Separation Science and Technology
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713708471

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To cite this Article Scott, Timothy C.(1990) 'Dimensional Analysis of Continuous High-capacity Electrodispersion of Aqueous Based Liquids in an Organic Continuous Phase', Separation Science and Technology, 25: 13, 1709 — 1721
To link to this Article: DOI: 10.1080/01496399008050418
URL: http://dx.doi.org/10.1080/01496399008050418

SEPARATION SCIENCE AND TECHNOLOGY, 25(13-15), pp. 1709-1721 (1990)

DIMENSIONAL ANALYSIS OF CONTINUOUS HIGH-CAPACITY ELECTRODISPERSION OF AQUEOUS BASED LIQUIDS IN AN ORGANIC CONTINUOUS PHASE

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ABSTRACT

High-intensity electric fields can be used to disperse aqueous-based solutions in a relatively nonconducting immiscible organic phase. Dimensional analysis of electrical dispersion performance from a single grounded nozzle between two charged electrodes can be characterized in terms of five dimensionless groups: an electrode height; nozzle-electrode distance; a nozzle Reynolds number; an electrical Bond number, which relates electrical to surface forces; and a Taylor number, which relates electrical to viscous forces. Experimental results on the electrodispersion of water in 2-ethyl-1-hexanol indicate that pulsed DC fields can accomplish electrodispersion utilizing a lower rms-voltage than steady DC fields. In addition, the pulsed-field-behavior varies with pulse frequency with 200 Hz fields being more effective for higher continuous-phase viscosities while 2000 Hz fields are more effective when the viscosity is lower. A steady DC field displays invariant behavior with changing viscosity. In the case of the 2000 Hz field, the Taylor number remains constant for all cases tested thus indicating that the dispersion behavior is controlled by the dynamic interactions of the forces induced by the transient field with the stability of the liquid stream emanating from the nozzle.

INTRODUCTION

A major problem that limits the use of solvent extraction and other liquid-liquid operations in industry is the efficient creation and control of mass transfer surface area. In practice, interfacial area for transport or reaction is usually created by a form of mechanical agitation. This general method may take on such forms as extrusion through sieve plates, use of impellers in tanks, or forced flow through packing. As varied as these approaches may appear, they all share a requirement for a significant input of energy into the bulk of both liquid phases to create a dispersed phase with a reasonable amount of surface area. Another approach to creating liquid-liquid dispersions which currently is producing considerable interest in the research arena, is the use of surfactants to produce microemulsions for "enhanced solvent extraction" (1). In these systems, high-surface-area emulsions are created through the addition of surface active agents. The characteristic size of dispersed phase entities is on the order of tens-of-angstroms; hence, the amount of surface area is extremely large. Problems in utilizing this approach stem from the need for appropriate surface active agents, a requirement to exert control over the motion of the dispersed entities, and coalescence and phase separation of the emulsion once transport operations are completed.

Another alternative for surface area production involves the use of high intensity transient electric fields to create aqueous-in-organic dispersions (2-4). The electric field shatters the aqueous phase into micron-sized droplets as it exits from a feed nozzle immersed in a nonconducting organic liquid. This creates an aqueous-in-organic dispersion with a large amount of interfacial area. In addition, the electric field can be used to control the motion of the dispersion against the flow of the continuous phase and also induce coalescence and phase separation. Energy usage in this technique is minimal as the electric field generally only acts at the interface between droplets and the continuous phase. A solvent extraction device utilizing electrodispersion and coalescence (the emulsion-phase contactor or EPC) has been patented (5), tested, and found to deliver an order of magnitude improvement in height of a theoretical stage over conventional laboratory scale extraction devices (4).

While the separation efficiency of the EPC was extremely high, the system was run at a low cross sectional throughput of liquids. In order to investigate the commercial applicability of such a device, it will be necessary to determine the inherent limits to electrodispersion capacity and dispersed phase hold-up. In this paper, an initial approach of dimensional analysis is taken to study the effects of varying fluid properties and electric field characteristics in order to optimize conditions for augmented electrodispersion capacities.

