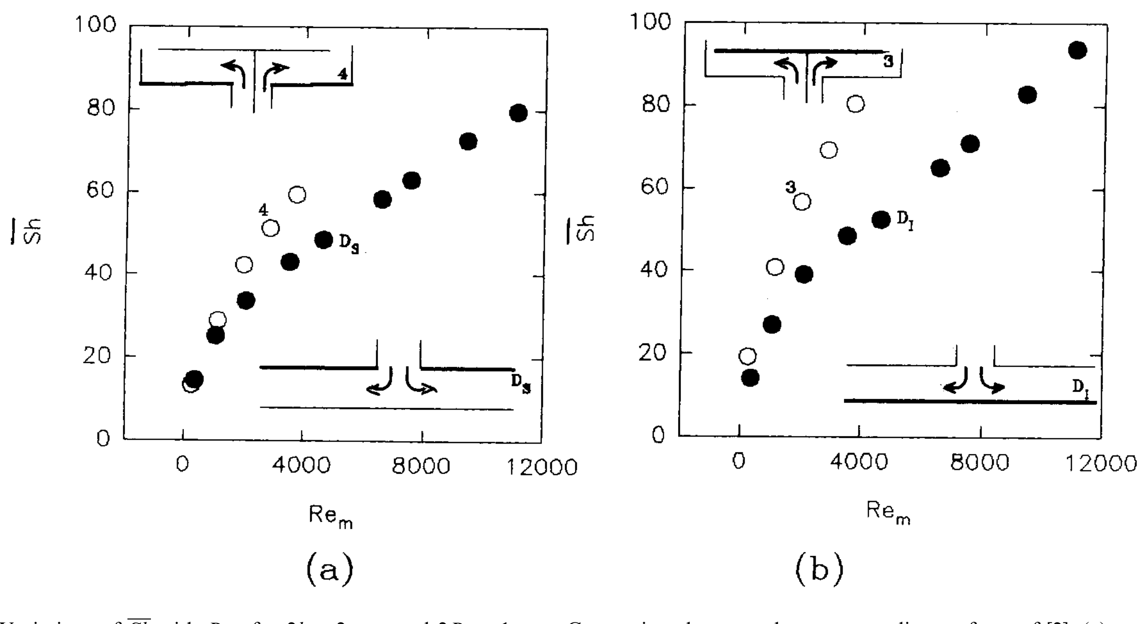


Fig. 7. Variations of $\overline{Sh}$ with Re_m for $2h = 2$ mm and $2R_1 = 1$ mm. Comparison between the corresponding surfaces of [2]: (a) annular disc; (b) full disc.

ure 6(a)); and (ii) for surface **4**, with the correlations established by the group of Jansson [3–6] or by the current authors from the results of his group (Figure 6(b)). A satisfactory agreement was achieved in both cases.

As stated above, surfaces **3** and **4** are comparable with discs D_I (lower) and D_S (upper), respectively, of [2], except for the presence of a supporting rod and the existence of lateral confinement. Figure 7(a) compares the behaviour of surface **4** and disc D_s and Figure 7(b) that of surface **3** and disc D_I for given geometric conditions $(2h; 2R_1)$. The diameters of the transfer surfaces are not the same in both works, but the small gap thickness (1 mm) makes this parameter negligible (flow rapidly established). It appears that, except at low Reynolds numbers, $\overline{Sh}$ is always higher when there is lateral confinement (surfaces **3** and **4**), probably because wall effects exist. Also, the presence of a cylindrical supporting rod may generate small recirculations in the region of its junction with the supported disc.

For the convergent (or inflow) channel, results obtained with surface **1** can be compared with those of Jansson et al. [2, 5] previously considered in [2]. However, such a comparison is not strictly correct because, as **1** and **4** were electrically connected in [2, 5], the value obtained for the mass transfer coefficient was an arithmetic mean value of the true mass transfer coefficients at surfaces **1** and **4**, respectively. It is obvious that such experimental conditions neglect a possible difference in the behaviour of these two surfaces and cannot be accepted, at least for several geometrical situations. This may explain the deviations observed in Figure 8 at low values of the abscissa. To support this comment, Figure 9 compares, for $2h = 2\,\text{mm}$ and given values of R_0, R_1, R_2, the behaviour of surfaces **1** and **4** (Figure 9(a)) and that of surfaces **2** and **3** (Figure 9(b)), in the form of $\overline{Sh}$ against Re_m. Even for such a very small

