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Overall mass transfer in swirling decaying flow in annular electrochemical cells

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Mass transfer coefficients between an electrolyte solution and the inner cylinder of an annulus were determined experimentally, using the electrochemical technique, for both laminar and turbulent swirling flows of a liquid induced by means of a tangential inlet in the annular gap. The average mass transfer coefficients were determined as a function of the axial distance from the entrance, for various diameters of the inlet duct and thicknesses of the annular space, for a Reynolds number range of 100 to 5900. Enhancement of mass transfer up to 400% was achieved in comparison to that obtained in fully developed axial flow. Correlations of the experimental data, taking into account the geometrical and hydrodynamic parameters influencing the overall mass transfer, are presented.

Nomenclature

A	Cathode surface area
C	Potassium ferricyanide concentration
D	Ferricyanide ion diffusion coefficient
d	Tube diameter
$e = R_2 - R_1$	Thickness of the annular gap
ERR	Mean square error between experimental and calculated data
F	Faraday's constant
$f(N)$	Function of the geometrical parameters
h	Local heat transfer coefficient
I_l	Limiting diffusional current
k	Mass transfer coefficient
L, L_1, L_2	Axial distances from the inlet
$L/2e$	Reduced axial coordinate
$N = R_1/R_2$	Radii ratio of the annular gap
n	Number of electrons involved in the electrochemical reaction
$Nu_x = hx/\lambda$	Local Nusselt number
Q	Volumic flow rate
R_1	External radius of the inner cylinder
R_2	Internal radius of the outer cylinder
$Re = 2eU/\nu$	Reynolds number
$Re_x = Ux/\nu$	Local Reynolds number
$S_0 = U_\phi/U = \frac{4(1-N)}{(1+N)}$	Initial swirl intensity
$Sc = \nu/D$	Schmidt number
$Sh = 2ek/D$	Sherwood number obtained in swirling flow
$Sh_a = 2ek/D$	Sherwood number obtained in fully developed axial flow
Sh_x	Local Sherwood number
U	Mean axial velocity in the annular gap
U_ϕ	Axial velocity in the inlet duct
x	Axial coordinate

Greek letters

$\alpha, \beta, \varepsilon, \xi, \sigma$	Correlation parameters
ϕ	Diameter of the tangential inlet
λ	Thermal conductivity
ν	Kinematic viscosity of the electrolyte
ϱ	Density of the working solution

1. Introduction

Swirl results from the application of a tangential component to the main axisymmetric axial movement of a fluid. From a hydrodynamic point of view, such flows can be classified into two different types according to the technique used to achieve the rotation of the gas or the liquid [1]:

1. Continuous swirl, which persists along the tube or annular space, can be induced by twisted tapes [2] or coiled wires of varying pitch, helix angle and wire diameter [3]. Such inserted elements generate flows which maintain their characteristics (angle of swirl, tangential velocity, . . .) over the entire length of the cell.
2. In the second kind of swirling flow, the rotation

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is achieved at the inlet section by means of inserted tapes [4] or tangential inlets [5, 6]. This kind of arrangement produces decaying or damped swirling flow and its properties vary with axial distance from the entrance.

Because of its simple design and easy maintenance (no moving parts or inserts, . . .), swirling flow induced by a tangential inlet is useful in several engineering applications such as enhancement of heat transfer in shell and tube heat exchangers without a significant corresponding increase in pressure drop [7], improvement of electrochemical metal removal from dilute solutions [8, 9] etc.

Despite the potential applications, both laminar and turbulent decaying swirling flows are little known phenomena. Nevertheless, several significant studies have been reported in the literature, most of which deal with swirling flows in pipes, only a few articles about annular gaps being available.

The main property of swirling flows induced at the inlet of any apparatus is the decay of the swirl intensity along the flow path because of the decrease in tangential velocity. Most investigators have described this decay using a dimensionless criterion S, the swirl number, defined as the ratio of the angular momentum to the linear momentum flux. Hay and West [10] have found that S decreases with the axial distance L from the entry section of a pipe swirling flow of air induced by various tangential inlets. At low Reynolds numbers, they correlated their experimental data by means of an empirical relation $S = a \times \exp[-bL/d]$ where d is the pipe diameter. Both a and b depend on the ratio between the inlet and the tube sections.