ELECTRIC FIELD EFFECTS ON CONDUCTING LIQUID DROPLETS

In contrast to electrochemical applications, the use of electric fields to control liquid-liquid processes primarily involves physical interactions between charges, electric fields, and conducting and/or dielectric liquids. Using the fundamental and constitutive relationships for electric fields and conservation and transport of charge (Maxwell's equations) one determines that electric field interactions are most prevalent in a region which contains a "discontinuity" of electrical properties (6-7). In liquid-liquid systems, this most often involves the interface between relatively conducting and relatively nonconducting liquids as well as interfaces between the liquids and solid and gas surfaces in the physical apparatus. Generally speaking, these interfacial effects manifest themselves as a resultant force or induced shear stress that can induce a static deformation of the interface and even steady or transient fluid motion in one or both phases.

The creation, contact, and interaction of droplets within a continuous phase are processes which are common to virtually all liquid-liquid operations. The situation which is of most importance for the present study is that of relatively conducting droplets in a relatively nonconducting continuous phase. This will usually involve aqueous based and "organic" based phases, respectively. Figure 1 illustrates some of the influences of electric fields on drop formation, translation and oscillation, stability and break-up, and coalescence.

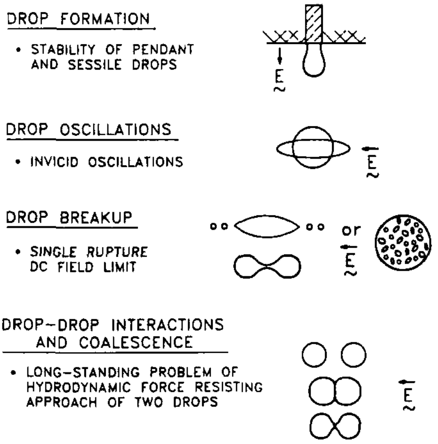

Fig. 1 Electrohydrodynamics in Liquid-Liquid Operations.

Placing a spherical, conducting droplet which is surrounded by a nonconducting continuum in a steady DC electric field will cause stresses to develop on the droplet (8). This force is imposed by the component of the electric field which is normal to the interface – the strength of which is proportional to the square of the field intensity. As the strength of the field is increased, the resultant force will cause the droplet to deform into an ellipsoid whose major axis lies parallel to the electric field lines (see Figure 2). In addition, the droplet will be polarized with either the induced or net charge (for charged drops) appropriately distributed on the droplet surface. There is no electric field inside the conducting droplet. If sufficient field strength is provided, the droplet deformation will become large enough to cause disintegration of the original droplet into a number of smaller daughter droplets (9-11). If a transient field is used, the droplet will deform during times of "high" field strength and relax back towards a spherical shape when the field strength is "low" thereby forcing oscillation about the spherical form. Transient fields can also be used to cause droplet disintegration; however, the field strength required is higher than when using a steady DC field (2, 12).

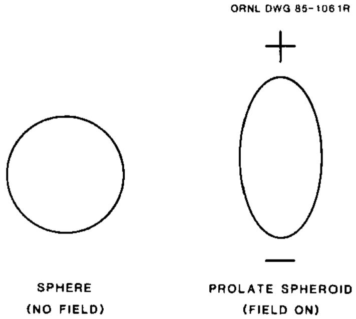

Fig. 2 Droplet Deformation in a Strong Electric Field.

Coalescence of charged and uncharged conducting droplets can be carried out under the influence of an electric field. Although the mechanisms involved have not been fully explored, several applications of steady and transient fields have been made to carry out phase separation in industry (13-15). The net result of electric fields imposed on swarms of conducting droplets is to polarize the drops and induce drop-drop interactions between oppositely polarized ends of neighbors. This increases the probability of drops coming into close proximity. Once the drops are close together, the (induced) charged ends constitute a secondary electric field which deforms and ruptures the separating continuous-phase-film to allow a single, larger entity to be formed. Hence, the purpose of the field is to promote drop-drop interaction and overcome the hydrodynamic resistance to coalescence. Formation of droplets from a nozzle or orifice is also affected by the presence of electric fields. The resultant force which occurs at the droplet-continuum interface serves to decrease the size of the detaching droplets relative to the no-field-case (16-18). If the electric field strength near a nozzle is increased past the point of single drop formation, jetting occurs which results in the formation of a dispersion of micron-sized droplets. This phenomenon has been noted in DC, AC, and pulsed-DC electric fields (2-6). Two interesting aspects of this type of approach are the droplet-size characteristics and the energy input requirements for creation of the dispersion. The initial droplet diameter in these types of operations is on the order of one micron with a size distribution as narrow as ± 20%. Unfortunately, the same field which initially disperses the droplets causes some coalescence to occur after droplet detachment so that longer residence time in an electric field will ultimately result in a more polydisperse suspension. Nonetheless, if reasonable dispersed-phase holdups can be obtained, this process should result in a several-orders-of-magnitude increase in surface area per unit volume in industrial devices.