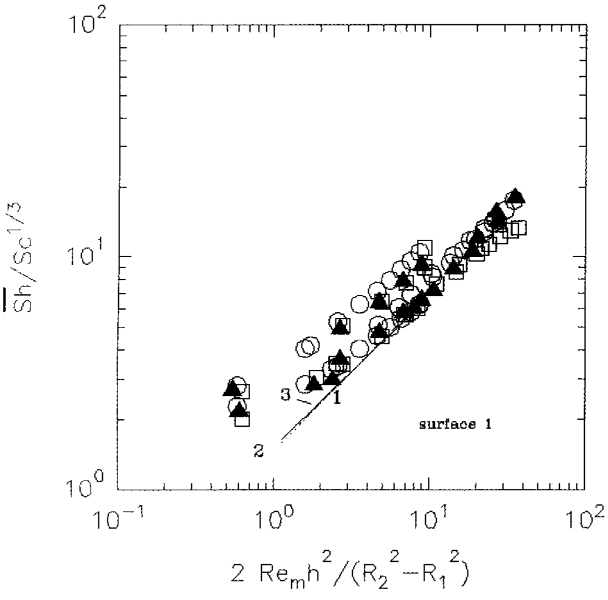


Fig. 8. Results obtained with surface **1** (pumped flow only. Comparison with the literature. Lines: (1) Jansson [5]; (2) Groroghchian [2]; (3) Groroghchian [2].

value of $2h$, it is clear that a given surface behaves distinctly if it is located in a convergent or in a divergent flow. It is noticeable that, due to the impingement of the entering jet on surface **3**, the mass transfer coefficient is higher for this surface.

4.2. *Rotation of the discs*

The empirical correlations shown in Figure 5 are compared Figure 10 with the correlations established in [1]. Figure 10(a) corresponds to the rotating disc in a convergent (surface **2**) or in a divergent (surface **3**) flow; Figure 10(b) corresponds to the stationary discs (surfaces **1** and **4**) in the same two flows. A quantitative agreement exists for the rotating disc (Figure 10(a)), in

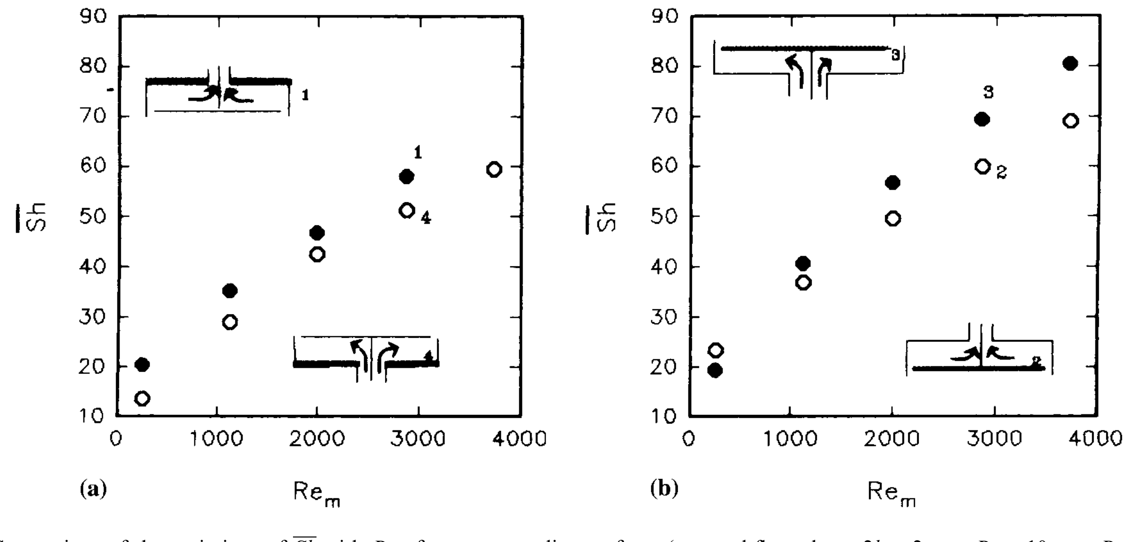


Fig. 9. Comparison of the variations of $\overline{Sh}$ with Re_m for corresponding surfaces (pumped flow alone; $2h = 2\,\text{mm}$; $R_1 = 10\,\text{mm}$; $R_2 = 25\,\text{mm}$): (a) surfaces **1** and **4**; (b) surfaces **2** and **3**.

