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Electrokinetic dewatering and thickening. I. Introduction and historical review of electrokinetic applications

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An introduction to electrokinetics and a historical review of electrokinetic devices is presented.

1. Introduction

Electrokinetics describes the movement of charged particles or water molecules in an applied d.c. electric field. It can be divided into two main areas, electro-osmosis and electrophoresis.

There can be few electrochemists who have not observed a rise in the level of electrolyte in the cathode compartment when using a very fine glass frit to separate the anode and cathode compartments of an electrochemical cell. This phenomenon is termed electro-osmosis and its observation dates back to 1802. It was first described in detail by Reuss (1808) [1] when he set out to repeat the experiments of Nicholson and Carlisle (1800) [2] on the decomposition of water by an electric current. Reuss placed powdered quartz at the bottom of a U-tube and found that on the application of an electric current, water rose about 23 cm in the arm containing the negative electrode. In other words, water had effectively been 'pumped' uphill against gravity without any mechanical moving parts.

Electrophoresis is the converse of electro-osmosis and relates to the movement of charged particles in the electric field. The migration of the particles is always in the opposite sense to the electro-osmotic water flow.

1.1. *Derivation of the electro-osmotic equations*

The origins of electrokinetics are embedded in double-layer theory [3–7] and the distribution of charge at surfaces. To assist the understanding of the derivations of electrokinetic expressions given later, some underlying assumptions are summarized.

In deriving equations describing electro-osmosis at a level sufficient for this study, the following assumptions need to be made.

(i) A low electrolyte concentration is necessary so that there is a diffuse charge region close to the solid surface, e.g. the wall of a pore in a glass frit.

(ii) The charge density associated with the liquid phase is diffuse and opposite to the charge density of the solid phase, e.g. pore wall of a glass frit.

(iii) The double-layer thickness is small ($\sim 100\,\mathrm{nm}$).

(iv) The surface water layer is immobile, while the water near to the wall of the pore is free to move in the applied electric field and is subject to the normal laws of friction.

(v) The impressed potential includes the double-layer potential.

(vi) The surface conductance of the wall of a pore is negligible.

Based on these assumptions, Helmoltz–Smoluchowski [8] showed that the flow velocity, v_F, was given by

$$v_F = \frac{\varepsilon \vec{F} \zeta}{4\pi\eta} \tag{1}$$

where $\vec{F}$ is the electric field strength, ε is the dielectric constant of bulk phase, η is the viscosity of bulk phase, and ζ is the electrokinetic or zeta potential. The zeta potential is defined as the work necessary to take a unit positive charge from the bulk liquid phase up to the strongly adsorbed rigid layer, and is generally less than ± 0.1 V. It is dependent upon the dielectric constant, viscosity, ionic strength, pH, etc. of the liquid phase. This contrasts with the total potential, E, which may readily be measured and is a thermodynamic quantity involving charge transfer at the electrode (conducting); this potential also includes ζ (a schematic representation is shown in Fig. 1).

If a capillary of constant cross-section, d, is now considered, the volume displaced per second, v, is given by

$$v = \frac{d\varepsilon\vec{F}\zeta}{4\pi\eta} \qquad (2)$$

and by the application of Ohm's Law,

$$d\vec{F} = (1/\lambda)I \qquad (3)$$

where I represents the current flowing through the capillary, and λ is the specific conductivity of the liquid, where

$$v = \frac{\varepsilon\zeta I}{4\pi\eta\lambda} \qquad (4)$$

From this equation it may be inferred that the flow velocity is independent of the radius of the capillary.

It was noted earlier that when electro-osmotic flow occurs, water is effectively 'pumped' through the capillary pore network of the porous plug that separates the cathode and anode compartments. For this to happen a pressure gradient must have developed so that flow could occur. It can readily be shown [3, 5] that when a voltage is applied through a capillary tube of length, l, and radius, r, a pressure, P, develops. This pressure can be expressed as

$$\Delta P = \frac{2\zeta\varepsilon\vec{F}l}{\pi r^2} \qquad (5)$$

Conversely, forcing of a liquid through a capillary system leads to the development of a potential, F_s, namely

$$F_s = \frac{\zeta\varepsilon\Delta P}{4\pi\eta\lambda} \qquad (6)$$

where F_s is termed the streaming potential.

