Electric Field Driven Separations: Phenomena and Applications

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REVIEW

Electric Field Driven Separations: Phenomena and Applications

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INTRODUCTION

The efficiency of separation processes can usually be assured either by an energy input or by external forces. The majority of conventional separations applies mechanical or thermal energy in combination with pressure or gravity forces. The ability of superimposed electric fields to improve separation processes has been well known for many years. The familiar industrial applications range from solid–solid separation in the beneficiation of ores in the mining industry, coalescence of "water-in-oil" emulsion in the petroleum industry, to cleaning of exhaust gases from solid particles in various technologies.

Over the past two decades an extensive effort has been directed to finding new applications of electrical energy in the field of heat- and mass-transfer operations and phase-separation processes. In many situations an electric field driven process can be considered competitively alongside mechanically or thermally driven operations. Some notable examples are liquid–liquid extraction, dewatering of fine suspensions, and electrophoretic separation of biological materials.

The direct utilization of electrical energy offers several advantages, particularly in multiphase systems. First, an electrical energy supplied to the system interacts selectively with an interface and to a lesser degree with the bulk. This can increase the rate of heat or mass transfer across the interface. Second, a superimposed field exerts electric body forces which contribute to the existing gravity force and which can be used for a levitation or a stabilization of the dispersed phase. Finally, due to the reversible

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nature of the electric stresses, the work done by electric forces is nondissipative. Therefore, the energy efficiency of electrically driven processes should be higher in terms of the second law compared to traditional mechanical or thermal processes.

In spite of these advantages, little is known either of the mechanism of the electrically aided processes or of the important parameters of fields or systems responsible for the effects. It is the purpose of this review to evaluate the major developments in this area and to discuss the engineering applications of the phenomena. The vast literature makes it impossible to cover all aspects of electrically driven separations in one review. Moreover, a number of reviews are available on particular processes, e.g., electrical coalescence (1), electrofiltration (2), and solvent extraction (3).

Therefore the treatment in this review has a general approach. In order to understand the underlying principles of operations, the second section describes the thermodynamics of systems in an electric field, while the third discusses the hydrodynamics of two-phase systems in an electric field. Section five presents some engineering applications. They are restricted to situations where a liquid is a continuous phase and the dispersed phase is formed of droplets of another immiscible liquid, gas bubbles, or fine solid particles. The paper concludes with some suggestions for the future work on this subject.

2. THERMODYNAMICS OF FLUIDS IN AN ELECTRIC FIELD

An electric field penetrates into a dielectric fluid and the field energy contributes to the internal energy of a system. This interaction has a great effect on thermodynamic properties of a dielectric and it also leads to the change in a phase equilibrium (4). The formulation of thermodynamics in electric fields requires some knowledge about the electric fields, including the relevant mathematical relationships (5, 6), that will be presented next.

2.1. Equations of Electrostatics

In the case of electrostatics, the Maxwell equations reduce to Gauss' law

$$\nabla \cdot \mathbf{D} = \rho_e \tag{1}$$

and to Faraday's law:

$$\nabla \times \mathbf{E} = 0 \tag{2}$$

The electric field in a polarizable fluid involves contributions from the free charges (displacement field) and from the induced polarization:

$$\mathbf{D} = \epsilon_0\mathbf{E} + \mathbf{P} \tag{3}$$

where the polarization $\mathbf{P}$ is the induced dipole moment per unit volume. We restrict our analysis to isotropic and linear dielectrics where

$$\mathbf{D} = \epsilon\mathbf{E} \tag{4}$$

and the permittivity ϵ depends on the fluid density and the temperature but it doesn't depend on the electric field. The equations of electrostatics are completed by the charge conservation equation:

$$(\partial\rho_e/\partial t) + \nabla\cdot\mathbf{J} = 0 \tag{5}$$

2.2. Phase Equilibrium in Polarized Systems

To study the effect of an applied electric field on phase equilibrium, the well-known thermodynamic concepts can be used, but some of them must be modified.

In order to establish an electric field in the system, additional work should be done on the system by external forces. For a system of volume V this extra work is (4)

$$W_e = \int_V \left(\int_0^D \mathbf{E}d\mathbf{D} \right) dV \tag{6}$$

and this expression gives also the density of energy storage in a system in an electric field equal to $\frac{1}{2}\epsilon E^2$. The fundamental equation for an open multicomponent system will be given by

$$dU = TdS - pdV + Ed(DV) + \sum \mu_i dn_i \tag{7}$$

According to this equation, the state of the system is described by the intensive variables T, p, and μ_i and the electric field E.

In the thermodynamics of systems in an electric field the concepts of the internal energy and that of the pressure are further modified. The modified internal energy of a fluid in an electric field is defined as the internal energy

of the total system (the fluid including the space) diminished by the energy needed to establish a field in the space of volume V:

$$U^* = U - \tfrac{1}{2}\epsilon_0 E^2 V \qquad (8)$$

The concept of the pressure for a fluid in an electric field is somewhat different from the pressure in the absence of a field. The augmented-pressure p^* (ρ, T, E) of a fluid in an electric field is equal to the sum of the zero-field pressure p_0 (ρ, T) at the same density and temperature and the extra terms derived from the electric stresses:

$$p^* = p_0 + p_p + p_s \qquad (9)$$

where $p_p = \tfrac{1}{2}(\epsilon - \epsilon_0)E^2$ is the fluid polarization pressure

$p_s = -\tfrac{1}{2}\rho\left(\dfrac{\partial \epsilon}{\partial \rho}\right)_T E^2$ is the electrostrictive pressure

It is now possible to formulate the modified fundamental equation

$$dU^* = TdS - p^*dV + Ed(PV) + \sum \mu_i dn_i \qquad (10)$$

and the modified Gibbs free energy:

$$dG^* = -SdT + Vdp^* - PVdE + \sum \mu_i dn_i \qquad (11)$$

According to the above relationship, the chemical potential depends not only on the temperature T, the augmented pressure p^*, and the concentrations of species, but also on the electric field.

