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TECHNICAL NOTE

# *On the generation of electrolyte flow by alternating electric and magnetic fields*

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## Notation

- $A$ Linearity constant between magnetic flux density and exciting current flow, mT $A^{-1}$
- $B_0$ Magnetic flux density, mT
- $f$ Frequency of the exciting and cell current, Hz
- $h$ Height of the concentric cylindrical electrodes, cm
- $I_0$ Magnitude of the exciting current flow, A
- $I_c$ Magnitude of the ohmic current flowing through the electrolyte, A
- $k$ Geometric shape factor, $R/r_0$
- $R$ Radius of the outer cylindrical electrode, cm
- $r_0$ Radius of the inner cylindrical electrode, cm
- $V_{eff}$ Effective [or root-mean-square (r.m.s.)] surface velocity, cm $s^{-1}$
- $\mu$ Electrolyte viscosity, Ns $m^{-2}$

The properties of convective motion generated in electrolyte solutions by combined electric and magnetic fields have so far received limited attention in the literature. Frary [1] described first the rotation of an electrolyte between two co-axial cylindrical electrodes in an axially imposed constant magnetic field, but it was only lately that Gak and co-workers [2–6] and Fradkina and Kozyukov [7] examined in depth the problem and some its related aspects. The specific problem of generating electrolyte motion via combined *alternating* fields has scarcely been studied theoretically [8, 9] and little experimental information [6, 9] is available. In this communication, experimental data recently obtained [10] under such conditions are summarized.

The experimental set-up is shown in Fig. 1.

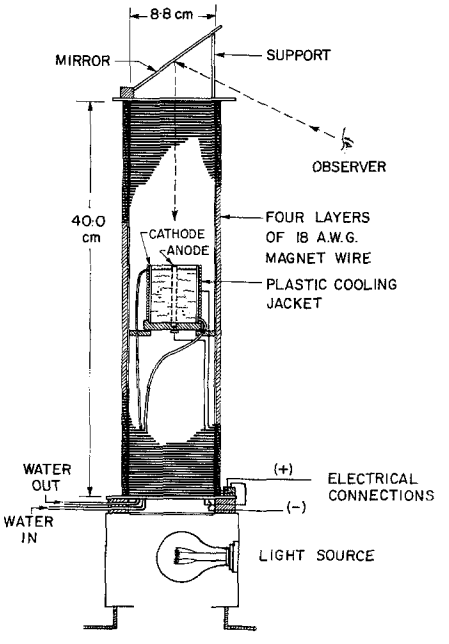


Fig. 1. Sketch of the solenoid and electrolytic cell set-up.

The axial magnetic field was generated via a heavy-armoured polythermaleze-coated 18 AWG magnet wire wound around a Plexiglass-acrylic hollow tube (1424 turns). The experimentally determined magnetic flux density/exciting current relationship ($B_0 = AI_0$; $A = 4{\cdot}40$) agreed well with theoretical [11] computations ($A = 4{\cdot}36$) which also indicated [12] high axial uniformity of the magnetic field (induced radial field of the order of $10^{-170}$ Tesla); the variation of the axial field strength between the two solenoid ends was about 0·32%. The solenoid was connected in series with a 'tuning-out' capacitor circuit containing capacitor banks in parallel. This arrangement allowed generation of

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the exciting current at frequencies which are resonance frequencies of the capacitor-solenoid system, whereby the auxiliary power amplifier required a relatively small operating power input (effective impedance is essentially the d.c. resistance of the solenoid). The electrolytic cell was made up of two concentric cylindrical copper electrodes (outer electrode diameter 5·0 cm, inner electrode diameter 0·9 cm, height 4·7 cm) screwed into a Plexiglass base and was situated in the centre of the solenoid. The bottom of the cell base was scored with circles at 0·5 cm intervals, concentric with the inner electrode, and the grooves were filled with indelible ink. The movement of the electrolyte surface was monitored by following the motion of light, insoluble particles (fish food) illuminated by a light source at the bottom of the solenoid. The position and the period of rotation of these particles around the cell axis was observed using a properly positioned mirror on top. The cell was kept at a nearly constant temperature by water circulating through a thermostatted bath (cell effectively operating at room temperature). The alternating current was generated via a variable-phase function generator and amplified by a 250 W a.c. power amplifier; the solenoid-capacitor circuit and the electrolyte cell were connected in series, as shown in Fig. 2. The electrolytes were aqueous solutions of copper (II) sulphate with a concentration range of 0·005–1·02 mol $dm^{-3}$.