In addition, the streaming current, I_s, can also be determined experimentally. The expression for I_s is obtained by substituting according to Ohm's law, i.e.

$$F_s = I_s R = I_s\left(\frac{l}{\pi r^2 \lambda}\right) \qquad (7)$$

Substituting Equation 6 leads to the expression for the streaming current

$$I_s = \frac{\Delta P r^2 \varepsilon\zeta}{4\eta\lambda} \qquad (8)$$

The technique for measuring the zeta potential by using streaming current or streaming potential measurements has been popular for several years. However, gross errors can arise from the assumptions that the dielectric constant is a true constant and surface conductance

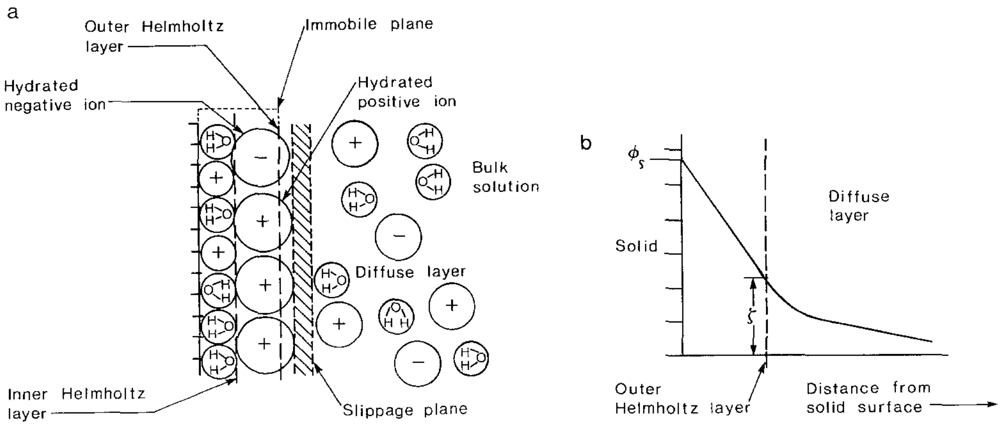

Fig. 1. (a) Schematic representation of the double layer at the solid–electrolyte interface. (b) The variation of potential across the double layer.

is negligible. In fact the dielectric constant will vary from a bulk solution value of 80 to a value of about 6 close to the pore wall where orientation of water molecules in the high potential field arises. Surface conductance arises as a result of the excess charge of the double layer in the mobile part of the liquid reinforcing the electro-osmotic flow. Because of these excess ions the double-layer conductance is greater than that of the bulk solution. The surface conductance is significant in dilute solutions and can be determined from measurements carried out for different electrolyte concentrations. It is necessary at low concentrations to adopt the volume flow, equation 4, namely

$$v = \frac{I_s}{4\pi[\lambda + 2(\lambda_s/r)]}\left(\frac{\varepsilon\zeta}{\eta}\right) \qquad (9)$$

The surface conductance, λ_s is appreciable in fine capillary systems (where the pore dimensions approach the double-layer thickness) and in dilute solutions typically below 10^{-3} M.

From the above it is apparent that care is necessary in interpreting experimental results, particularly in the case of measurements of the zeta potential in ill-defined systems. Measurements carried out by Mason and co-workers [9–12] showed for the case of compressible materials, e.g. pulp, fibres, etc., that unless account is taken of the tortuous nature of the pore network and the variation of conductivity with the mass–volume ratio, values of the zeta potential must be interpreted with care. For further details on these aspects [13, 14] should be consulted.

It follows from Equation 2 that the electro-osmotic liquid flow is directly proportional to $\vec{F}$ which, from Equation 4, is also directly proportional to I. In practice this is true, but the greater part of the current is faradaic in nature producing hydrogen and oxygen at the electrode surfaces.