This experimental result was confirmed by theoretical work [11, 12] for incompressible flow in the laminar regime. Such a decrease in the swirl number also occurs in turbulent swirling flow [4, 13, 14].

The aim of our study was to measure the mass transfer betweeen a swirling liquid and the inner cylinder of an annular gap. All the studies dealing with this topic showed up the increase in heat or mass transfer by swirling flows. Sharma *et al.* [15] have investigated the overall heat transfer coefficients between the inner wall of a tube and water in swirling flow induced by two opposite tangential inlets. They have found that the rate of heat transfer is three to four times as high as for axial flow. For helices inserted along the entire length of a tube, Burfoot and Rice [2] have reported that the increase in heat transfer coefficients can be as large as a factor of three using a 'kinetic mixer' made of alternate clockwise and anticlockwise twists. Hong and Bergles [16] established an empirical correlation expressing the decrease in a swirling liquid flow, induced by twisted tapes, in relation to axial flow.

Experimental and theoretical work dealing with transfer phenomena in annular swirling flows is very scarce, but it seems that, as in tubes, the rate of both heat and mass transfers increases with the swirl intensity. Shoukry and Shemilt [5] have investigated mass transfer enhancement for annular pipes subjected to entrance turbulent swirling flow induced by a tangential inlet of different diameters for a range of Reynolds numbers from 2000 to 15 000. The rate of mass transfer, measured by means of the same electrochemical technique as the one used in the present work, was found to decrease along the flow path to become the same as that obtained for developed axial flow, because of the swirl decay. Mass transfer enhancement was found to be at a maximum when the diameter of the inlet duct was equal to the thickness of the annular gap.

The purpose of this paper is to present experimental mass transfer results in concentric cylindrical cells under the combined effects of axial and tangential flow at the inlet of an annulus. The electrochemical method was used to determine the average mass transfer between the liquid and the annular core at different distances from the entrance and for various inlet diameters and thicknesses of the annular gap.

2. Experimental

2.1. *Flow apparatus*

A schematic flow diagram is shown in Fig. 1. The annular test section was made of an Altuglass outer tube, 390 mm long and with a 25 mm internal radius R_2. The inner cylinder consisted of three nickel active parts 100 mm long, insulated from each other with PVC elements. One of these sections acted as the cathode, whereas the other two were used as the anode. So the mass transfer was investigated for three different mean axial positions from the inlet: 50, 160 and 270 mm (see Fig. 2). Experiments were made for three internal cylinders of radius R_1 equal to 18, 10.5 and 8 mm. The swirl motion of the liquid was induced by means of a tangential inlet equal in diameter ϕ (ϕ = 7, 14.5 and 17 mm) to the thickness e ($e = R_2 - R_1$) of the annular gap.

Note that by using such an experimental arrangement the overall mass transfer coefficient was not

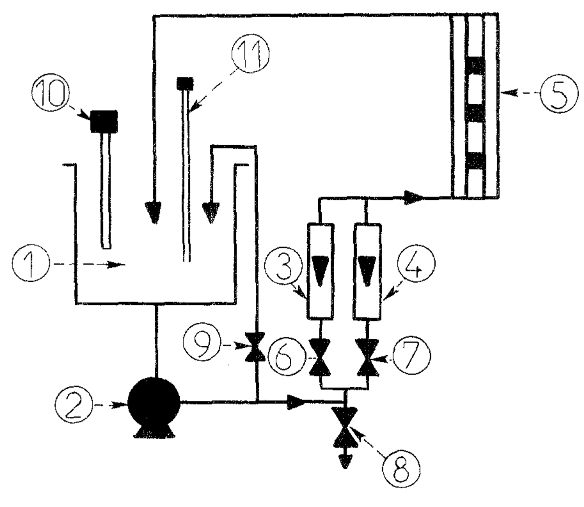

Fig. 1. A general view of the experimental apparatus: (1) Tank; (2) Centrifugal pump; (3) and (4) Flowmeters; (5) Electrochemical cell; (6) and (7) Flow adjustment gates: (8) Drain pipe; (9) By-pass; (10) Temperature regulation; (11) Nitrogen injection.

measured from the entrance into the cell for both upper positions of the cathode. Actually, the diffusional boundary layer only builds up from the time the fluid gets to the leading edge of the cathode, not as soon as it flows into the cell.

