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SHORT COMMUNICATION

Transient and optical studies of free convective mass transfer during electrodeposition at single and multi-cylinder cathodes

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1. Introduction

A recent paper [1] described measurements of free convective mass transfer using the limiting electrolysis current technique at vertical arrays of horizontal cylindrical cathodes. The distribution of mass transfer up an array was measured and for any particular cylinder the current was found to depend on the concentration and velocity fields rising from cylinders immediately below. The purpose of the present communication is to present further visual evidence of the existence and properties of the convective plumes above cylinders in free convection and also to describe simple transient experiments demonstrating the convective interaction between cylinders. In the experiments to be described, the apparatus was basically similar to that previously described except that for the optical experiments the electrolyte was contained in a tank fitted with plane glass sides, the tank being incorporated into a conventional Schlieren optical system which allowed photography of the convective phenomena using a 35 mm camera.

2. Experimental

2.1. *Transient studies*

In these experiments, conducted with a pair of cylinders, the upper cylinder was first operated alone in the steady state at limiting current. The lower cylinder was then suddenly switched into the circuit and the current flowing at the upper cylinder was continuously monitored. The experiments were performed with cylinders of diameter

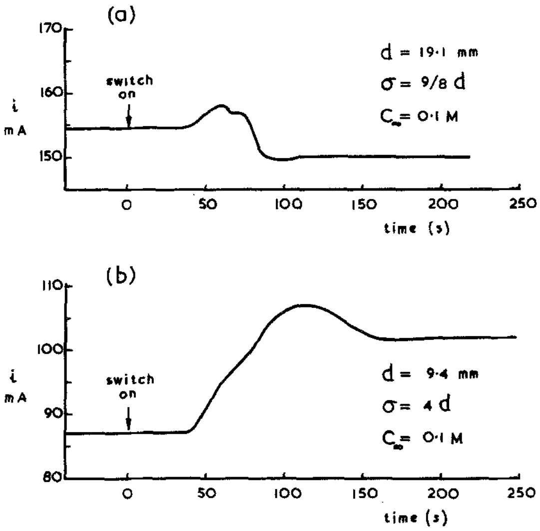

Fig. 1. Current-time plots for upper cylinder of an array of two upon sudden switch-on of lower cylinder.

9·4 and 19·1 mm and at spacings of 4, 2, 5/4 and 9/8*d* in 0·1 M $CuSO_4$. Two typical examples of the recorder traces obtained are shown in Fig. 1. There is a considerable lag following the switch-on of the lower cylinder before any effect is noticeable at the upper one. This is of course due to the time taken for the diffusion boundary layer to build up before becoming unstable and for the resultant convective plume to rise to the upper cylinder. In Fig. 1a, as the plume impinges on the upper cylinder there is a distinct enhancement of the current which passes through a maximum and then falls and settles to a new steady state limiting value lower than that recorded for the cylinder acting alone. This case corresponds to the result shown in Fig. 6b of Reference [1].

In the trace of Fig. 1b, the large mass transfer enhancement due to the disturbance caused by the impact of the lower plume is followed by a settling of the limiting current to a new steady value considerably higher than that for the cylinder acting alone. This accords with the earlier findings for widely spaced cylinders as indicated by Fig. 6c of Reference [1]. This transient technique thus provides a convincing demonstration of the possible effects of boundary layer carry-over from lower to higher cylinders in an array.