1.2. *Derivation of electrophoretic equation*

The phenomenon of electrophoresis refers to the movement of solid particles (generally in the size range below 20 μm) suspended in a liquid under the influence of an electric field. The solid particles acquire a surface charge either from their own intrinsic surface ionization (e.g. clays, biological cells) or by the adsorption of polyelectrolytes, surfactants or ions onto their surfaces (e.g. polyvinyl chloride, alumina).

In the case of colloids the surface area of the particles is large relative to the volume of the particles and therefore the electrostatic repulsions predominate over the Van der Waals interaction. The electrostatic repulsion forces arise from electrical double layers, which, between adjacent particles, prevent the particles coagulating or agglomerating. When an electric field is applied across the colloidal suspension the charge on the particle interacts with the field and it moves towards the electrode of opposite charge. This is analogous to electro-osmotic movement in which an electrical double layer exists at the phase boundary between the solid and liquid phases. In this case, however, the direction of movement is in the opposite sense so that the velocity is formally negative, namely

$$v_E = -\frac{\varepsilon\zeta\vec{F}}{4\pi\eta} \qquad (10)$$

where v_E is the electrophoretic velocity.

It may be inferred that the electrophoretic velocity (or mobility) is proportional to the field and to zeta potential. The field can obviously be increased to increase the mobility but how can the zeta potential be varied? As already discussed it is the electrostatic repulsions between particles that lead to colloid stability; therefore, by increasing the concentration of added electrolyte the diffuse double layer can be compressed, so reducing the distance of closest approach and, therefore, the zeta potential. If sufficient electrolyte is added, coagulation or coalescence will occur as the Van der Waals attraction forces begin to dominate. If contact absorbing ions are added, these adsorb as the terminology suggests, on the particle surface within the inner Helmholtz plane and result in a sharp linear potential drop. These ions bring about coagulation more effectively than non-contact adsorbing ions which need to be added in larger quantities (assuming similar valency states) to bring about coagulation because they populate the outer Helmholtz plane.

Some of these later principles are embodied in the Schulze–Hardy rule which states that the precipitating effect increases markedly with increasing valency of the ion. The ion which is effective in causing precipitation of a colloid is the one which is opposite in sign to that of the colloidal particles. For a more complete discussion of the fundamentals of colloid science, references [15–17] should be consulted.

2. Applications

2.1. *Electro-osmotic processes*

2.1.1. Production of silicic acid. It is possible to produce pure silicic acid from solutions of waterglass contained in the anodic compartment of an electrolytic cell with a clay diaphragm providing separate anode and cathode compartments. An initial small voltage is applied which causes the waterglass to migrate into the cathode compartment. The voltage rises during the migration process owing to the lowering of the conductance of the solution and this is accompanied by electro-osmotic water transport. The process can produce very concentrated solutions of silicic acid.

2.1.2. Electro-osmotic dewatering of peat. This is one of the earliest examples of electrical methods applied to the removal of water. In the patent assigned to Schwerin [18] peat pulp was placed in a box with perforations in the base which acted as the cathode. The anode was placed on top of the peat. After application of the voltage and dewatering to a prescribed level the peat was removed. This process was operated batchwise and was therefore labour intensive. Schwerin [19], however, patented a continuous process in which the material to be dewatered was placed between two electrodes which also served as conveyors for the material to be dewatered. The lower electrode — the cathode to which the water was ‘pumped’ in the applied field — was permeable, and as the material undergoing dewatering was moved along between the conveyor belts the upper anode belt was gently pressed against the material so ensuring good contact with the electrodes. No details of dewatering rates or power consumption were given for this particular design. However, Schwerin [20] did provide experimental details for the case of peat contained between a wire gauze cathode and a plate anode. On applying a potential equivalent to 4–5 $\mathrm{V\,cm^{-1}}$ a solid crust containing 50–60% moisture was obtained and it was observed that between 13 and 15 kW h were required to remove 10^3 litres of water. (Further details regarding the patents assigned to Schwerin may be consulted in [21].)