Criteria of equilibrium in electromagnetic systems in terms of extensive properties are the same as those of classical thermodynamics; for example, an isolated system of constant energy and volume will attain equilibrium at the maximum entropy. An analysis of conditions of equilibria in multiphase systems in terms of intensive properties shows that the criteria for equilibrium for heat transfer and transfer of species between phases remain unchanged in the presence of a field, whereas the criterium of mechanical equilibrium is altered from the usual equality of pressure in the phases (4). The condition of thermal equilibrium means equal temperature in all phases, and the condition of chemical equilibrium means equal value of chemical potential for each substance in all phases. However, the chemical potential in electromagnetic systems also depends on the electric field and
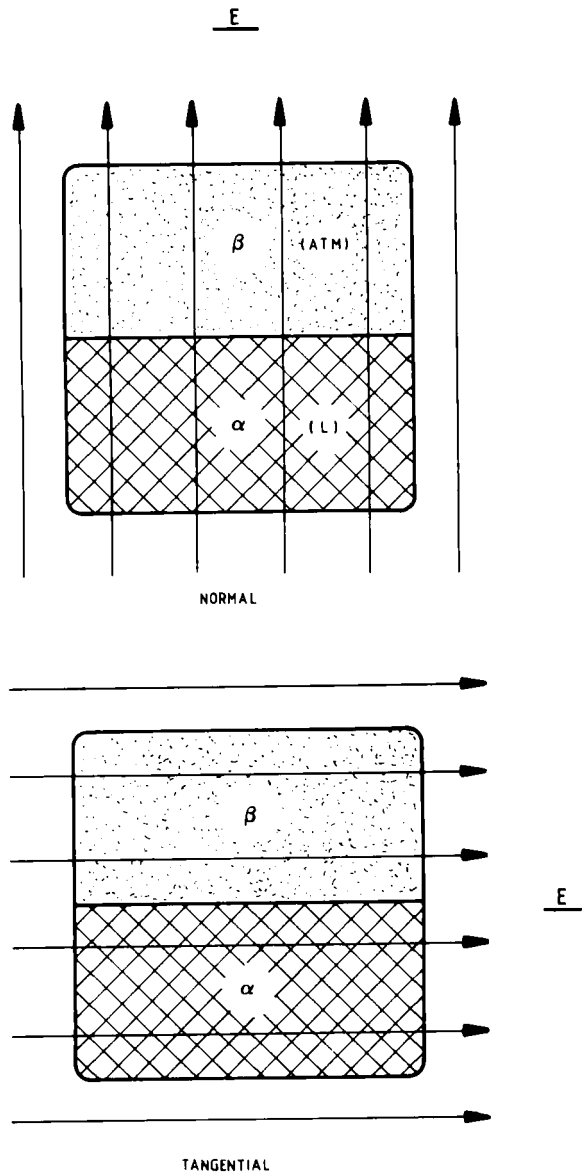
FIG. 1. Systems of two phases α and β with electric field oriented normal and tangential to the phase boundary.

thus the presence of an electric field is able to change the activity coefficients of some species (7).

The condition of mechanical equilibrium in the presence of a field depends on the orientation of the field and the geometric arrangement of the phases, as sketched in Fig. 1. If the electric field is oriented normal to the boundary of two phases α and β (electric displacement is continuous across the boundary), then the condition of mechanical equilibrium is

$$p_\alpha^* + \frac{P_\alpha^2}{2\epsilon_0} = p_\beta^* + \frac{P_\beta^2}{2\epsilon_0} \tag{12}$$

whereas in the case where a phase boundary is oriented tangential to the field (electric field is continuous across the boundary), this condition now becomes

$$p_\alpha^* = p_\beta^* \tag{13}$$

In the latter case the pressure is uniform through the system whereas in the former the condition of equilibrium is a nontrivial pressure difference between the two phases. For example, let us consider a boundary between a polarizable liquid ($\epsilon_L > \epsilon_0$) and the atmosphere ($\epsilon_{ATM} = \epsilon_0$). In the case of a normal field at the interface between phases:

$$p_L^* + \frac{P_L^2}{2\epsilon_0} = p_{ATM}^* = p_{0\,ATM} \tag{14}$$

The presence of an electric field reduces the thermodynamic pressure in the liquid which can fall below the vapor pressure, leading to a so-called "electrical cavitation" (8). Similar effects are manifested at an interface between a perfectly conducting liquid and a nonpolarizable atmosphere.

3. ELECTRIC FIELD EFFECTS ON HYDRODYNAMICS

The effects of electromagnetic fields on fluid mechanics have been the subject of fundamental studies for at least a century. This interest results from wide field–fluid interactions in meteorology and more recently from a technological potential for applications in areas as diverse as nuclear fusion, ink-jet printing, medicine, and chemical engineering. The broad field of fluid mechanics in the presence of electromagnetic field is usually divided into three main categories:

Magnetohydrodynamics—the fluid mechanics of electrically neutral but conducting fluids in the presence of a magnetic field (9).

Ferrohydrodynamics—the science of the interactions between artificially made magnetic liquids and magnetic fields (*10, 11*).

Electrohydrodynamics—the subject of this paper, the branch of fluid mechanics concerned with electric field effects (*12, 13*).

Electrohydrodynamics deals with the fluid mechanics influenced by electrical forces which can arise either due to free charges present in a fluid or due to polarization of matter.