Figs. 3–5 show the effect of the current frequency and magnitude on the average surface velocity at selected electrolyte concentrations. The velocity values were computed from the radius of the observed circular particle motion and the measured period of rotation (average of several measurements). These typical diagrams indicate that the induced velocity markedly increases with the applied current magnitude and decreases with an increase in current frequency, whereas the effect of electrolyte concentration is much less appreciable.

The inverse effect of frequency, observed also by Gak in a similar single experiment [6] cannot be explained at present in a simple and satisfactory manner. From a magnetohydrodynamic analysis [6, 10] the average surface velocity may be written as

$$V_{\text{eff}} = -\frac{B_0 I_c r_0}{2\pi h \mu} \frac{(k+1)(k^3-1) - 6k^2 \log_e k}{9(k^2-1)(k+1)} \tag{1}$$

where $k$ is the geometric aspect ratio, $k = R/r_0$; Equation 1 is the corrected form of an earlier reported [2] relationship. For a fixed cell geometry and in view of the linear relationship existing between exciting current and magnetic flux density, $V_{\text{eff}}$ = constant $(I_0 I_c)$, and since $I_0$ and $I_c$ are in phase, $V_{\text{eff}}$ must be frequency-independent at any experimental frequency, provided the analysis leading to Equation 1 is correct. Gak proposed that an increase in electrolyte viscosity with increasing frequency might be responsible for the experimentally observed phenomena, quoting the work of Litovitz and Davis [13] on relaxation effects. Using pertinent data of Stuehr and Yaeger [14], the so-called primary relaxation frequency of $CuSO_4$ is about 15 MHz, which is well beyond the audio-frequency range employed here and therefore can by no means account for the decrease in velocity shown by the experiments. In view of these points, the applicability of Equation 1 is highly dubious.

*Table 1. Results of a linear least-squares analysis on the experimental $\log_{10} V_{\text{eff}}$ versus $\log_{10} f$ data*

| *Magnitude of a.c. current flow* (A) | *Least-squares line* | | *100 × standard deviation* |
|---|---|---|---|
| | *Slope* | *Intercept* | |
| 0·2 | −1·0538 | 1·2112 | 2·48 |
| 0·4 | −1·0094 | 1·6891 | 2·13 |
| 0·6 | −0·9368 | 1·8066 | 3·68 |
| 0·8 | −0·8504 | 1·7977 | 3·45 |
| 1·0 | −0·8260 | 1·8922 | 2·38 |
| 1·2 | −0·7983 | 1·9297 | 2·12 |
| 1·4 | −0·8089 | 2·0460 | 2·56 |

One possible explanation of the effect might be sought in the electric circuit configuration of the experimental apparatus so far employed. If the electrolytic cell is envisaged as a parallel resistor-capacitor circuit on which an alternating current is imposed, then applying elementary a.c. theory one can show that, if the circuit time constant is large, the effective value of the surface velocity should be inversely proportional to the frequency of the exciting current. As shown in Table 1, the

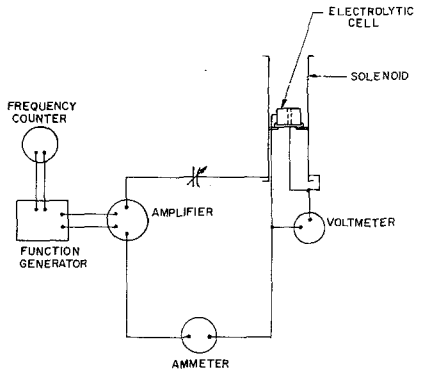


Fig. 2. Electrical connections of the experimental apparatus.

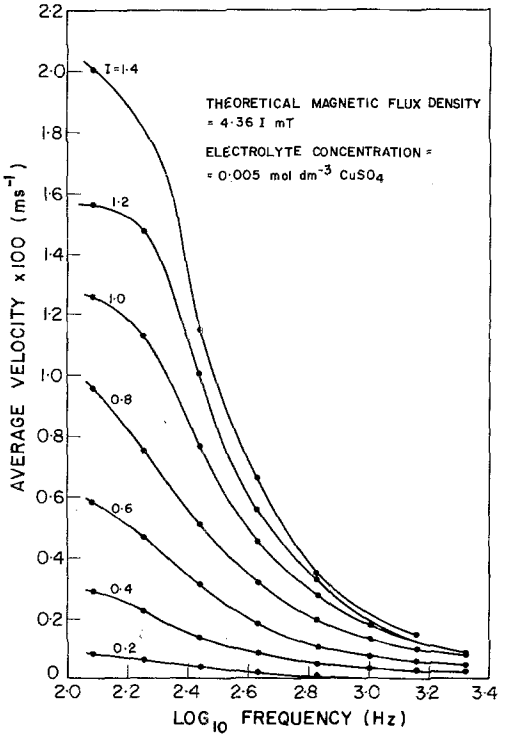


Fig. 3. Average particle velocity versus frequency at low electrolyte concentration.