It is also important to note that energy requirements for electrodispersion are much less than those typically needed to obtain an equivalent droplet size. Conservative estimation of this advantage indicates that electrodispersion requires far less than 1 % of the energy required from typical mechanical agitation (3). The primary reason being that the electric field effects are manifest directly at the interface while mechanical agitation must input energy into the bulk of both of the liquid phases.

DESCRIPTION OF THE MODEL SYSTEM

It is evident that the use of electric fields to create aqueous-in-organic dispersions is an efficient technique for creating large amounts of surface area for mass transport and/or reaction systems. The question at this point in time then is – what are the inherent limitations (if any) on the capacity and dispersed phase hold-up of devices based on this technology? In this paper an initial approach will be taken towards the study of the question of capacity of electrodispersion processes. More specifically, we are interested in discovering the lowest voltage input required to disperse a given amount of liquid. Limitations to dispersed phase hold-up will be a topic of future investigation.

Capacity in this case will initially be examined in terms of the amount of dispersed-phase material which can be produced per unit time per cross section of a model device. Hence, the entity of interest is the dispersion flux. Figure 3 contains a schematic diagram of the model system to be considered in the present study. The system of interest is that of a single nozzle which is placed between two parallel plate electrodes with the bottom of the nozzle even with the top of the electrodes. Electrode height is designated by h, horizontal distance between top of electrodes and bottom of nozzle, l, and radius of the nozzle opening is denoted by, a.

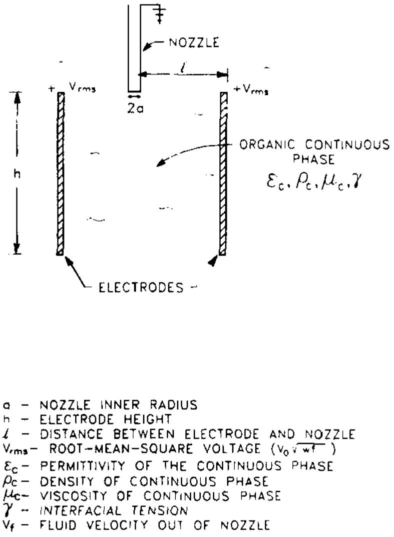

Fig. 3 Model System for Dispersion Studies.

The nozzle is grounded while the plates are subjected to an electrical potential, V_{rms}. The voltage may be transient in nature and therefore will be characterized by the root-mean-square (rms) voltage value. The volume between and surrounding the electrodes and nozzle is filled with a relatively nonconducting "organic" liquid with physical properties as follows ε_c electrical permittivity, density ρ_c, and viscosity μ_c. The velocity of aqueous phase through the nozzle is denoted by V_f and the interfacial tension between the liquid-liquid pair is denoted by γ.

In order to examine the controlling relationships in this system, dimensional analysis has been carried out utilizing the aforementioned 9 characteristic entities of the model system. Table I contains a list of the five dimensionless groups which can be obtained from this parameter set. The five characteristic groups are a scaled electrode height, h*, a scaled distance between nozzle and electrode, l*, a Reynolds number for flow out of the nozzle, Re, an electrical Bond number which is characteristic of the ratio of electrical forces to interfacial forces, Ne, and a Taylor number which is characteristic of the ratio of electrical forces to viscous forces, Ta.