From the tank (see Fig. 1), the solution, which was maintained at the constant temperature of 30° C, flowed through a centrifugal pump to one of two rotameters where the volumic flow rate was measured in a range 20 to 1000 $dm^3 h^{-1}$. Then, the electrolyte entered the annular test cell tangentially and was recycled to the tank by means of a tangential outlet.

2.2. *Electrochemical method*

The experimental determination of the overall mass transfer coefficient between the electrolyte and the different active sections of the annular core was performed using a polarographic method. The electrolyte was an aqueous solution of 2×10^{-3} M potassium ferricyanide, 5×10^{-2} M potassium ferrocyanide and 0.5 M sodium hydroxide. At 30° C, the physical properties of this solution are: density $\varrho = 1028\, kg\, m^{-3}$, kinematic viscosity $\nu = 8.73 \times 10^{-7}\, m^2 s^{-1}$ and diffusion coefficient of ferricyanide ions in the electrolyte $D = 6.95 \times 10^{-10}\, m^2 s^{-1}$. The mass transfer coefficient k was obtained by means of diffusion controlled reduction of the ferricyanide ions on the cathode. Under these conditions, k is calcuated using the expression

$$k = I_l/(nFAC) \qquad (1)$$

where I_l is the limiting current, n the number of electrons involved in the electrochemical reaction, F Faraday's constant, A the cathode surface area and C the potassium ferricyanide concentration in the solution.

In the experimental arrangement, where the cathode was placed downstream from the anodes, the increase in the potassium ferricyanide concentration, due to the anodic reaction, at the leading edge of the cathode is smaller than 0.6% and can be considered negligible.

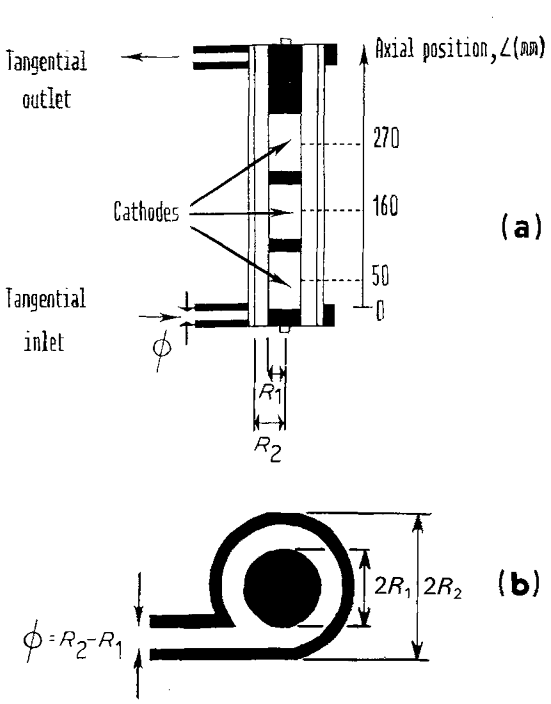

Fig. 2. The electrochemical cell: (a) a general view; (b) the tangential inlet.

3. Results

3.1. *Experimental domain*

The range in the experimental variables is tabulated below:

Volumic flow rate: $Q(dm^3 h^{-1})$	20–1000
Radius of the outer cylinder: R_2 (mm)	25
Schmidt number: $Sc = \nu/D$	1255
Reynolds number: $Re = 2eU/\nu$	
For R_1 = 18 mm and ϕ = 7 mm:	100–4400
For R_1 = 10.5 mm and ϕ = 14.5 mm:	120–4400
For R_1 = 8 mm and ϕ = 17 mm:	130–5900