3.1. Momentum Transfer and Forces in Fluids Stressed by an Electric Field

The motion of a fluid under an applied electric field can be described by the usual principles of conservation of mass and of momentum. For incompressible fluids these principles are the equation of continuity

$$\nabla \cdot \mathbf{v} = 0 \tag{15}$$

and the equation of motion (*4, 12*):

$$\rho \frac{D\mathbf{v}}{Dt} = \nabla \cdot \mathbf{T} + \rho \mathbf{g} \tag{16}$$

where $D\mathbf{v}/Dt$ is the substantial derivative of the velocity with respect to time and $\mathbf{T}$ is the total stress tensor. The total stress is usually decomposed into the mechanical, the electrical, and the viscous component, respectively:

$$\mathbf{T} = -p_0(\rho, T)\mathbf{I} + \mathbf{T}_e + \mathbf{T}_v \tag{17}$$

The electric component $\mathbf{T}_e$ can be expressed using the thermodynamic concepts introduced in the previous section (*8*):

$$\mathbf{T}_e = -(p_s + p_p + \tfrac{1}{2}\epsilon_0 E^2)\,\mathbf{I} + \mathbf{DE} \tag{18}$$

Introducing the thermodynamic and field parameters into Eq. (16), one gets the generalized equation of motion:

$$\rho \frac{D\mathbf{v}}{Dt} = -\nabla(p^*) + P \cdot \nabla E + \eta \nabla^2 \mathbf{v} + \rho \mathbf{g} \tag{19}$$

which reduces to the well-known Navier–Stokes equation in the absence of electrical effects.

The equation of motion can be represented in an alternative form using the concept of the body forces (per unit volume):

$$\rho\frac{D\mathbf{v}}{Dt.} = \mathbf{f}_p + \mathbf{f}_e + \mathbf{f}_v + \mathbf{f}_g \tag{20}$$

The terms familiar from fluid mechanics are the pressure force $\mathbf{f}_p = -\nabla p_0$, the viscous force $\mathbf{f}_v = \eta \cdot \nabla^2 \mathbf{v}$, and the gravitation force $\mathbf{f}_g = \rho\mathbf{g}$. The electric body force $\mathbf{f}_e$ is given as (14)

$$\mathbf{f}_e = \rho_e\mathbf{E} - \tfrac{1}{2}E^2\nabla\epsilon + \nabla\left[\tfrac{1}{2}\rho\left(\frac{\partial\epsilon}{\partial\rho}\right)_T E^2\right] \tag{21}$$

The first term is the ordinary electrostatic Coulombic force, the second term represents a force in an inhomogeneous dielectric in an electric field, and the last term (the electrostriction) gives a force on a dielectric in an inhomogeneous electric field. Electrical forces are in general quite small, but in situations where the other body forces are small, the forces associated with an electrical field become significant.

Most of the electrically driven separation processes apply one or two of these driving forces. Electrophoretic separations rely on the application of the momentum exchange due to the charged particles (term 1 in Eq. 21) whereas the momentum transfer due to different phases, e.g., solid particles or gas bubbles in a liquid (term 2 in Eq. 21) is called "dielectrophoresis."

3.2. Surface Area Generation Using Electric Fields

Dispersion systems are commonly used to increase the interfacial area and improve the rates of heat and mass transfer between one or more phases. This section deals with the application of electric fields to increase the interfacial areas, whereas the next section discusses the electrical enhancement of mass transfer coefficient.

The majority of studies on surface area generation has been devoted to systems composed of electrically conducting droplets in insulating liquids. We begin the brief survey with an analysis of the stability of such systems subjected to an electric field because the disruptive electrical stresses in excess can overcome the cohesive effect of interfacial tension, resulting in an electrostatic break-up of the disperse phase. Taylor (15) has shown that a neutral droplet placed in a dc electric field elongates due to polarization in a nearly prolate ellipsoidal shape (Fig. 2), whose major axis lies parallel
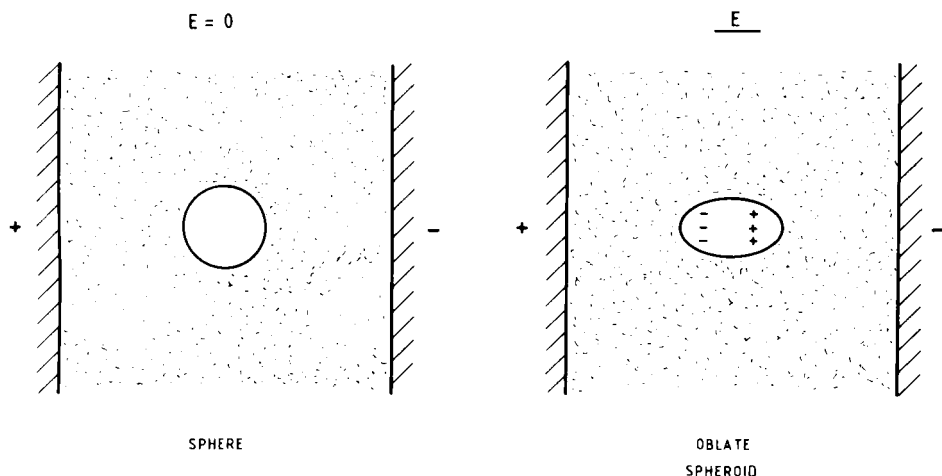
E = 0

E

SPHERE

OBLATE
SPHEROID

FIG. 2. Droplet deformation in an electric field.

to the electric field lines. The eccentricity of the ellipsoid is an increasing function of the Weber electrostatic number (8, 16):

$$\mathrm{We}_e = \frac{\epsilon \cdot E^2 \cdot d}{\sigma}$$

At the critical value of $\mathrm{We}_e = 0.420$, the instability point is reached and the original droplet disintegrates into a number of smaller daughter droplets.

Another kind of electrostatic disintegration can occur when a droplet acquires charge, for example, by contacting a charged electrode. Rayleigh (17) showed that a charged drop becomes unstable if a drop charge exceeds $Q > 8\pi \sqrt{\epsilon_0 \sigma R^3}$ (MKSA), and then a drop ejects some charged daughter drops.