Table I. Governing Dimensionless Groups for the Model System

Name	Formula
Dimensionless electrode height (h^*)	$\frac{h}{a}$
Dimensionless distance (ℓ^*)	$\frac{\ell}{a}$
Nozzle Reynolds No. (Re) (inertial/viscous)	$\frac{\rho_c a V_f}{\mu_c}$
Electrical Bond No. (Ne) (electrostatic/surface)	$\frac{\varepsilon_c V_{rms}^2}{\gamma a}$
Taylor No. (Ta) (electrostatic/viscous)	$\frac{\varepsilon_c V_{rms}^2}{V_f \mu_c a}$

EXPERIMENTAL APPARATUS AND PROCEDURES

Dispersion experiments were carried out in a rectangular glass vessel (5.1 x 7.6 x 20.3 cm tall) which had a single stainless steel nozzle placed between two stainless steel parallel plate electrodes. The nozzle and electrodes were placed in the center of the vessel to minimize any possible wall effects. The column was water-jacketed to allow for running experiments either above or below ambient temperature. DC electric fields were generated by a Hypotronics model 825C power supply and pulsed fields were generated by a Velonics model 660 power supply. The continuous phase was 2-ethyl-1-hexanol and the dispersed phase was distilled water (mutually saturated). Experiments were run using a matrix of conditions shown in Table II. Observations were made as to the field strength required to obtain complete dispersion of the water flowing out of the nozzle. Nine different types of electric field were used, DC, pulsed-200 Hz and pulsed-2000 Hz each utilized with three different electrode heights. In the case of pulsed fields, the duty cycle of the pulses was always less than 0.5% of the time between pulses. This was done to investigate the effects of field type and geometry on dispersion. Experiments were run at four temperatures 10, 20, 40, and 60°C in order to change the physical properties of the liquids. As can be seen, the property which changes the most is the viscosity of the continuous phase. Electrode spacing, nozzle size, and flow rate of water were all held constant throughout the course of this study.

Table II. Conditions Used in Experiments (System: water/2-ethyl-1-hexanol)

Parameter	Values	Comments
Electrode heights	7.62, 3.3, 1.27 cm	Width of electrodes 3.3 cm
Types of Electric Field	DC, 200 Hz, 2000 Hz	Pulsed D.C. square wave 0.5% duty cycle
Temperature	10, 20, 40, 60° C	Continuous phase visc. 17.1 to 1.9 CP, resp., γ = 12.5 to 16.5 dyne/cm resp.
Nozzle Inner Radius (a)	0.055 cm	Constant
Nozzle-electrode distance (l)	0.95 cm	Constant
Fluid Velocity (V_f)	2.77 cm/sec	Constant

DISCUSSION OF RESULTS

Variation of the electrode height, type of field used, and temperature of the fluids yielded information regarding several aspects of the dispersion process. Increasing the electrode height had the effect of increasing the vertical component of the electric field. This yields information about the optimum field geometry for dispersion. An electrode width of 3.3 cm was used in all experiments. Information obtained in preliminary experiments indicated that increasing electrode width beyond this value had no effect on performance. Figures 4-6 contain plots of the rms-voltage required for dispersion as a function of Re (changing viscosity) for the three electrode sizes for the DC, 200 Hz, and 2000 Hz fields, respectively. The DC field shows no preference for a particular electrode size and the dispersion voltage is essentially constant over the range of Re shown. This behavior seems reasonable because one would not expect the steady force exerted by the field to couple with the flowing liquid. The 200 Hz field shows completely different behavior. The longer electrodes give much better dispersion performance (lower field needed) thus implying that a significant vertical component is required in the field. In addition, the value of the required field strength increases with increasing Re. The 2000 Hz field also displays better performance with the longer electrodes although not quite as great as an extent as the 200 Hz field; however, the behavior of field strength as a function of Re is the opposite of the 200 Hz case. The required field strength decreases with increasing Re.