2.1.3. Drying of cellulose-based materials. The drying of materials such as pulp, cotton, cloth, etc. has been investigated by Coblens [22]. In this process the material to be dried was contained between two nichrome grid electrodes which were then subject to pressure, removing some of the water. The applied pressure was then removed and both d.c. and a.c. currents were applied. The logic behind using both d.c. and a.c. current sources was that the d.c. component provided the electro-osmotic driving force while the a.c. components acted purely as a heat source. In reality, the heating effect probably outweighed the electro-osmotic contribution to the overall dewatering process. This hybrid electrical technique was used for the moulding of cellulose-based materials into preferred shapes.

2.1.4. Dewatering of limestone and clay. The electro-osmotic dewatering of finely divided limestone and clay particles suspended in water has been examined by ICI [23]. The apparatus consisted of two electrodes. The cathode floated on the surface of the slurry while the anode was located in the bottom of the tank and consisted of a shallow brass box. A perforated lid and a pipe were fitted to the anode box so that a vacuum could be applied to remove electrolytically generated gas and to assist the removal of water from the compacting slurry. A d.c. voltage of 230 V (tank depth 1.1 m) was applied, resulting in an initial current density of 8.3 $\mathrm{A\,m^{-2}}$ which, as the water moved to the cathode, increased to 25.8 $\mathrm{A\,m^{-2}}$. This current density was maintained until the dewatering rate began to fall. It was calculated that 1.89 kW h were required for the removal of 20 litres of water and over a 28 h period the water content of the limestone was reduced from 82.5 to 32.6% while gravity settlement over the same time period resulted only in a water content of 62.8%.

2.1.5. Hydraulic pressure/electro-osmosis. The use of hydraulic pressure in conjunction with electro-osmosis was cited by Coblens [24] and Fjell [25]. In this work animal, vegetable and mineral materials were subjected to electro-osmotic dewatering. The apparatus described by Fjell consisted of a cylindrical chamber containing vertical slits covered with a thin porous material which allowed water to pass through, but contained the material to be dewatered within the cylinder. The cathode, the lower electrode at which water was removed electro-osmotically, rested on a perforated disc. The anode was positioned vertically above the cathode and was carried on an advancing press plate. Schwerin also described the use of an electro-osmotic filter press [26].

2.1.6. Adaptations to dewatering designs. The Motherwell Bridge and Engineering Co. Ltd patented several dewatering designs [27], many based on helical bladed scrapers rotating concentrically in an outer tube transporting the sludge from the inlet to the discharge point during the dewatering process. The inner helical electrode was connected as the cathode and the outer tube as the anode; water was attracted towards the cathode where it passed through perforations provided in the cathode. Another design employed a perforated endless belt to which were attached blades at right angles. These aided the transfer of sludge through the electro-osmotic dewatering zone and transported the dewatered solid to the discharge zone.

2.1.7. Dewatering of sewage. A patent relating specifically to the dewatering of sewage has been described by Greyson [28]. This apparatus consisted of a rectangular container, with an inclined base, fabricated from a fine metal mesh with holes small enough to prevent passage of sewage fines. The metal mesh also served as the cathode. Suspended above this was a movable metal grid anode fabricated from platinized titanium which could be advanced to maintain contact with the compacting sewage cake. The dewatered material was subsequently scraped off the cathode screen. As a result of the reduced moisture content it could more readily be disposed of as landfill or fed with other high calorific waste products to an incinerator. Greyson also found that the cathode cake, even when in contact with a 2% solid suspension could be dewatered to levels of solids in the region of 20%. Levels of solids in the range 30–35% could be attained, but only with an increase in the energy requirement. The increase was attributed to the transition between the removal of bulk and bound water, the latter corresponding to the higher energy requirement. The most important conclusion drawn by Greyson was that electro-osmotic dewatering occurred with all sewage sludges regardless of their prior treatment or geographical location. He also concluded that electro-osmotic dewatering sewage sludge was economically competitive with other dewatering techniques.