Figure 3 shows two distinctly different electric techniques that have been examined to create large interfacial surface area in liquid–liquid systems. Such areas have been obtained in most designs (18–23) by droplet formation in charged nozzles or orifices. The force balance during drop formation is satisfied by the interfacial tension, gravitational, and electrostatic forces (24). If the electric field strength is low and the electrostatic and gravitational forces act in the same direction, single drops of smaller volume are formed than at the no-field condition. At high field strength the electric stresses can dominate and the discrete droplet regime is changed into the
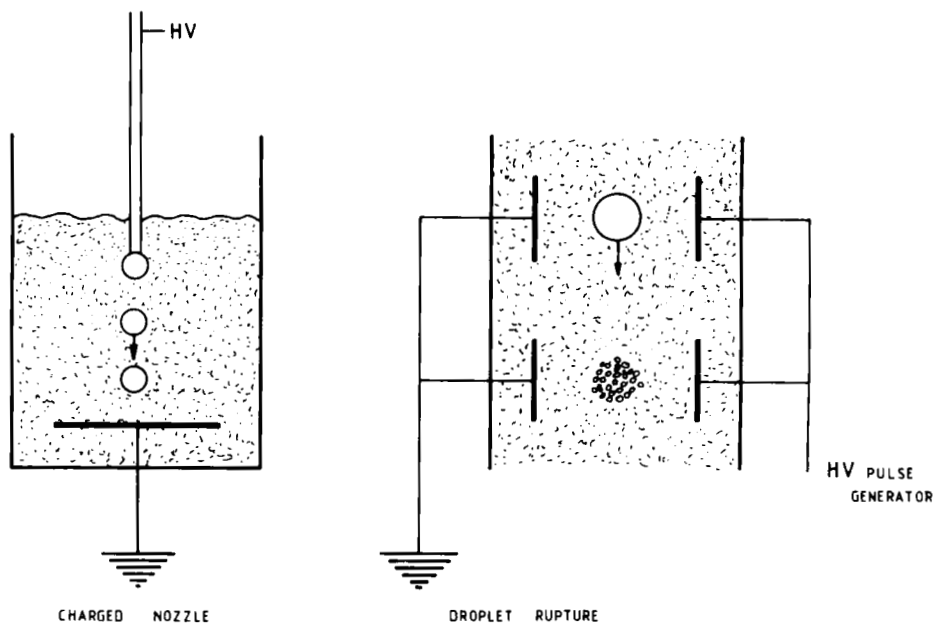
FIG. 3. Surface area generation in an electric field.

dispersion-regime (jetting) and a continuous stream of very small droplets is produced (25, 26).

The second way of electrical dispersion is the direct use of strong electrical stresses to rupture a liquid–liquid interface. The most efficient are high-intensity pulsed electric fields which allows the creation of a very large interfacial area by means of droplet rupture into extremely small droplets, even as small as 5 μm (27–29). Another approach to a direct electrohydrodynamic dispersion is based on the electric field induced instability of a flat liquid–liquid interface (30, 31). The dispersion of a water phase has been achieved from a water film which flowed down an inclined plate electrode into a continuous dielectric liquid phase.

The application of electric size reduction of gas bubbles in a liquid has been much less investigated. The studies have been restricted to the formation of small bubbles from charged needles in insulating liquids under a strong nonuniform electric field (32–34). Substantial bubble size reduction was observed, but the mechanism of this dispersion techniques is not completely elucidated. It involves electrical pressure effects, the existence of corona discharge, and electrohydrodynamical flow (35).

Finally, it should be stressed that in both investigated systems (liquid–liquid and gas–liquid), the energy input of an electrical technique is estimated to be about 1% of that required when mechanical agitation is used to produce droplets or bubbles of the same size (35, 36).

4. MASS TRANSFER IN AN ELECTRIC FIELD

Many separation processes such as solvent extraction, gas–liquid absorption, or liquid–vapor distillation involve a contact between a dispersed phase in the form of droplets or bubbles and a continuous fluid phase. The mass transfer rate in these systems is proportional to the interfacial surface area and to the overall mass transfer coefficient. The application of electric fields to increase the interfacial contact area has been discussed in the preceding section whereas this section concerns the electrical enhancement of the mass transfer coefficient in dispersed systems.

A number of experimental and theoretical studies has been made on electrically augmented mass transfer separations, in particular on electrical dropwise extraction. Most of the experimental results demonstrate that significant transfer rate enhancement can be achieved by using electric fields, typically the rise is by a 2 to 6–10 factor compared to the no-field case (18, 37). On the other hand, rather limited theoretical studies have been conducted on the subject matter. We describe the most important mechanisms of mass transfer enhancement below.

It is generally known that the specific rate of mass transfer depends on the physicochemical properties of a system, as well as on the hydrodynamic state of the boundary between contacting phases. The available theoretical analyses suggest that the mass transfer improvements are mainly obtained by producing a higher degree of fluid turbulence within and around dispersed phase as the result of the interactions between the field and the interface, whereas the physicochemical properties of a system are probably not changed by the field.

Different mechanisms promoting interfacial turbulence operate on a dispersion system in the presence of an electric field:

   Higher terminal drop velocities resulting from electrical forces of attraction exerted on the drops in the direction of motion (18, 26, 38, 39).
   Generation of the electrically driven circulating flow in the neighborhood of the interface (40–43).
   Alteration of the velocity profiles within and around individual droplets due to the oscillations by pulsed electric fields (44–47).
   Interfacial-tension-induced surface flows (Marangoni effects) due to the presence of electric charges (48–51).

All the above mechanisms can be explained on the basis of the behavior of electrical charges in liquid dispersions (8). Most liquids are characterized by a very small relaxation time that is the ratio of the electrical permittivity to the conductivity. Therefore, the charges initially present in the bulk of a continuous liquid phase will be quickly transported to an interface of the dispersed phase, where the electrical conductivity and permittivity are discontinuous. This will result in a permanent charge build up at the drop (bubble)/continuous phase interface.

The first mechanism operates in a dc electric field where the Coulomb force causing motion is opposed by the form and viscous drag forces. It has been shown (18) that the resulting terminal velocity of droplets can exceed two times that of uncharged droplets of the same size. The circulation motion in the neighborhood of the interface due to the second mechanism appears even at a stagnant drop. The previous treatment (see Section 3) has illustrated that a uniform field acting on the charge distribution produces stresses on the drop surface. The normal stress is responsible for the drop elongation, whereas the tangential stress generates the circulating creeping motion (52). Such flow can significantly increase the mass transfer rate between the stagnant drop and the continuous phase (40, 41). On the other hand, this mechanism plays no role in the mass transfer enhancement for a translating drop in an electric field (42).