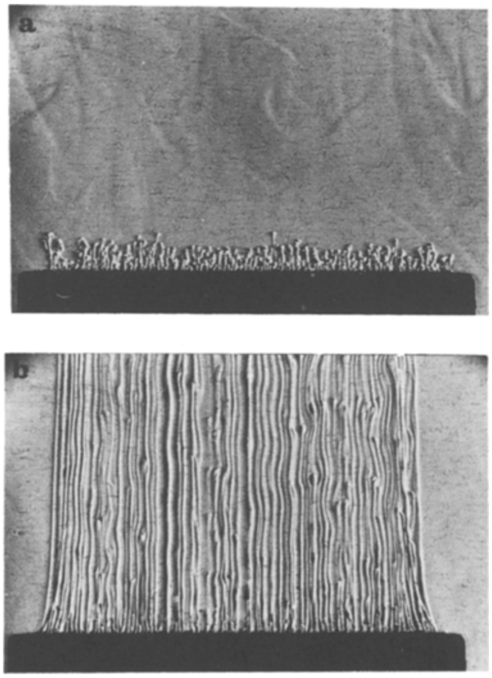

Fig. 2. Development of convection above a single horizontal cylinder during copper deposition at different times following the sudden switch-on of potential, $d = 19{\cdot}1$ mm, $c_\infty = 0{\cdot}1$ M $CuSO_4$. (a) $t = 30$ s; (b) $t = 75$ s.

2.2. *Visualization of boundary layer carry-over*

Two photographs showing the development of the convective flow structure above a single cylinder following sudden switch-on of a potential corresponding to the limiting current are shown in Fig. 2. This is for the 19·1 mm cylinder in 0·1 M $CuSO_4$. A striking feature of the flow is its distinctly striated form – a strong contrast with the cohesive boundary layers formed at heated cylinders in air, an example being shown in Fig. 3. No striations

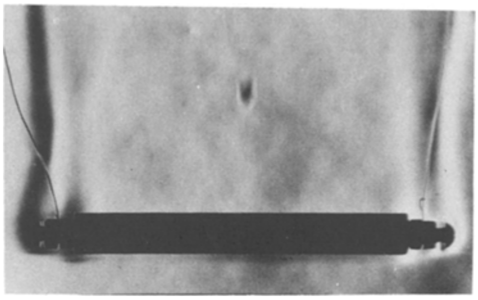

Fig. 3. Schlieren photograph of natural convection above a heated horizontal cylinder in air, $d = 1{\cdot}25$ cm, $T_\infty = 21°C$, $T_{\text{cylinder}} = 150°C$.

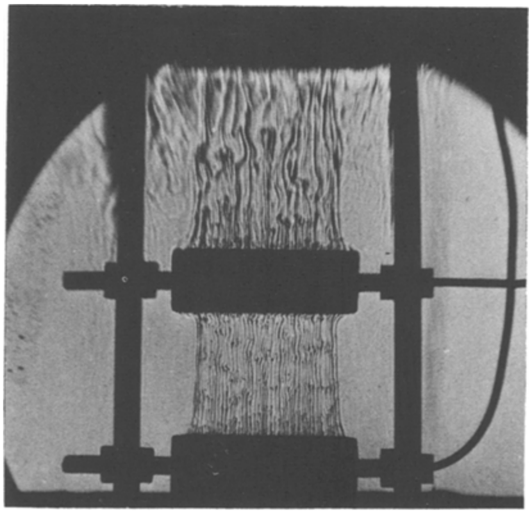

Fig. 4. Free convective mass transfer at a pair of simultaneously active cylinders, $d = 19{\cdot}1$ mm, $\sigma = 4d$, $c_\infty = 0{\cdot}1$ M $CuSO_4$.

are apparent, only the extreme edges of the plume being visible. A more interesting and instructive approach to visualization of the heat transfer case is the use of the interferometer which, viewing axially, produces interferograms such as are frequently shown in heat transfer texts [e.g. 2].

The difference in convective behaviour may be largely attributed to the relative sizes of the Schmidt number (for mass transfer) and the Prandtl number (for heat transfer) which are 2000 and 0·7 respectively, the heat transfer system being able to maintain stable boundary layers up to much greater thicknesses.

A further interesting phenomenon is illustrated in Fig. 4 which shows the convective structure above two cylinders operating simultaneously at steady state at a spacing of $4d$ in 0·1 M $CuSO_4$. It is noticeable that the striations in the flow above the lower cylinder are much more regular, finer and well-defined than those above the upper cylinder. The convection from the lower body obviously causes unsteadiness on mixing with the flow at the upper cylinder. A similar effect at a four-cylinder array has been shown elsewhere [3].