experimental logarithmic plots of these two quantities have slopes ranging from −0·8 to −1·05 in contrast to the theoretical value of −1 of the parallel circuit. While this is a fairly good agreement, the values of the cell capacitance and resistance, computed from the intercepts of these plots, disagree with direct measurements and estimations and, in consequence, this explanation, although probable, cannot be firmly recommended.

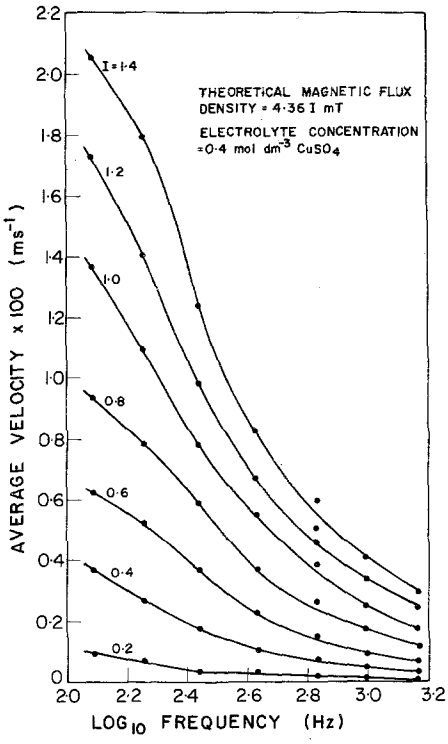


Fig. 4. Average particle velocity versus frequency at medium electrolyte concentration.

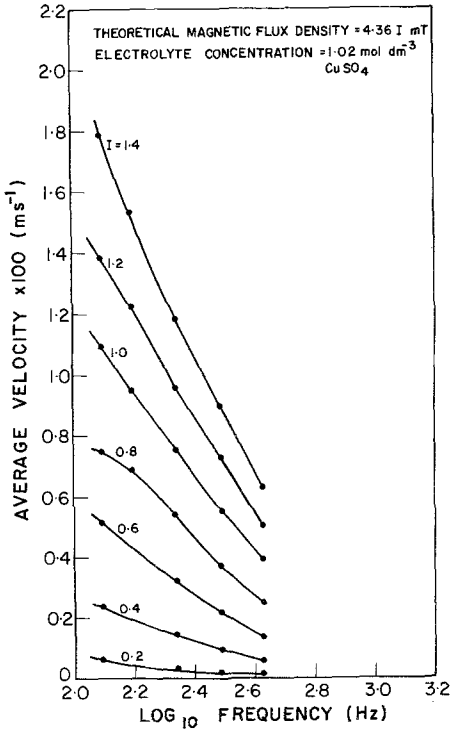


Fig. 5. Average particle velocity versus frequency at high electrolyte concentration.

An alternative interpretation of the experimental findings might be sought in the nonlinear effect of pulsation on the liquid medium and/or the particle [15]. Lack of symmetry in a pulsed liquid system might result in nonlinear behaviour [16] i.e. net momentum or mass transfer under symmetrically oscillatory perturbation conditions. If the retarding and accelerating forces acting on the particle are not in phase, an internally generated phase-shift would be set up and the net effect could be retardation of the surface velocity (in the r.m.s. sense). No direct evidence can be offered at this stage in quantitative support of this conjecture.

In conclusion, the adverse effect on the fluid motion of an alternating magnetic and electric field in transverse configuration has now been sufficiently demonstrated via experiments, but without a full understanding of the observed phenomena. Further experimental studies will be needed to ascertain whether the decrease in surface velocity with increasing frequency of the current flow is indeed caused by the electric circuit configuration as suggested inconclusively by the observations presented here. At any rate, there is adequate information at hand to design magnetoelectric cells in which bulk flow motion takes place at a predetermined r.m.s. velocity. Potential applications might arise in flow control and related areas.

**Acknowledgement**

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