In the case of translating drops, the rate of mass transfer can be increased by electric-field-induced oscillations. Forced droplet oscillations have been shown to enhance the mass transfer rate by 30 to 40% (44) and the direct heat transfer rate by 200 to 300% (53). Theoretical analysis based on the flow visualization technique has shown (45) that the induced oscillations alter fluid motion in and around droplets, and the resulting velocity can be modeled by the vectorial addition of a circulatory Hadamard–Rybczynski flow and an oscillatory motion caused by the prolate-to-oblate ellipsoid shape change of the droplet.

The last of the above-mentioned mechanisms can be attributed to the local variation in the surface density of electric charges, which gives local variations in the effective interfacial tension and can lead to interfacial-tension-induced surface flows and increased mass transfer rates (48).

5. APPLICATION OF ELECTRIC FIELDS TO SEPARATION PROCESSES OCCURRING IN LIQUIDS

Electric separation techniques have been in commercial use for nearly 70 years. The applications which have the longest history and are still in use are the beneficiation of ores in the mining industry, electrostatic gas cleaning, electrical emulsion breaking, and dielectric heating and drying. Recent advances in understanding electric field phenomena are not only

interesting studies by themselves but they have also stimulated incentives for the improvement of existing separations and for the introduction of new processes. Electrically driven separations nowadays receive wide attention both on a laboratory scale and in industrial practice, especially as fossil fuels become less accessible. Specific cases of electric separations are considered below in some detail.

5.1. Electrical Coalescence

The problem of effective removal of dispersed droplets from another continuous liquid phase is important and widespread in many industrial processes. The classical example of separating emulsified drops in liquid–liquid extraction is performed in stagewise mixer-settlers, where rapid phase separation is required after each mixing step. The fundamental drawbacks of existing gravity separators are their large size and high capital costs.

Of the many proposed different improvements of phase separation (54) (e.g., additives, packings, centrifuges), the application of an electric field seems to be the most promising. Electrical coalescers have been successfully used over many years for the removal of water during desalting of crude oil in the petroleum industry (1). Electrical coalescence has recently been considered as a promising technique in other fields such as the liquid membrane extraction process, where the breaking of a liquid emulsion is a key step in this technology (55–57), direct liquid–liquid emulsion heat transfer (e.g., water desalination), and separation of two liquid phases formed as the product of reaction of synthesis.

Efficient demulsification can be achieved both with dc fields (58–64), particularly pulsed dc fields (65–68), and more commonly with ac electric fields (67–71). In spite of a relatively wide application, the mechanism of electrical coalescence is poorly understood because of the complexity of hydrodynamical and electrical phenomena. The entire process of liquid–liquid separation proceeds in three stages. During the first stage, small droplets coalesce and grow into larger drops which settle easily in the next stage. The final stage involves coalescence of large drops with the continuous phase. The presence of an electric field probably promotes all stages; however, the way in which it occurs remains in doubt.

A number of different mechanisms have been proposed, and they involve such effects as chain formation, electrophoresis, dielectrophoresis, dipole coalescence, and random collision (1, 66). The formation of chains of droplets oriented along the electric field lines originates from the induced polarization forces (55). In systems with a relatively high conducting dispersed phase (typically water), this phenomenon can lead to sparking and a short-circuit. An increase in the number of random collisions has been

proposed (*59*) as a dominant mechanism in systems with a low conducting continuous phase where droplets with stable charges travel between electrodes, collide with each other, and coalesce. The dipole coalescence is due to an interaction between induced dipoles that tend to line drops up, bring them closer, and finally cause coalescence. Electrophoresis and dielectrophoresis are described in Section 3.

5.2. Electrically Driven Solvent Extraction

The process of electrically augmented extraction has received considerable attention over the past two decades. A comprehensive review on this subject has recently been published by Scott (*3*). Contrary to the previously described coalescence, electrically augmented extractors are not yet widely used in industry. However, recent developments achieved on a laboratory scale demonstrate the expected economic advantages of the direct use of electrical energy in this area.

As mentioned before, the efficiency of solvent extraction depends upon both the interfacial liquid–liquid area and the overall mass transfer coefficient which is controlled by the level of turbulence near the interface. In order to provide a large contact area and high turbulence, an extra input of mechanical energy is supplied to the conventional extraction equipment. This is usually in the form of agitation as in rotary-agitated columns (e.g., Oldshue–Rushton column) or of pulsation as in reciprocating-plate columns (*72*). In this respect an electric extraction can be considered as an example of energy-augmented mass transfer separation processes. The specific advantages of the direct utilization of an electrical energy is its selective interaction with the interface or with the dispersed phase only, whereas the mechanical energy influences all the phases present in the system, which is not generally required. For this reason the use of electric energy is more efficient than that of other energy forms. Typically, the expenditure of a few watts can improve the efficiency of a laboratory extractor by a factor of 2 to 3 (*18*).

The mechanism of solvent extraction involves dispersion of one phase in the other, mass transfer between phases, and coalescence followed by phase separation. The effects of an electric field on all these steps were discussed in the previous section, and we will only describe some proposed systems for electrical extraction below. The developed continuous flow extraction systems can be broadly classified as charged nozzles or plates devices, spray columns with vertical electrodes, and emulsion-phase contactors. Figure 4 shows the first two types of electrical extractors. The charged plates or nozzles devices (*18, 73–78*) are a modification of the existing sieve-plate extraction columns where the plates also serve as the electrodes. Various electric potentials of a dc field are applied to the suc-