2.1.8. Use of freezing in dewatering process. To increase the dewatering energy efficiency above 20–30%, Simon and Carves Ltd [29] have utilized freezing to rupture the sludge cell walls, releasing the bound water and enabling electro-osmotic dewatering to continue more economically. The apparatus consisted of two endless nylon mesh belts contacting two stainless steel electrodes. The first stage in the overall process consisted of an initial electro-osmotic dewatering zone which was followed by a freezing zone. After freezing the sludge advanced into a thawing zone and subsequently into a second electro-osmotic zone where a sludge of between 30–40% was produced.

2.1.9. Electro-osmotic water transport. This method can also provide a means of reducing the frictional losses between two conducting bodies separated by a moist solid. By applying a small voltage between the two bodies, water can be moved towards the negative electrode and acts as a lubricant [30]. This approach has been applied to a tractor-drawn ploughshare where it has been shown that it is possible to reduce the power required to move the ploughshare through the soil by making it the cathode, so reducing the frictional loss with the soil [31]. Similar reductions in friction have been achieved in pile driving operations and during the extrusion of clay bodies [32, 33]. The Dillingham Corporation Limited (Canada) have used electro-osmotic techniques to stabilize the silt-beds during the construction of the Kootenay Canal [34]. In this application water was caused to move away from the working area, where construction was taking place, by cathodes buried some distance away.

The above has dealt exclusively with electro-osmosis, i.e. where water and, to a lesser extent, solids have been transported to the cathode. However, several important processes rely on electrophoretic transport to effect concentration at the anode and electro-osmotic transport to remove water at the cathode.

2.2. *Electrophoretic processes*

2.2.1. Deposition of rubber from latex. The earliest published application of electrophoresis to an industrial process is that of rubber from latex by electrophoretic deposition, and was described in a British Patent granted to Cockerill in 1908 [35]. The apparatus was based on an endless belt cathode and anode; the two belts were kept apart by small insulating strips. The cathode was located above the anode and both were fabricated from aluminium plates linked together with pins.

A variation on this process was patented by Sheppard and Eberlin [36]. They found that sulphur, fillers and vulcanization accelerators could be codeposited with the rubber. For example, thiosulphate added to the rubber latex could be anodically oxidized to sulphur *in situ* during the deposition process.

2.2.2. Thickening of kaolin. Probably the best known electrophoretic process is that employed in the thickening of kaolin [37, 38]. This process was operated by the Carlsbad Kaolin Electro-osmosis Company at Prochezau, and similar units as used in Germany, Austria and Czechoslovakia (up to about (1940) have been operated in Stoke on Trent, UK [39]. The kaolin (hydrated aluminium silicates) was fed in at the bottom of the apparatus and was prevented from settling or stratifying by paddles. An anode cylinder of hardened lead, containing 15% antimony and covered with a layer of vulcanized rubber, was partially immersed in the slurry. The cathode consisted of a semi-cylindrical metallic mesh located coaxially with the anode. On applying a voltage, the kaolin particles migrated to the anode where they formed a compact layer, which underwent further dewatering by electro-osmosis because of the porous nature of the deposit. The compacted layer of kaolin was subsequently scraped off the rotating drum. The remaining dilute clay liquor was recycled to the front end of the extraction plant.

It was reported that to dewater 30% solids slurry to 65% solids required typically 80 kWh tonne^{-1} of dry clay. A machine based on Schwerin's design [37] consisted of an anode 1.5 m in length and 0.26 m in diameter and produced between 200 and 250 kg of dry clay per hour for a current of ~ 170 A at 100 V.

2.2.3. Dewatering of cement slurries. Electrophoretic deposition has been applied to Portland Cement by Hall and in a series of articles he discussed his ideas on the construction of a suitable device for dewatering cement slurries [40]. In this series of articles he presented data on the installation and operational costs of a plant based on an endless belt anode. He further discussed the economic advantage of a higher than normal slurry feed, produced by continuous electrophoretic deposition, in reducing the capital and running costs of a cement drying kiln. He pointed out that the cost reductions could be reflected either in lower capital costs for the same throughput or conversely in a higher throughput for the same plant size.