3.2. *Infuence of the axial position*

In Fig. 3, we have reported our experimental results, obtained with the 7 mm tangential inlet and the 18 mm inner cylinder, in terms of Sherwood number Sh ($Sh = 2ek/D$) against Reynolds number Re for the three different cathodes positioned at $L/2e$ (reduced axial coordinate) equal to 3.57, 11.42 and 19.29 from the entrance. The experimental data shows that at a given Reynolds number the average mass transfer coefficient decreases with the increase in the axial distance of the active surface from the inlet section, which is due to decay of swirl along the flow path. This is in agreement with the decay of heat or mass transfer usually assumed in such a system, and especially with the investigation of Shoukry and Shemilt [5] in a similar apparatus. For $Re > 2000$, $Sh \propto Re^b$, with $b > 1.0$ (Fig. 3), for the three reduced axial positions of the cathode. This experimental fact is very important because it means that, for a given geometry, the space

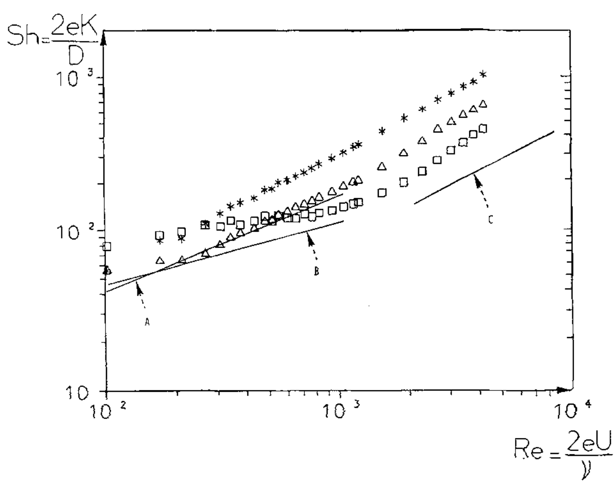

Fig. 3. Influence of the axial distance from the inlet on the mass transfer; comparison with developing and developed axial flow, for $N = 0.72$: $*$, $L/2e = 3.57$; $\triangle$, $L/2e = 11.42$; $\square$, $L/2e = 19.29$. Region A — Developing laminar axial flow in an annulus. Region B — Fully developed laminar axial flow in an annulus [18]. Region C — Fully developed turbulent axial flow in an annulus [19].

time yield of the electrochemical cell, which is proportional to k/Q [17], increases with Q. This result shows that the swirling flows may be of interest for electrochemical applications.

On Fig. 3, we have plotted the curve giving the Sherwood number obtained in the case of developing laminar axial flow in an annulus as a function of Reynolds number [17]. One can observe that for $Re < 1000$ the variation of the Sherwood number with Reynolds number is quite similar, $Sh \propto Re^{0.5}$, for the swirl flow and for the developing laminar axial flow. However, a further comparison will be made between mass transfer obtained in swirl flow and in fully developed laminar axial flow. This comparison is usual for swirling flows [5], particularly for swirling decaying flows, which tend to Poiseuille flow when the distance from the entrance is increased. Moreover, no single correlation exists for developing laminar axial flow in an annulus owing to the strong influence of the type of inlet.

The results obtained in fully developed axial flow in annuli are also plotted on Fig. 3 (from [18] for $Re < 1000$, and [19] for $Re > 2000$). Note that, for the three different locations of the cathode, the values of the mass transfer coefficients are greater than those obtained, for the same Reynolds number, in fully developed axial flow. This shows that the swirl is not completely decayed when the flow reaches the top of the cell.

In order to appreciate the mass transfer enhancement due to the swirling motion in an annular flow pipe, by comparison with that obtained in fully developed axial flow, we have plotted in Fig. 4 the ratio between Sh and Sh_a as a function of the reduced axial distance from the inlet ($L/2e$). Sh_a is the Sherwood number corresponding to the fully developed axial flow which is determined using the following correlations.

For $Re < 1000$:

Assuming a developed laminar velocity profile as soon as the flow enters the annular gap, Turitto [18] has shown that the average Sherwood number between two axial distances L_1 and L_2 can be calculated as follows

$$Sh_a = 1.00\,[2f(N)ReSce]^{1/3}\left[\frac{L_2^{2/3} - L_1^{2/3}}{L_2 - L_1}\right] \quad (2)$$

where $f(N)$ is a function of the radii ratio N ($N = R_1/R_2$) and is given by the expression

$$f(N) = \frac{2\left[-2N^2 + \dfrac{1 - N^2}{\ln(1/N)}\right]\left[\dfrac{1 - N}{N}\right]}{1 + N^2 - \left[\dfrac{1 - N^2}{\ln(1/N)}\right]} \quad (3)$$