C — continuous phase

D — dispersed phase

CHARGED PLATES

VERTICAL ROD ELECTRODES
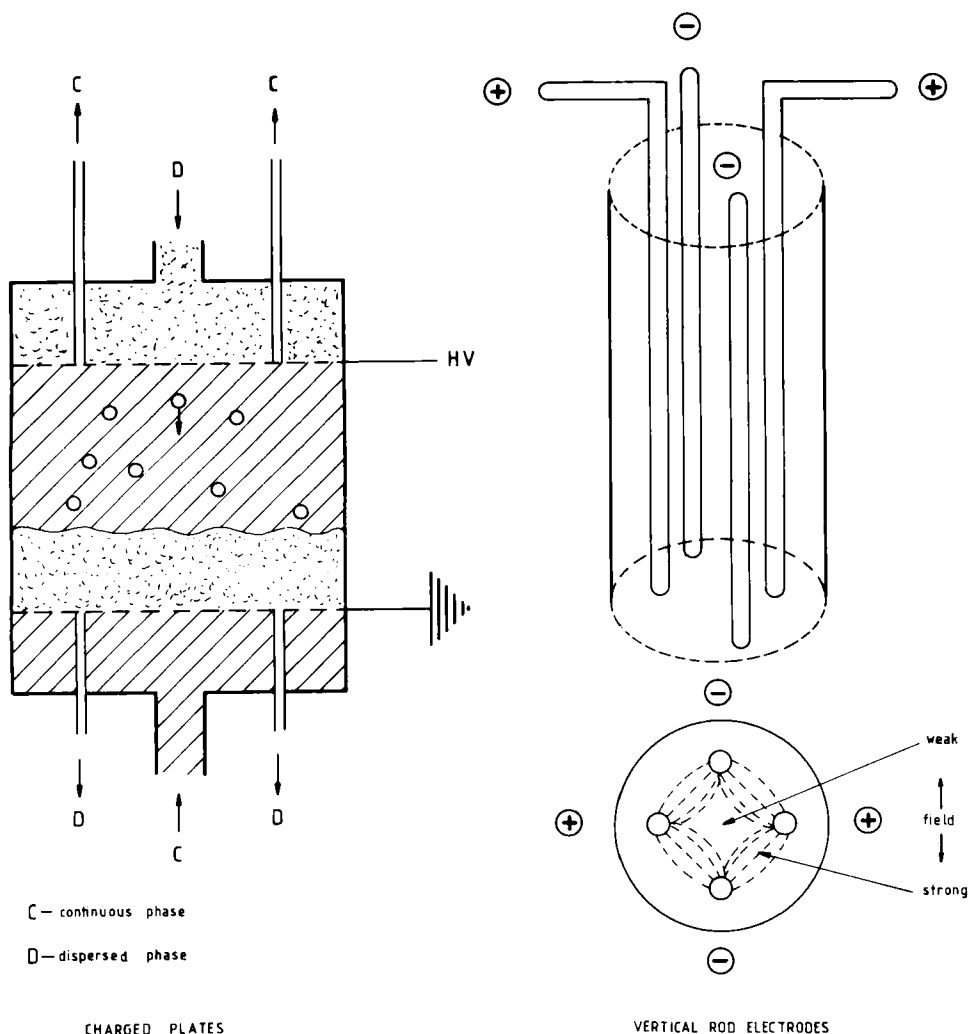
FIG. 4. Schematics of electrical extractors.

ceeding plates, and both droplet formation and mass transfer are controlled by the field in this way.

The second type of electrical contactor uses a column with long vertically installed rod electrodes (*79–81*). The nonuniform electric field is obtained by the arrangement of four-pole electrodes with reverse polarity. This configuration creates regions of the weak field where electrical coalescence

of the drops takes place as well as regions of the strong field where redispersion of the drops becomes active. The repeated droplet breakage and recombination enables mass transfer to improve in these devices by a factor of 2–5 over the no-field case.

The most promising industrial application is the emulsion-phase contactor developed by the Oak Ridge National Laboratory (*82*). This extractor employs transient electric fields such as high-intensity ac or pulsed dc fields which are very efficient in droplet rupture, as was noticed in Section 3.2. The dispersed phase is introduced between horizontal electrode pairs where the droplets are ruptured to create a high-surface-area emulsion. A mechanism similar to that of coalescence-redispersion also operates in this case because the coalescence of small droplets follows the rupture steps. The performance of this type of extractor, when expressed in terms of the number of theoretical transfer stages per centimeter of emulsion height is 1.7 stages/cm compared to the York–Scheibel (0.1 stages/cm) and Podbielniak extractors (0.17 stages/cm).

5.3. Electrofiltration of Fine Suspensions

A number of industrial processes deal with dewatering of fine or colloidal suspensions. Conventional mechanical dewatering such as cake filtration or centrifugation is restricted to particles larger than 10 μm. Suspensions containing smaller particles are usually dewatered by costly thermal drying. The application of a dc electric field provides a promising alternative in these cases.

Solid–liquid separations using electric fields are based on electrokinetic effects which have been known since the beginning of the nineteenth century. Most substances suspended in polar liquids (e.g., water) acquire a surface charge due to a number of mechanisms, including ion and surfactant adsorption, their own ionization, or nonstoichiometric dissolution. Solid particles normally have a negative charge sign; to maintain the electroneutrality of the whole suspension, each particle is surrounded by a cloud of liquid containing, in this case, positively charged ions. This cloud is called the diffuse double layer. During the relative solid motion in a liquid, a few liquid layers adjacent to the solid move together with a particle while the rest of the double layer stays with the bulk of the liquid. The electric potential at the plane of separation is called the "zeta potential" and is an easily measurable electrokinetic property. The magnitude of the zeta potential in most systems of interest is of the order of tens of millivolts.

Electrokinetic effects involve interactions between charged solid surfaces, surrounding double layer and electric fields. The most important effects in solid–liquid separations are electrophoresis and electroosmosis. During electrophoresis the charges on solid particles migrate in an external

electric field through a relatively stationary liquid to an electrode. If solid particles are immovable, as in a porous filter cake, the presence of an external electric field will force liquid to flow through the porous solid, and this phenomenon is called "electroosmosis." The mechanisms of electrophoresis and electroosmosis are identical, and the distinction between these phenomena depends on the relative mobility of the solid and liquid phases. The electrophoretic velocity of a particle and the electroosmotic velocity of a liquid are directly proportional to the electric field, the dielectric constant of a liquid, and the zeta potential, and they are inversely proportional to the liquid viscosity.

