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Mass transfer at the walls of a couette-type cell with small gaps in the laminar vortex regime

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Mass transfer studies in annular cells with an inner, rotating cylinder are reported. Relatively small gaps are considered (2.5 mm, 5.0 mm and 7.5 mm) and the laminar vortex regime is explored. The results show discrepancies with correlations from the literature, probably due to the fact that the vortices have a tangential wavy movement.

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1. Introduction

Mass transfer at a cylindrical electrode (radius R_1) rotating with angular velocity ω on the axis of a cylindrical tube (internal radius R_2) has received considerable attention, both experimentally ([1–3] for example) and theoretically [4–6]. The most recent extensive review of this problem was published by Gabe [7]; however, only laminar and turbulent hydrodynamical regimes were distinguished although the latter includes a variety of hydrodynamical conditions.

It is known [8] that the flow between concentric rotating cylinders becomes unstable when the characteristic, dimensionless Taylor's number

$$(Ta) = \frac{R_1 \omega e}{\nu} \left(e/R_1 \right)^{1/2} \quad (1)$$

reaches the critical value $(Ta)_c \sim 40$. This first instability, which bounds the pure laminar regime, corresponds to the appearance of toroidal vortices (Taylor vortices) such as those represented in Fig. 1a. For narrow intercylinder gaps $e = R_2 - R_1$, this instability is followed at $(Ta)'_c > (Ta)_c$ by a second which induces the formation of tangential waves (see Fig. 1b) whose wavelength varies with (Ta); the lower the ratio e/R_1, the nearer $(Ta)'_c$ is to $(Ta)_c$ [9]. Empirically it is predicted that the conditions for the second instability cannot be satisfied if R_2/R_1 is greater than about 1.4 [9]. Beyond the laminar vortex regime, the turbulent regime would appear.

The laminar vortex regime has been studied in relation to the cooling of electric motors, generally in studies of heat transfer from the internal rotating cylinder towards the outer stationary cylinder through an air gap [10–12]. The results, when referred to only one of the transfer surfaces (assumed to have the same heat transfer coefficient), lead to the expressions given in Fig. 2. Only Mizushina [13] has simulated heat transfer with electrochemical mass transfer; he considered the inside wall of the outer cylinder as the transfer surface. From overall mass transfer experiments he deduced the correlation plotted in Fig. 2; it would be easy to see that the other empirical solutions, which are not plotted in Fig. 2, are in good agreement with it (in Becker's correlation [10], F is a geometrical factor whose value is approximately one).

All of these correlations were established for gaps e varying from 8 mm up to 25 mm and thus relate to experiments in which vortices of large sizes were produced. The influence of such large vortices could be demonstrated only if the active electrode height L was sufficiently large compared with the size of the vortices; such a condition was not always fulfilled in experimental work from which very useful correlations were produced [1, 3]. It has also to be noted that in the laminar vortex regime, the transfer (Sherwood number, (Sh) or Nusselt number, (Nu)) varies as $(Ta)^{1/2}$.

Local velocity gradients have been electrochemically measured by Cognet [14] at the

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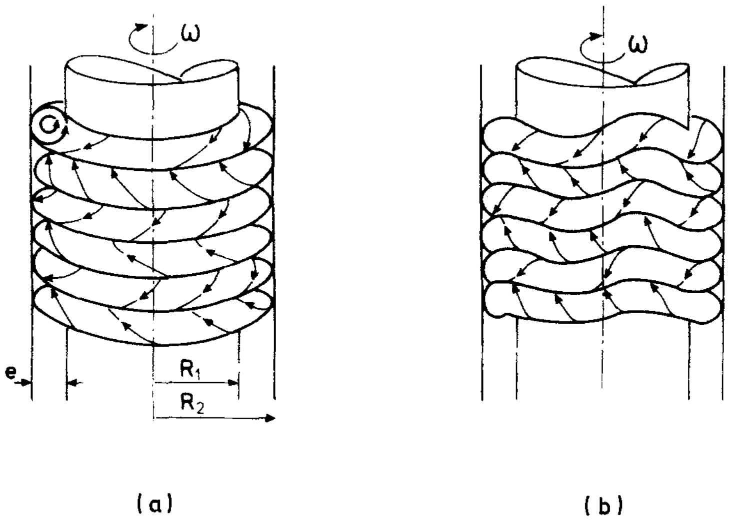

(a) (b)

Fig. 1. Schematic representation of regular vortices between two cylinders. (a) Taylor vortices, (b) vortices with circulating tangential waves.

stationary outer cylinder ($R_2 = 22$ cm, $e = 1$ cm); the empirical correlation deduced for the space-averaged shear stress allows us to deduce, by applying the Chilton–Colburn analogy between mass and momentum transfer [15], a solution (see Fig. 2) which agrees well with the others, thus confirming the validity of the analogy for this problem, at least for the outer cylinder.