2.2.4. Electrophoresis/mechanical dewatering. Electrophoresis has been used to supplement mechanical dewatering. Centrifugal separation coupled with electrophoresis for the separation of solids from fluid suspension is an example of this approach. In the case of clay, the initial solids content could vary from as low as 5% to as high as 35%. The centrifuge described by the Bird Machine Co. [41] was based on a frusto-conical shell. The large diameter end was sealed by an end plate and the small diameter end left open. Passing through the centrifuge shell (anode), and axially located, was a worm or screw with widely spaced spiral turns or convolutions of progressively diminishing radius toward the open end of the centrifuge but spaced from the wall by a considerable gap. The centrifuge and worm were rotated in the same direction, but the speed of rotation of the worm was greater than that of the centrifuge; this resulted in the movement of solids out through the open end of the centrifuge.

2.2.5. Concentration of rubber latex. This formed the basis of a large industry in Malaya up to the late 1950s. Although termed electrodecantation, a term coined by Pauli [42–44], the process was electrophoretic in nature. The principle of the technique has been outlined by Murphy [45]. It utilizes the fact that negatively charged latex particles will move in an applied electric field towards the anode. By placing a semipermeable membrane in front of the anode the latex particles were prevented from contacting the anode and latex concentrated on the face of the membrane. If the current density was maintained at a sufficiently low value, latex could be concentrated to 50% in the upper region of the cell, due to its lower density, leaving a clear serum in the lower region of the cell. In order to increase the output from the cell several membranes were placed between the electrodes. Concentrate was drawn off continuously from the top of the cell and clear serum from the bottom of the cell at a rate which matched the inlet flow of fresh latex. The choice of the feed concentration and the applied current density was crucial to the operation of the cell. If a high feed concentration (30% latex) and high current density were used, latex deposited on the membrane as a solid – not the preferred product form. If, however, a low current density was employed, a reduced membrane deposit was obtained and a latex concentrate was also obtained – the preferred product. In order to reduce membrane deposition the current was reversed every 4 min. In this way it was possible to effect concentration without deposition. Typically, concentrations of 50% latex were obtained; solids levels beyond this were not discussed. It is understood that the formation of solid on the membrane was the major problem in operating this latex plant.

In the case of PTFE [46] and other polymers [47] deposition has generally been used to insulate wire. However, du Pont [46] have used the electrodecantation technique to thicken PTFE dispersions up to 74% solids. Again, current reversal was applied every 3–5 min.

2.3. *Electrophoretic coating processes*

In the field of coatings, electrophoresis is used extensively in the electrocoat process for the coating of car bodies. In this process, the car body is made either the anode or cathode depending on the particular paint resin in use. On application of a d.c. supply the resin is attracted to the car body where it is deposited electrophoretically and then stoved onto the body. For an introduction to the electrophoretic deposition of paint references [48, 49] may be consulted.

Electrophoresis has also found other uses in the coatings industry and metal oxides, carbides, borides and alloys [50–53] have been deposited from an organic media onto metal substrates, e.g. molybdenum, kovar. Depending on the substrate, different physical treatments are applied, e.g. isostatic densification, sintering in hydrogen, sintering in argon, or a combination of one or more of these treatments, resulting in a very adherent coating. The coatings prepared by this technique are reported to give a three-fold increase in tool life over an uncoated, high-speed steel drill of the same geometry. In other examples improved abrasion resistance at elevated temperature has been claimed.

2.4. *Electrophoretic forming*

Interest in the forming of ceramic bodies by electrophoretic means has grown over the past 40 years [54, 56] and an upsurge in the technology is apparent from an examination of the literature. This has in part been due to the use of β-alumina in the sodium–sulphur battery programme [57–60]. Briefly, alumina powder is milled with a solvent medium in an alumina ball mill for a predetermined time. Depending on the solvent medium used, the grinding and ageing times affect the zeta potential of the particles and are consequently important experimental parameters. Anodic electrophoretic deposition is then carried out between 280 and 1400 V cm^{-1} on a stainless or other scratch-resistant alloy mandrel to produce the 'green body' prior to the final sintering operation.