Electrophoresis and electroosmosis can enhance conventional solid–liquid separation processes in many ways. The most simple use of electrophoresis is in the sedimentation of fine particles where the settling rate of a slurry in a gravity field is enhanced by the electric field imposed (83). Similarly, electroosmosis can be directly employed to dewater colloidal and gelatinous sludges (84–87) or even to collect groundwater during civil engineering operations.

The majority of applications of electrokinetic effects relate to the enhancement of conventional solid–liquid filtration known as electrofiltration. Electrofiltration techniques can be classified into two principal categories:

1. Cake-forming methods, where a feed suspension is separated into a high solid cake and a filtrate (2, 88–91).
2. Methods for limiting cake growth, where the final products are a thickened slurry and a filtrate (92–96).

Devices operating according to the first principle are commercially applied on an industrial scale to dewater mineral slurries, mainly kaolin suspensions, and to concentrate polymer suspensions, e.g., PVC latex. Figure 5 shows the principle of cake-forming electrofiltration. Electrodes of opposite polarity are placed in suspension, and when an electric current is applied a cake is deposited on the anode. At the same time, electroosmosis in the formed cake pumps liquid back to a suspension and a high solid cake is produced. The filtrate is continuously removed from the cathode by the common action of electroosmosis and vacuum. The main advantage of this type of electrofiltration is a very high solid content in the cake produced, up to 80%, and therefore the final drying stage can be significantly shortened.

The second electrofiltration technique employs an electric field in a direction normal to the flow of a suspension in order to keep solid particles away from the filtration medium, and cake formation is prevented in this

ANODE   CATHODE

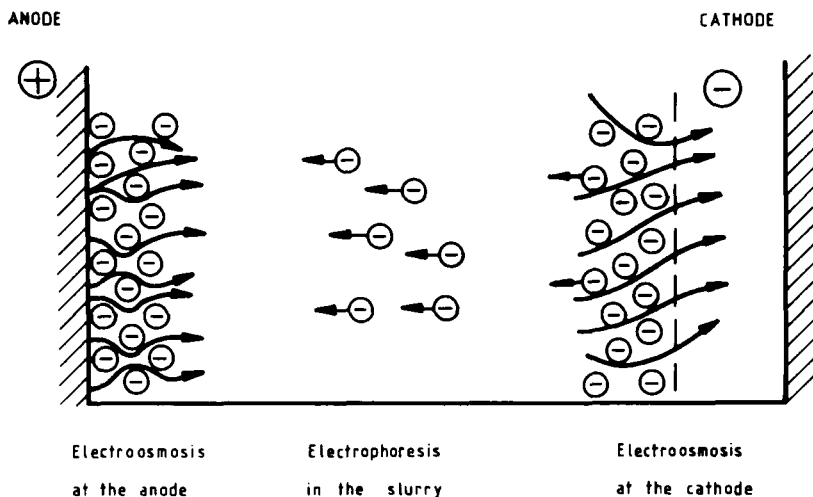| Electroosmosis | Electrophoresis | Electroosmosis |
| at the anode | in the slurry | at the cathode |

FIG. 5. Principle of cake-forming electrofiltration.

way. This process combines the well-known principle of crossflow filtration and electrophoretic migration. In conventional crossflow filtration a feed slurry is pumped across the filter medium at high flow rates in order to shear the cake off the medium. The behavior of the crossflow electrofilter can be characterized by three separate regimes dependent on the ratio of the applied electric field to the critical value of the field (93). At the critical potential a particle migration velocity due to the movement of filtrate toward the filtration medium is balanced by the electrophoretic velocity. In this case no cake is formed and the filtration rate is constant. At the supercritical field the particles are removed from the filtration medium and the filtration rate is the highest, whereas at the subcritical field a cake of limited thickness is formed and the filtration rate is reduced. Crossflow electrofilters have been proposed for removal of fine particles suspended in nonaquous slurries, such as those produced in coal liquefaction (93–96), and for thickening of colloidal solutions of protein by membrane ultrafiltration (97). There are also some successful applications of this principle for membrane fouling prevention in micro- and ultrafiltration (98).

A mechanism similar to crossflow electrofiltration operates in a process called electrical field-flow fractionation (99–101). This technique is suitable for fractionation of dissolved solutes or suspended particles in a fluid flowing laminarly in a narrow conduit. The electric field causes charged species to migrate in a region near the wall where the flow velocity is the lowest,

and the species concentrated in this region therefore becomes more re-
tarded compared to the species in the central region of the conduit.

5.4. Continuous Flow Electrophoresis

Electrophoresis provides a useful tool for the purification and separation
of biological products such as cells and macromolecules without damaging
or degrading them. In the past century a variety of analytical- and prep-
arative-scale electrophoretic techniques have been developed, and the ma-
jority of these methods is restricted to batch separations (*102, 103*). The
commercialization of developments in biotechnology requires large-scale
separations for downstream processing (*104*). In order to separate small
quantities of a product, a direct scale-up of an appropriate batch analytical
technique may be sufficient, whereas in many cases a continuous separation
may be needed.

Continuous flow electrophoresis (CFE) is a promising method for large-
scale continuous separation, as this technique has been successfully used
on a preparative scale for cell separations and the isolation of biopolymers.
The development of CFE began with the pioneering work of Hanning (*105,
106*). A schematic representation of CFE is presented in Fig. 6. In the
CFE apparatus the buffered carrier fluid flows through a narrow slit and
a uniform electric field is applied normal to the direction of flow. A mul-
ticomponent feed mixture is continuously injected into the fluid as a thin
stream. The mobile species migrate laterally in the electric field with dif-
ferent specific velocities, and they are finally collected as separate fractions
at the device exit.