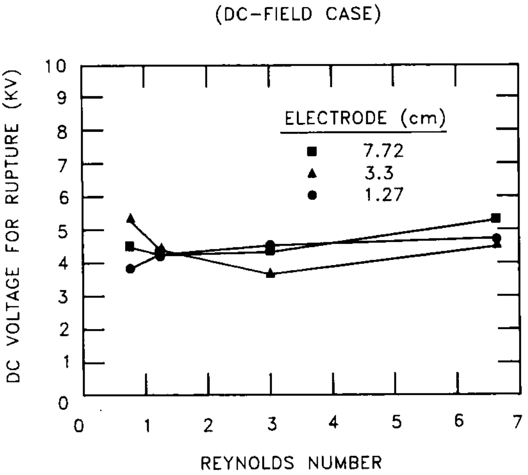

Fig. 4 Field Strength for Dispersion vs Reynolds Number (DC Field Case).

The three types of fields were utilized to see if any resonance effects could be detected as in the case of free drops (2,4,5). The DC field was considered the base case in that only the forces at the surface (interface) should be important in the dispersion process. The 200 Hz field was more characteristic of the frequency of small free droplets while the 2000 Hz field was utilized to investigate resonance of drops attached to a nozzle. The 2000 Hz value was not based on calculation because suitable treatments do not exist, but rather it was chosen

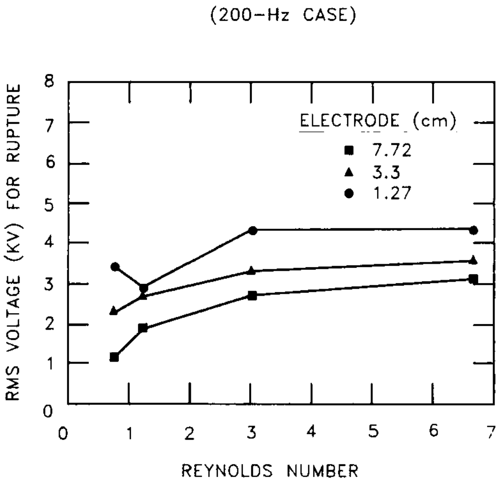

Fig. 5 Field Strength for Dispersion vs Reynolds Number (200 Hz Case).

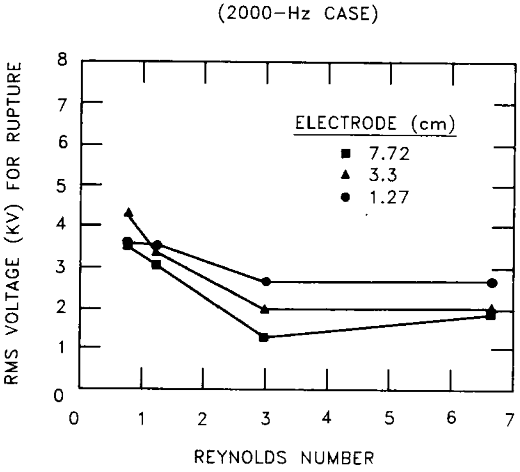

Fig. 6 Field Strength for Dispersion vs Reynolds Number (2000 Hz Case).

because it was significantly above the general frequency range of macroscopic-sized free drops.

Figure 7 is a plot of the Bond number, Ne, as a function of Re (inversely proportional to the continuous phase viscosity) for the three types of field. In each case, the data is taken from the long (7.62 cm) electrode runs. It is evident that the three fields behave differently. The DC field displays a relatively constant Ne throughout the range of Re employed. This is further illustrated by including the data from all three electrode sizes (Figure 4). There is no consistent pattern for field strength versus Re. This is as expected as the change in viscosity should not have a bearing on the Ne required to disperse the liquid because the steady force exerted is an interfacial phenomenon. The Ne for the 200 Hz field increases as the viscosity decreases; thus, indicating that at lower viscosities the system requires more electrical force to induce rupture. This behavior implies that there is an interaction between the transient nature of the imposed force and the stability of the liquid stream emanating from the nozzle. The opposite behavior is observed for the 2000 Hz field, that is, the amount of electrical force necessary for dispersion decreases along with the viscosity. This also indicates an interaction of the dynamics of the imposed electrical forces with the stability of the dispersing phase.