For $Re > 2000$:

Assuming a linear velocity distribution in the region close to the wall, Ross and Wragg [19] have determined the following expression for the Sherwood number

$$Sh_a = 0.807\,Sc^{1/3}Re^{0.6}\gamma^{1/3}(2e)^{1/3}\frac{L_2^{2/3} - L_1^{2/3}}{L_2 - L_1} \quad (4)$$

with

$$\gamma = 0.046\left[\frac{1 - N}{1 - \delta^2}\right]^{0.2}\left[\frac{\delta^2 - N^2}{N(1 - \delta^2)}\right] \quad (5)$$

$$\delta = \left[\frac{1 - N^2}{2\ln(1/N)}\right]^{1/2} \quad (6)$$

Considering the observation mentioned above, diffusional boundary layer building up from the leading edge of the cathode, we have taken $L_1 = 0$ and $L_2 = 10$ cm for the three axial locations of the mass transfer surface.

Using Equations (2) and (4), we have reported our experimental data in Fig. 4 in terms of Sh/Sh_a against Re. For the three axial positions ($3.57 < L/2e < 19.29$), the enhancement of mass transfer is very significant, up to a factor of four. Like Shoukry and Shemilt [5], we have found that Sh/Sh_a decreases with $L/2e$ because of the decay of the swirl motion with the distance from the inlet section. When $L/2e$ increases, the swirl flow tends towards Poiseuille flow, thus Sh/Sh_a tends towards one.

On Fig. 4, we also notice that Sh/Sh_a, for a given axial position, increases with Re, both in laminar and turbulent flows, so the mass transfer coefficients in swirling flow increases more quickly with Re than in fully developed axial flow.

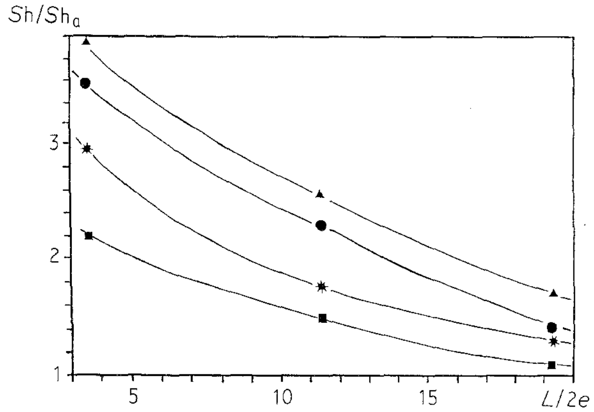

Fig. 4. Mass transfer enhancement in terms of Sh/Sh_a: ■ $Re = 500$, ✱ $Re = 1000$, ● $Re = 2500$, ▲ $Re = 4000$.

3.3. *Influence of the initial swirl intensity*

The swirl intensity is often indicated by a Swirl number S which may be calculated knowing the tangential and axial velocity profiles, numerically or experimentally. In this work, we have chosen to take into account the effects of initial swirl intensity, using a dimensionless parameter S_0 which is the ratio between the fluid velocity in the entrance duct ($U_\phi = 4Q/\pi\phi^2$) and the mean axial velocity in the annular gap ($U = Q/\pi[R_2^2 - R_1^2]$).

In Fig. 5 we have plotted the variations of Sherwood number with Reynolds number, for the lower cathode ($0 \leqslant L \leqslant 10$ cm), as a function of S_0. There

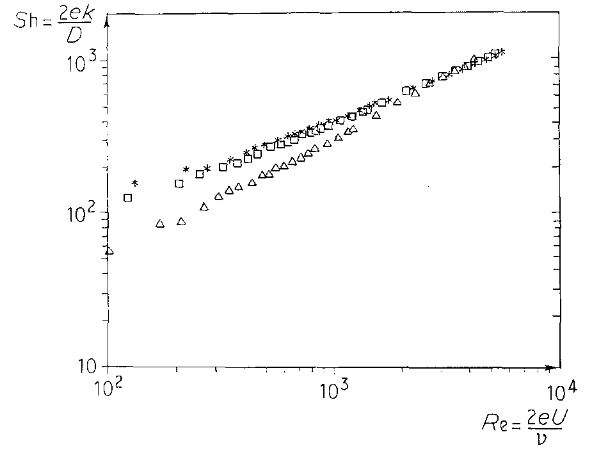

Fig. 5. Influence of the initial swirl intensity on the mass transfer for the lowest active section of the cell: ∗ $e = \phi = 17$ mm; $S_0 = 7.8$; □ $e = \phi = 14.5$ mm; $S_0 = 9.8$; △ $e = \phi = 7$ mm; $S_0 = 24.6$.