Scaling-up of continuous flow electrophoresis is hindered by electroki-
netic and hydrodynamic factors (*107–109*). In practice the cross-sections
of fraction streams at the exit are distorted into a crescent shape that is
due to the superposition of two hydrodynamic effects. They result from
the electroosmotic flow along the transverse walls and from the induced
laminar velocity profile in the axial direction. Moreover, the flow field is
distorted by instabilities resulting from the thermal convection created by
Joule-heating. Various attempts have been proposed to stabilize the flow
profile and to improve the resolving power of classical CFE. The most
successful are operation at zero gravity (*110, 111*), recycling of eluent (*112*),
separation in a packed annular column (*113, 114*), and operation in a
nonuniform electric field (*115*).

6. RECOMMENDATIONS FOR FUTURE WORK

The place in separation technology currently occupied by electric field
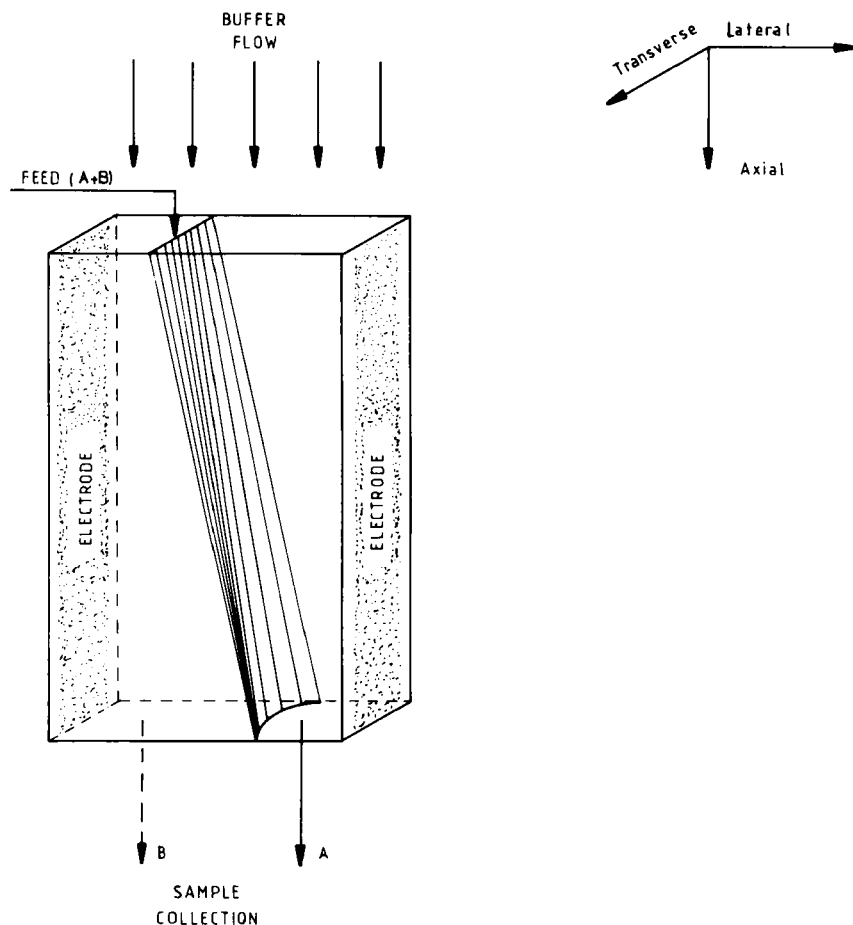driven processes is modest but expanding. The results up till now dem-

FIG. 6. Schematic representation of continuous flow electrophoresis.

onstrate the potentialities of the direct use of electrical energy in many fields. On the other hand, much development work is still needed before new electrically augmented separations will be used to a significant extent in industry. There are many areas in which the hydrodynamic and transfer characteristics are not clearly understood.

Future research should include the following studies.

1. The majority of experimental and theoretical studies concern liquid–liquid and solid–liquid systems. Only preliminary hydrodynamic results are available for gas dispersion in liquids. The data on possible mass

transfer enhancement in the latter systems are needed to evaluate the possibility of using electric fields in bubble columns and slurry reactors.

2. A number of important experimental results exist for emulsion coalescence, but no theory has been forthcoming. Theoretical studies must be performed in order to understand the coalescence mechanism needed for the development of electrical extractors and the scale-up of electrical coalescers.

3. The complex flow characteristics of continuous flow electrophoresis have been the subject of many investigations. Insufficient data on flow and temperature profiles are available for the scale-up of this separation process, especially for the proposed modifications.

4. It has been pointed out in the literature that electric fields are effective in preventing membrane fouling. There remains considerable scope for innovation in this area.

5. Many separations are carried out in systems with a high hold-up of an electrically conducting phase dispersed in an insulating continuous phase. In order to prevent short-circuits and to reduce Joule heating, the optimal configurations of electrodes, including coated electrodes, and the possibility of using pulsed fields should be evaluated in more detail.

NOTATION

d	droplet diameter (m)
$\mathbf{D}$	electric displacement vector (s·A/m^2)
$\mathbf{E}$	electric field vector (V/m)
$\mathbf{f}$	force density (N/m^3)
$\mathbf{g}$	acceleration of gravity (m/s^2)
G	Gibbs free energy of system (J)
$\mathbf{I}$	unit tensor
$\mathbf{J}$	current density vector (A/m^2)
n	number of moles (mol)
p	pressure in the presence of field (Pa)
p_p	polarization pressure (Pa)
p_s	electrostrictive pressure (Pa)
$\mathbf{P}$	polarization vector (s·A/m^2)
Q	total charge (C)
S	entropy of system (J/K)
t	time (s)
T	temperature (K)
$\mathbf{T}$	stress tensor (Pa)
U	internal energy of system (J)
$\mathbf{v}$	velocity vector (m/s)
V	volume (m^3)

W	work done on a system (J)
ϵ	permittivity (F/m)
ϵ_0	permittivity of free space (8.854×10^{-12} F/m)
η	viscosity (kg/m·s)
μ	chemical potential (J/mol)
ρ	density (kg/m³)
ρ_e	volume charge density (C/m³)
σ	interfacial tension (N/m)
∇	nabla

Subscripts

e	electric
i	species i
0	value in the absence of a field (except in ϵ_0)
v	viscous

Superscript

*	modified

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