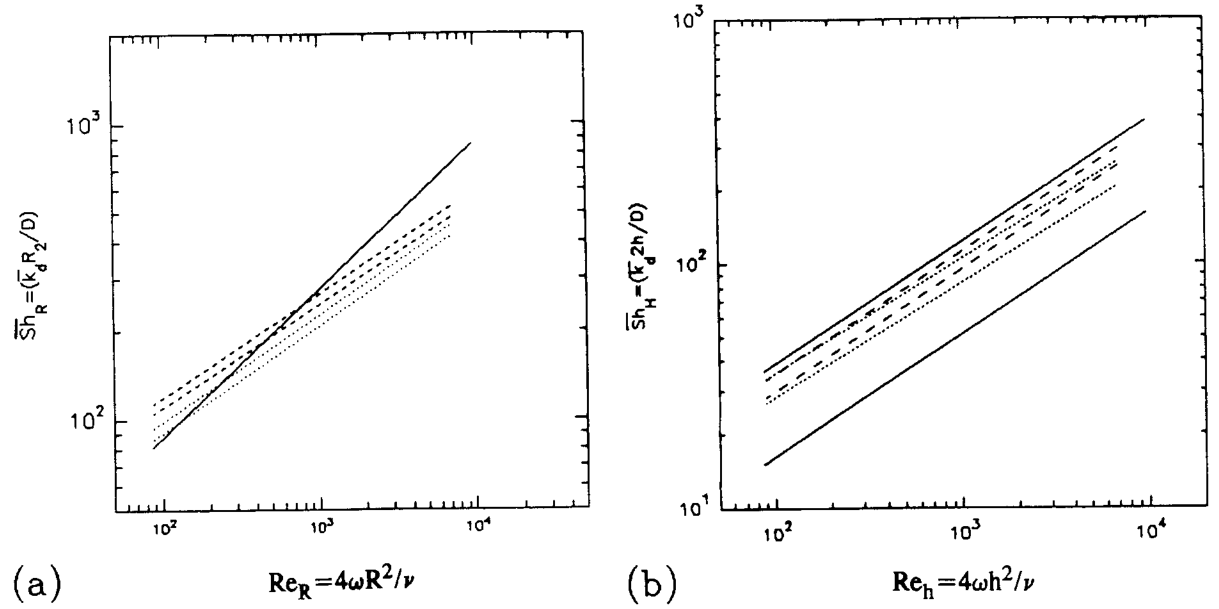


Fig. 10. Results obtained with rotation alone: Comparison with the results published in [1] for mass transfer to the discs in a closed cylinder: (a) rotating disc; (b) stationary disc. Key: (——) from [1]; (– – ––) in flow region; (······) outflow region.

spite of a difference in the exponent of Re_R, as mentioned previously. Concerning the annular stationary discs (Figure 10(b)), the correlations obtained (dotted lines) are localized within the domain of validity of the correlation established in [2], a domain which is delimited by two extreme values of $2h/R_2$. This localization may explain the fact that the flow near the stationary annular disc is not altered by the rotation of the cylindrical rod. Finally, and at least in the present geometrical situations, only the mass transfer at the rotating disc is modified, and lowered, by the presence of such a rod.

5. Conclusions

The mass transfer behaviour of four discs in an assembly was examined experimentally in the two extreme cases of pumped flow between stationary discs only and of flow resulting from the rotation of the discs only.

In the case of pumped flow only, the flow is convergent or divergent between each pair of surfaces, and an effect of the container walls may exist. The average mass transfer at the stationary annular discs, through the central hole of which the liquid is flowing, is nearly independent of the radial flow direction (outflow or inflow). This is not true for the stationary full discs. Satisfactory empirical correlations were obtained for each of the four surfaces.

The results obtained in the second extreme case (only rotation of the full discs) show that mass transfer to any of the two sides of the rotating disc is not as dependent on the rotation velocity as at the stationary disk, probably because the presence of a rotating supporting rod. A further experimental study with the same cell will combine pumped flow and rotation of the full discs, a situation which renders the problem much more complex. The results will be presented in Part II.

Acknowledgements

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References

1. E.B. Cavalcanti and F. Cœuret, *J. Appl. Electrochem.* **26** (1996) 655.
2. E.B. Cavalcanti and F. Cœuret, *J. Appl. Electrochem.* **28** (1998) 1419.
3. G.A. Ashworth and R.E.W. Jansson, *Electrochim. Acta* **22** (1977) 1295.
4. J. Ghoroghchian, R.E.W. Jansson and R.J. Marshall, *Electrochim. Acta* **24** (1979) 1175.
5. R.E.W. Jansson and R.J. Marshall, *The Chemical Engineer* (Nov/Dec 1976) 769.
6. G.A. Ashworth, 'Electrochemical Capillary Gap and Pump Cells', PhD thesis, University of Southampton, Great Britain (1977).
7. J.R. Selman and C.W. Tobias, 'Mass Transfer Measurements by the Limiting Current Technique', in *Adv. Chem. Eng.* (Academic Press, New York) **10** (1978) 212.
8. F. Kreith, E. Doughman and H. Kozlowski, *J. Heat Transf.* (May 1963) 153.
9. E. Bakke, J.F. Kreider and F. Kreith, *J. Fluid Mech.* **58** (Part 2) (1973) 209.
10. F. Kreith, J.H. Talyor and J.P. Chong, *J. Heat Transf.* (May 1959) 95.
11. F. Kreith, *Int. J. Heat Mass Transf.* **9** (1966) 265.
12. F. Kreith, 'Transfert de Chaleur dans le Cas d'un Ecoulement Radial entre Deux Disques Parallèles', Thesis, University of Paris, France (1965).
13. E.B. Cavalcanti, 'Transfert de Matièere aux Electrodes d'une Cellule Combinant Ecoulement Forcé et Rotation', Thesis, University of Rennes1, Rennes, France (1997)
14. V.G. Levich, 'Physicochemical Hydrodynamics', (Prentice Hall, New York, 1962).