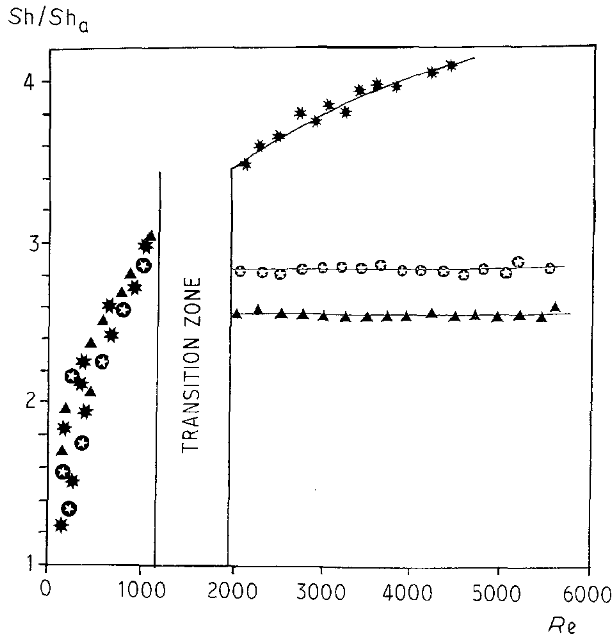

Fig. 6. Influence of the geometrical parameters in terms of Sh/Sh_a for the lowest mass transfer section: △ $e = \phi$ 17 mm; $S_0 = 7.8$; ✪ $e = \phi = 14.5$ mm; $S_0 = 9.8$; ✱ $e = \phi = 7$ mm; $S_0 = 24.6$.

is a decrease in the overall mass transfer with S_0 for a given low value of Reynolds number ($Re < 1000$), whereas for higher values of Reynolds number ($Re > 2000$), the effect of S_0 decreases, becoming negligible. To characterize this experimental fact, we have plotted, in Fig. 6, the variations of the ratio Sh/Sh_a as a function of Reynolds number, thereby eliminating the contribution of the axial flow to mass transfer. We observe two different zones:

For $Re < 1000$: the ratio Sh/Sh_a is practically independent of the geometrical parameter N ($N = R_1/R_2$); therefore N influences Sh and Sh_a in the same way, that is Sh and Sh_a decrease with N.

For $Re > 2000$: the ratio Sh/Sh_a increases with S_0, the tangential velocity contribution becomes predominant and increases with S_0, which in turn leads to an augmentation of the mass transfer coefficients. In fact, for high Reynolds numbers, the flow becomes close to that observed in a rotating cylinder cell. In this case, Arvia and Carrozza [20] have shown that the mass transfer increases with the ratio R_1/R_2, as in our work (see Fig. 6). Sh/Sh_a is quite independent of Re for a given value of S_0. Contrary to the laminar case, the swirl intensity is independent of Reynolds number for the turbulent flow regime.

3.4. *Correlation of the experimental results*

We have correlated our experimental data using a single equation taking into account the different parameters which contribute to the mass transfer.

(i) $L/2e$, to characterize the swirl decay.

(ii) S_0, to express the initial swirl intensity.

(iii) Contribution of the geometry of the annular gap:

For $Re < 1000$: we have shown experimentally that the dependence of the mass transfer coefficients on the ratio of the radii, N, has the same order of magnitude as that observed in fully developed axial flow (Fig. 6). Thus, we used in our correlation the function $f(N)$ given in [18].