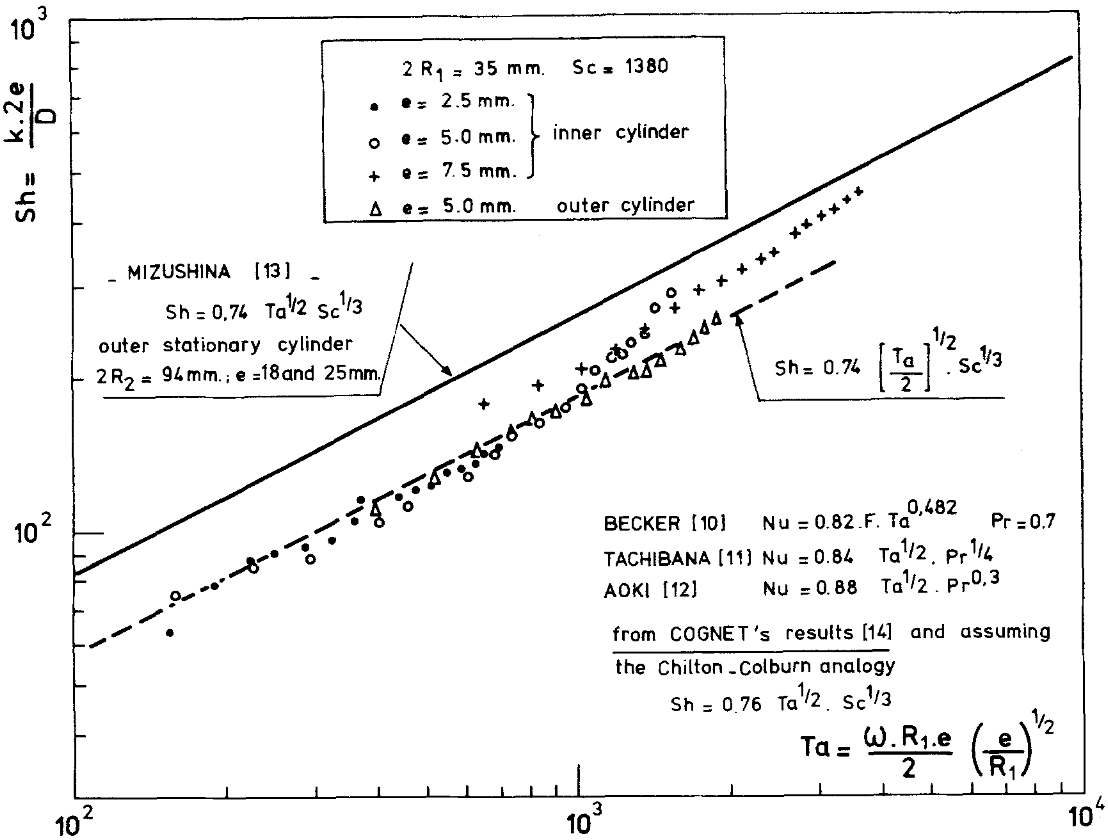

Fig. 2. Comparison of mass and heat transfer results obtained in the laminar vortex regime.

2. Experimental

The experimental cell was similar to that described elsewhere [16] but in these experiments the outer cylinder could be changed to give three values of the intercylinder gap width e ($e = 2.5$, 5.0 and 7.5 mm); also, for $e = 5.0$ mm, the cell allowed the determination of the mass transfer coefficient both at the rotating inner cylinder ($R_1 = 17.5$ mm) and the stationary outer cylinder. In all cases the length of the transfer surface was $L = 10$ cm; this was located in the middle part of the cell (total length of the annular space: 29.6 cm). The experimental conditions were identical to those used in [16], i.e. cathodic reduction of potassium ferricyanide, Schmidt number $(Sc) = 1380$, temperature $t = 30°$ C.

3. Results and discussion

The experiments reported here were performed in order to examine the particular case of no axial flow (rotation alone) in contrast to the normal, electrochemical, concentric-cylinder reactor in which the mass transfer enhancement follows from the combination of axial electrolyte flow in the annular space and rotation of the inner cylinder [16]. The other limiting case (axial flow alone) served to test the validity and the precision of the experimental technique. The experiments led [17] to mass transfer data in excellent agreement with Ross and Wragg's conclusions [18]. (Sc) was also varied and its influence as $(Sc)^{1/3}$ confirmed [16].