The forming of clay bodies as a continuously extruded band for the production of wall tiles has been patented by Chronberg [61, 62]. The device employs two zinc-plated drum anodes which rotate in opposite directions. The cathode is located above and between the drum anodes with the 'slip' fed continuously into this region and returning to a holding tank. On start-up the anodes are in contact and as clay deposits one of the anodes is slowly moved outwards until the desired thickness of clay is obtained. The extruded clay band is then transferred by a moving belt to the next unit process.

2.5. *Electrophoretic separations*

Electrophoresis applied to biological systems (protein, nucleic acids, etc.) dates back to about 1900 and has been used in both the analytical field and in the separation of proteins on a larger scale. The separation process relies on the fact that each molecule has a different mobility. The mobilities are not generally too different, so high fields and long path lengths (or conversely long residence times) are necessary to effect the separation in highly buffered solutions.

Details of electrophoretic separation techniques can be found in references [63–68]. An electrophoretic separator has been developed by AERE Harwell [69] for blood plasma separation. The device employs a vertical rotating outer cylinder to provide stable laminar flow of the buffer electrolyte, so avoiding convective turbulence which is normally caused by resistance heating. The mixture to be fractionated is injected into the carrier solution through a thin slot in the base of the device and is separated in the electric field as it travels upwards in the inter-electrode gap. Provision of a splitter in the outlet of the cell provides for up to 30 fractions to be collected.

2.6. *Electrophoresis applied to the purification of water*

Water purification and treatment is an area of continuous worldwide study and the application of electrophoretic techniques has been one of the many processes examined in the field of 'membrane processes'. Bier and others [70–73] have examined the removal of particulate matter such as silt, algae etc. as well as humic acid, proteins etc. using the technique of forced-flow electrophoresis. They used a filter (cloth or porous PVC) to separate the anode from the cathode, so that each electrode was contained in a separate compartment. The raw water was fed or pumped through the anode chamber, some of the liquid passing through the filter into the cathode chamber. The negatively charged impurities entered the anode chamber and migrated towards the anode in the applied field. If the migration of the impurity was equal to or greater than the hydraulic flow rate, the impurities did not pass through.

A variation of forced-flow electrophoresis has been applied by Henry and co-workers [74, 75]. Their apparatus utilized a combination of hydraulic shear flow parallel to the electrodes to minimize accumulation of solid particles on the filter, and electrophoretic migration further to minimize solid accumulation on the filter. In both the above techniques electro-osmotic water flow enhanced the filtration rate.

2.7. *Application of dielectrophoresis*

On the fringe of electrokinetics is the phenomenon known as dielectrophoresis. This is the behaviour of neutral matter in a non-uniform electric field.

It is possible to express the electric force, F, on a neutral body in a static field at equilibrium as:

$$F = (p\nabla)E_e \tag{11}$$

where p is the constant dipole moment vector, ∇ is the three-dimensional vector operator, and E_e is the external field.

If the dielectric neutral particle is isotropically, linearly and homogeneously polarizable then the electric force can be expressed in terms of the applied external field, namely

$$F = 1/2\,\alpha V \nabla |E_e|^2 \tag{12}$$

where α is the dipole moment per unit volume in unit field, and V is the volume of the particle. This implies that the force is independent of the direction of the applied field and is dependent only on the volume and polarizability of the body and the square of the external field.

Applications to liquid pumping, classification, separation of minerals and biological systems have been examined using dielectrophoresis and are outlined by Pohl [76]. Theoretical studies have also been carried out in the author's laboratories [77] on the effects of non-uniform fields on the long-range electrical forces of translation.

The above survey of the electrokinetic literature is by no means exhaustive, but it is hoped that it will allow the reader to appreciate more fully a little-publicized area of electrochemistry. In a further two papers [78, 79] the electrophoretic deposition of ball clay and other materials will be examined.

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