For $Re > 2000$: we have assumed that the influence of the geometry is given either by the ratio N as in [21] for the expression of the friction factor in annular swirl flow, or in the same way as in fully developed axial turbulent flow [19]. So the contribution of the geometry of the annulus can be expressed in terms of

$$fN) = a\left[\frac{1-N}{1-\delta^2}\right]^{0.2}\left[\frac{\delta^2-N^2}{N(1-\delta^2)}\right] \qquad (7)$$

with

$$\delta^2 = \left[\frac{1-N^2}{2\ln(1/N)}\right] \qquad (8)$$

where a is a constant which will be integrated in the first term of our correlation.

(iv) Influence of the Reynolds number:

In Fig. 3 two flow regions can be seen: $Re < 1000$ and $Re > 2000$ with an intermediate zone between 1000 and 2000. These different flow regimes correspond to laminar and turbulent swirling flows, but the transition regime is difficult to explain because it is not present in all cases, for example for the lower cathode when $\phi = e = 14.5$ and 17 mm (see Fig. 4). Thus, we have correlated our experimental data for the two ranges of Reynolds numbers using the following expression, assuming that Sh is proportional to $Sc^{1/3}$,

$$Sh = \alpha Sc^{1/3} Re^{\beta} f(N)^{\varepsilon}\left[\frac{L}{2e}\right]^{\xi} S_0^{\sigma} \qquad (9)$$

The parameters Re, $L/2e$ and S_0 are not independent, thus the different constants α, β, ε, ξ, σ are determined simultaneously by means of multi-linear regression. To evaluate the validity of our correlation equations, we have calculated the relative mean square error as follows

$$\text{ERR} = \left[\frac{1}{N_{\text{exp}}}\sum_{i=1}^{N_{\text{exp}}}\frac{[Sh_i^{\text{calc}} - Sh_i^{\text{exp}}]^2}{[Sh_i^{\text{exp}}]^2}\right]^{1/2}$$

where N_{exp} is the number of experimental data, Sh^{calc}

the value of the Sherwood number calculated using the correlation and Sh^{exp} the experimental Sherwood number.

We obtained the following empirical equations:

For $Re < 1000$

$$Sh = 1.99Re^{0.51}Sc^{1/3}\left[\frac{L}{2e}\right]^{-0.23} f(N)^{+0.07}S_0^{-0.28} \quad (10)$$

with a relative mean square error (ERR) of 9.6% ($N_{exp} = 291$). This correlation can be applied for: $100 \leqslant Re \leqslant 1000$; $1.5 \leqslant L/2e \leqslant 19.3$; $7.8 \leqslant S_0 \leqslant 24.6$; $0.32 \leqslant N \leqslant 0.72$.

We notice the decrease in Sherwood number with the axial distance from the inlet of the cell ($\xi = -0.23$) and with S_0 ($\sigma = -0.28$). The mass transfer rate is nearly proportional to $Re^{0.5}$. This result corresponds to the variation of mass transfer usually assumed for developing Poiseuille flow in a tube or an annulus. Thus we have rewritten our correlation as follows

$$Sh = 2.50Re^{0.5}Sc^{1/3}\left[\frac{L}{2e}\right]^{-0.23} S_0^{-0.30} \quad (11)$$

and in this case, ERR is equal to 9.7%.

For $Re > 2000$:

In a first step, the following form of the correlation is used.

$$Sh = 0.18Re^{0.77}Sc^{1/3}N^{0.004}\left[\frac{L}{2e}\right]^{-0.27} S_0^{-0.0004} \quad (12)$$

The mass transfer is quasi-independent of the ratio N. In a second step we have used the geometric parameter $f(N)$ defined for turbulent axial flow. Thus

$$Sh = 0.18Re^{0.77}Sc^{1/3}\left[\frac{L}{2e}\right]^{-0.26} fN)^{+0.15}S_0^{-0.0004} \quad (13)$$

with a relative mean square error (ERR) of 10.8% ($N_{exp} = 128$).

The function $f(N)$ seems to give a better representation of the geometric factors than the ratio N. The correlation, Equation 13, is valid for: $2000 \leqslant Re \leqslant 5900$; $1.5 \leqslant L/2e \leqslant 19.3$; $7.8 \leqslant S_0 \leqslant 24.6$; $0.32 \leqslant N \leqslant 0.72$.