These pulsed-field-results can be generically explained in terms of a resonance process. It is well known that droplet oscillation and break-up in free solution is characterized by a natural frequency phenomenon. That is to say the droplet can be most easily ruptured if oscillated at this frequency (19). It is also established that the resonant frequency of such droplet/continuous-phase systems increases as the viscosity of the continuous phase is decreased. The trends shown in these results are consistent with this behavior as the 200 Hz field more effectively couples with the high viscosity case and the 2000 Hz field with the low-viscosity case.

Figure 8 is a plot of the Taylor number, Ta, as a function of Re for the three types of field with the long (7.62 cm) electrodes. Ta for the DC field increases as the viscosity decreases. As Ta is inversely proportional to the viscosity (see Table I), this is to be expected for a constant electrical force term. Ta also increases for the 200 Hz field but with a slightly higher ratio than the DC field case because the electrical force increases while the viscosity decreases. The 2000 Hz field displays a constant value for Ta over the range of Re investigated. This is interesting in that the dispersion process which is caused by imposition of an electrically induced surface force occurs under conditions in which the ratio of electrical to viscous forces (Ta) remains constant. This again implies that the dynamic interaction between field and dispersing liquid is extremely important in controlling the behavior of the system.

CONCLUSIONS

High-intensity steady and transient electric fields can be used to disperse aqueous-based solutions into a relatively non-conducting, essentially-immiscible organic phase. The characteristic droplet size for such operations is on the order of microns; hence, vast amounts of surface area may be produced for transport operations. Examination of a model system of a single grounded nozzle between two charged electrodes has revealed several differences between using steady DC and pulsed DC electric fields for the dispersion process. In general, it appears that one may use a lower rms-voltage with pulsed fields versus a steady field

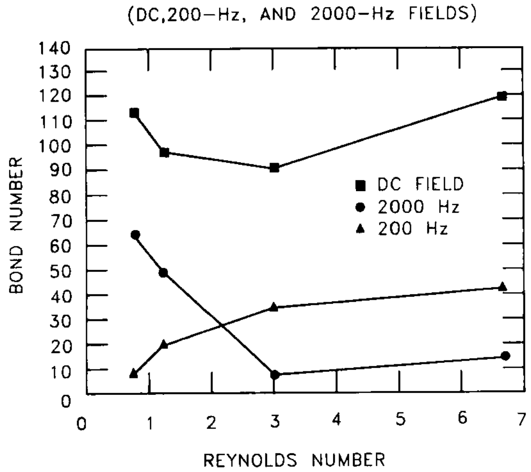

Fig. 7 Bond Number vs Reynolds Number (7.62 cm Electrodes).

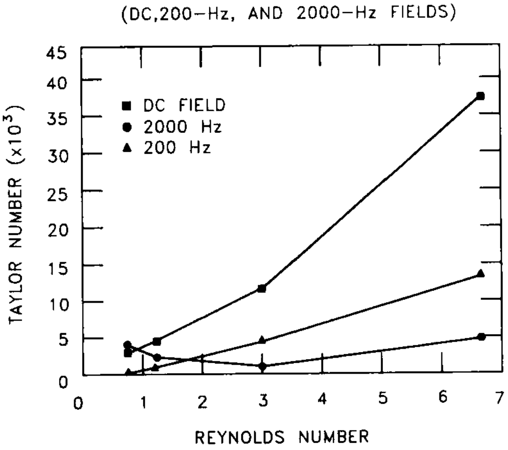

Fig. 8 Taylor Number vs Reynolds Number (7.62 cm Electrodes).

and that the degree of interaction of pulsed fields with the process varies with the pulse frequency thus suggesting a type of resonance of transient field with the dispersion process. In order to further understand this interaction, basic information must be obtained on the resonant frequencies of liquids (drops) emanating from nozzles – an area which has not been substantially addressed in the literature.

The capacity of electrodispersion systems has been increased by two-orders-of-magnitude over the initial emulsion-phase contactor by use of improved electrode designs and transient fields. In order to further increase the possible throughput to levels near current industrial devices, the final factor- of-four (or so) gap must be closed by taking advantage of full knowledge of the dynamical interactions between transient field and stability of liquid jets and droplets.

ACKNOWLEDGEMENT

This research program was sponsored by the Office of Basic Energy Sciences, U.S. Department of Energy under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

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