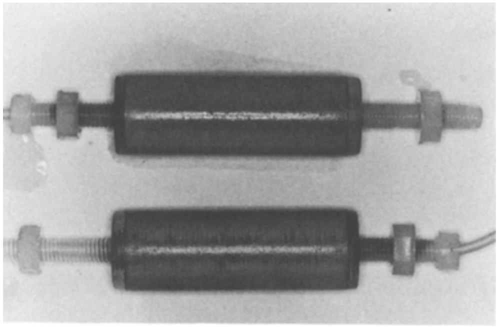

Fig. 5. The electrodeposit formed at cylinders operated at conditions corresponding to Fig. 4.

A direct consequence of this behaviour is apparent in Fig. 5 where the resultant electrodeposits along the upper surfaces of both cylinders of a pair operating simultaneously under conditions similar to those of Fig. 4 have been photographed. The pattern in the deposit on the lower cylinder is very distinct and corresponds to the regular flow striations observed. The pattern produced suggests that the flow striations are spacially stable. The deposit pattern at the upper cylinder is much less distinct confirming the suggestion based on the flow visualization photograph that the flow here is much more erratic and unsteady.

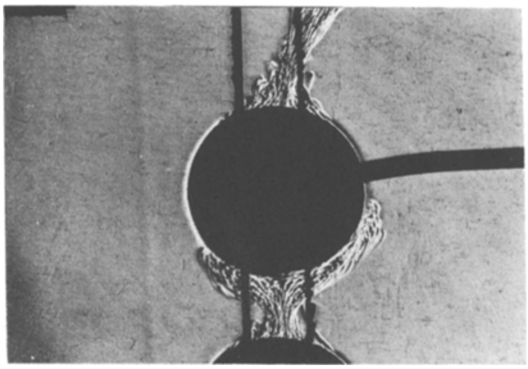

Fig. 6. Flow disturbance during the impact of a convective plume from a lower cylinder on to a higher cylinder.

The optical technique was also used for visualizing the interaction between cylinders during the onset of convection. Thus Fig. 6 shows the impact, at $t = 45$ s after switch-on of the convection plume from a lower to a higher cylinder. The flow disturbance is the cause of the increase in mass transfer observed in the current-time plots of Fig. 1 where the increase begins to be noted at $t = 40$ s.

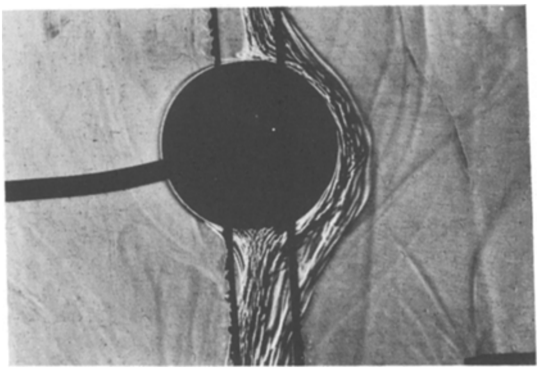

Fig. 7. Maldistribution of a plume from a lower cylinder around a higher cylinder.

Finally, a tendency for a severe maldistribution of an ascending plume around a higher cylinder was revealed by the optical studies. A case is shown in Fig. 7 where the plume from the lower cylinder completely side-tracks the higher cylinder. The convection appeared pseudo-stable in this position and could remain for many minutes before gradually becoming properly distributed. This effect is clearly a potential source of error and non-reproducibility in experiments of this type and emphasises the importance of working in initially totally homogeneous and stagnant conditions.

References

[1] A.F.J. Smith and A.A. Wragg, *J. Applied Electrochem.* 4 (1974) 219.

[2] F. Kreith, 'Principles of Heat Transfer', 2nd ed. p.341, International Text Book Company, London (1965).

[3] A.A. Wragg and M.A. Patrick, 'Extended Abstracts'. 25th I.S.E. Meeting, Brighton, September (1974).