As can be observed, the power of S_0 is very low; thus the mass transfer is independent of the initial swirl intensity. In this correlation, the power of the Reynolds number is very close to 0.8, which is the value obtained for fully developed turbulent axial flow in annuli using the Chilton–Colburn analogy [17]. Thus the following modified correlation can be used

$$Sh = 0.14\ Re^{0.8}Sc^{1/3}\left[\frac{L}{2e}\right]^{-0.26} [fN)]^{0.16} \quad (14)$$

with a mean deviation equal to 12.5%. In laminar and turbulent swirling flows, the power of $L/2e$ is practically the same, thus the decay of the swirl motion does not depend on the flow regime.

4. Comparison with other work

Shoukry and Shemilt [5] have studied mass transfer in swirling annular flow for various diameters of the tangential inlet and three different axial positions of the active section ($L/2e = 8.46, 43.90$ and 79.33). For the $\frac{1}{2}$in inlet diameter and the same thickness of the annular gap ($e = \phi = \frac{1}{2}$in $= 1.27$ cm), they have correlated their experimental results by the following relation

$$Sh = 0.079Re^{0.81}Sc^{1/3} \quad (15)$$

with $L/2e = 8.46$, $3000 \leqslant Re \leqslant 20\,000$, $R_1/R_2 = 0.5$, $S_0 = 12.0$.

Applying our correlation Equation (4) to the geometrical and experimental domain of [5], we obtain

$$Sh = 0.105Re^{0.80}Sc^{1/3} \quad (16)$$

which may be compared with Equation (15), with a mean deviation of 15%.

Hay and West [10] have investigated the local heat transfer for air flowing through a pipe with a swirling motion downstream from a tangential inlet. They have correlated their experimental results for various dimensions of tangential slots and $Re > 4000$ in the form

$$Nu_x = 0.119Re_x^{0.8} \quad (17)$$

where Nu_x is the local Nusselt number ($Nu_x = hx/\lambda$) and Re_x the local Reynolds number ($Re_x = Ux/\nu$).

Equation (17) can be written for mass transfer as

$$Sh_x = 0.134Sc^{1/3}Re_x^{0.8} \quad (18)$$

Upon integration between two axial distances from the inlet, L_1 and L_2, we obtain

$$Sh = 0.167Sc^{1/3}Re^{0.8}d^{0.2}\left[\frac{L_2^{0.8} - L_1^{0.8}}{L_2 - L_1}\right] \quad (19)$$

where d is the diameter of the tube.

Using $2e$ as the equivalent diameter of the annular space, and the different values of L_1 and L_2 of our work, the two categories of correlations are compared:

1. Correlation of Hay and West [10]:

$$\text{For } e = 7\,\text{mm} \qquad Sh = 0.129Sc^{1/3}Re^{0.8} \quad (20)$$

$$\text{For } e = 14.5\,\text{mm} \qquad Sh = 0.150Sc^{1/3}Re^{0.8} \quad (21)$$

$$\text{For } e = 17\,\text{mm} \qquad Sh = 0.155Sc^{1/3}Re^{0.8} \quad (22)$$

2. Our correlation (Equation 14):

$$\text{For } e = 7\,\text{mm} \qquad Sh = 0.128Sc^{1/3}Re^{0.8} \quad (23)$$

$$\text{For } e = 14.5\,\text{mm} \qquad Sh = 0.151Sc^{1.31}Re^{0.8} \quad (24)$$

$$\text{For } e = 17\,\text{mm} \qquad Sh = 0.162Sc^{1/3}Re^{0.8} \quad (25)$$

Our results are in good agreement with those of Hay and West [10]; it thus seems possible to use the empirical correlations of swirling flow in a pipe to estimate both mass and heat transfers in swirling annular flow.

5. Conclusion

Mass transfer coefficients between a liquid in swirling flow and the inner cylinder of an annulus have been measured using an electrochemical method. The different parameters influencing the overall mass transfer have been extensively analysed. Enhancement of the average mass transfer coefficient up to 400% in comparison with fully developed axial flow has been obtained using a tangential inlet. Swirling flows can induce good space time yield; therefore, they are very interesting in electrochemical cells applied to industrial processes. Correlations, given for both laminar and turbulent regimes, take into account all the parameters of the study and describe with good approximation the experimental data and those given in the literature.

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