Microelectrodes made of platinum wire, diameter 0.4 mm, and positioned either in the wall of the nonconducting lower section of the outer cylinder or at the surface of the rotating cylindrical electrode allowed the following observations:

(a) The demonstration, through periodic oscillations of the limiting current, of the existence of vortices with waves such as are depicted in Fig. 1b; separate experiments involving local injection of a coloured tracer confirmed their existence.

(b) That the order of magnitude of the fluctuations was 10% around the mean value of the current.

The experimental overall mass transfer coefficients are represented in Fig. 2 as a plot of (Sh) versus (Ta). One can see that, at least for the smallest gaps ($e = 2.5$ mm and 5.0 mm), the points fall well below Mizushina's correlation but would be correctly described (broken line) by this correlation if (Ta) were replaced by $(Ta)/2$. At $(Ta) > 1000$ the results obtained for $e = 5.0$ mm at the inner surface deviate from those corresponding to the outer cylinder; this is probably due, as shown by Kataoka [19], to secondary vortices which initiate the turbulent regime and appear near the inner cylinder. The results obtained for $e = 7.5$ mm (which is not a small gap width) are situated between both plotted lines.

Fig. 3 shows another comparison between the experimental results and Eisenberg's correlation [1] incorporating the ratio R_1/R_2 as a correcting factor [7] for the rotating cylinder electrode in turbulent flow. Since the correlation crosses the cloud of points the system may be seen to be turbulent; however, the mean scatter (about 20%) is too large and (Sh) varies as $\omega^{1/2}$ rather than $\omega^{0.7}$. It is interesting to note from Fig. 2 that, for the smallest gap widths, the mass transfer coefficient has the same value as if the vortices were of large size and rotating at a speed $\omega/2$, the cylinder being thus rotating with respect to the vortices at the relative angular velocity $\omega/2$. Such an explanation agrees with the literature which indicates, at least for moderate (Ta) values, that the tangential waves in narrow gaps between cylinders rotate at a speed approximatively equal to the mean between the velocities of the two cylinders [9, 14]. Also, in both the latter references it is shown that the ratio of the wave speed to the cylinder velocity tends to 1/3 for high (Ta) values. The fact that the cell with $e = 7.5$ mm gives results different from the other cells could be explained by the corresponding value 1.43 of R_2/R_1 which is near to the critical value for the occurrence of the second instability [9].

4. Conclusions

The following conclusions may be drawn from the experiments:

(a) The presence of vortices between rotating concentric cylinders increases the mass coefficient at the wall. Correlations from the literature for the cases of vortices of large size are in agreement.

(b) In the laminar vortex regime, the vortices behave differently when the gap width between the cylinders is small: tangential waves appear

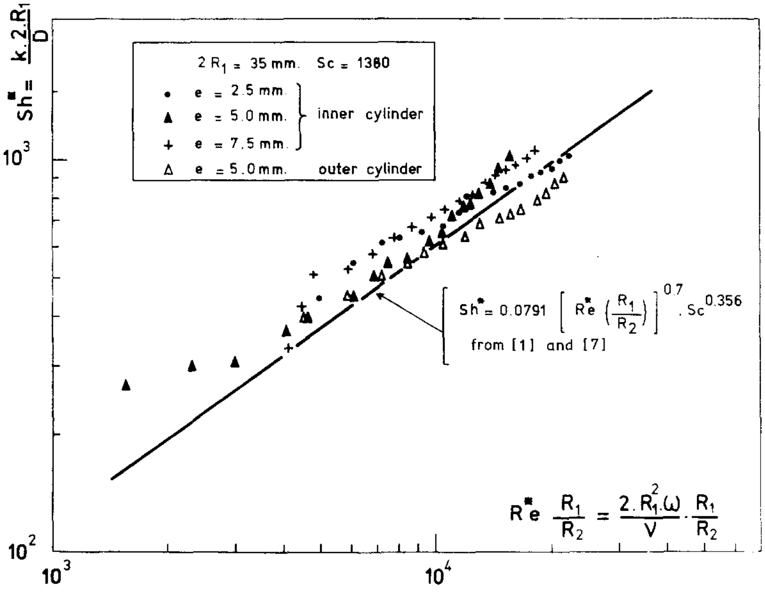

Fig. 3. Comparison of the results with Eisenberg's correlation [1].

which may be responsible for decreasing the wall to liquid mass transfer coefficients.

(c) Although many papers have been published on nonlaminar flow between rotating cylinders, mass transfer data are scarce for narrow gaps. Due to the interesting aspect of the electrochemical reactor combining Taylor vortex flow and constant axial flow rate [20], this case of nonaxial flow could merit further attention.

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