Electric Field Effects on Drop Size and Terminal Velocity in Liquid-Liquid Systems

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Introduction

The extraction rate of a mixer-settler system or a plate column is directly related to the surface area of the contacting phases and the mass transfer coefficient. To increase the extraction efficiencies, contactors are designed to produce dispersions of large interfacial area and much mixing. A relatively new way of obtaining increases in the interfacial areas is the use of electric fields (Thornton, 1968; Bailes, 1981).

When a droplet of a relatively conductive liquid is formed in the presence of an electric field, conductive species within the droplet are ionized and result in a net electric charge. If the conductivity is high enough, these conductive species will rapidly migrate to the droplet surface and produce a charge distribution on the surface of the drop. This charge distribution then interacts with the field to produce an electrical stress. This stress tends to pull liquid out of the nozzle as charged drops of small sizes. Within the continuous phase, these charged drops accelerate due to the applied field until the forces of gravity and the electric field are balanced by drag. The result of the applied electric field is drops of smaller sizes with higher terminal velocities relative to no field (Carleson and Berg, 1983).

Such drops, due to their smaller sizes, should have higher transfer rates. Charged drops in electric fields also have higher velocities and consequently shorter residence times. This effect would cause a reduction in extraction efficiencies. The net effect upon extraction efficiencies depends upon the effect of the field upon both drop size and velocity. Experimental work was conducted to determine the effect of electric fields upon the drop size and velocity.

Experimental

The experimental apparatus consisted of a vertical, glass-walled column 0.15 m square and 0.45 m tall similar to that described by Carleson and Berg (1983). Single drops were formed by a hypodermic needle and allowed to fall through the continuous phase. The needle was connected to an upper, charged plate by a wire. The systems studied included: water droplets in heptane, water droplets in pentane for two different needle sizes, and glycerine drops in pentane. The drop charge was measured when the drops fell to the bottom of the column and hit a stainless steel screen that was connected to a microammeter. A Hycam high-speed motion picture camera was used for taking pictures of the drops as they formed and fell.

A parallel electric field was generated by connecting the upper stainless steel plate (0.14 × 0.14 m) to a high-voltage DC power supply and the lower stainless plate to electrical ground. The drop size was determined from the dispersed phase flow rate (0.3 or 0.5 mL/min) and drop formation time based upon photographs. The drop velocity was also determined from the pictures of the drop.

Results

Based upon electric field theory, the charge density, q, induced upon the upper plate is

$$q = \epsilon K E \tag{1}$$

where E is the applied field, ϵ = the permittivity of free space, and K = dielectric constant of the continuous phase. Figure 1 shows a linear variation in drop charge density with applied field for low to moderate field strengths.

The drop volume measurements are plotted as a function of the charge parameter group, $\epsilon K A E^2/g\Delta\rho$, in Figure 2. The coordinates of this plot were selected based upon a force balance for the drop.

$$2\pi r_n \sigma f = \Delta\rho g V + \epsilon K A E^2 \tag{2}$$

$$V = V_o(f/f_o) - \epsilon K A E^2/g\Delta\rho \tag{3}$$

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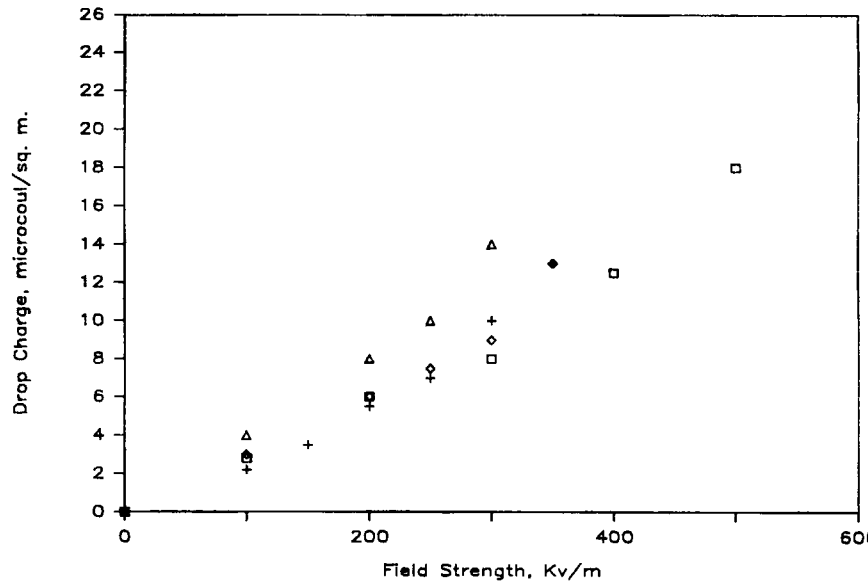

Figure 1. Drop charge vs. field strength.

□ Water-heptane (22 gage needle)
+ Water-pentane (22 gage needle)
◇ Water-pentane (18 gage needle)
△ Glycerine-pentane (18 gage needle)

where σ = interfacial tension, r_n = needle outside diameter, $\Delta\rho$ = density difference, g = gravitational constant, A = drop surface area, V_o = drop volume at zero field, and f = Harkins correction factor. Over the range of drop sizes produced, the ratio f/f_o does not change appreciably and can be considered roughly as one. Initially the drop volume decreases rapidly with the charge parameter and then decreases approximately linearly. This same trend is shown in the gas-liquid work of Carleson and Berg (1983) and Takamatso et al. (1981). The nonlinear region is larger for the larger sized drops. Bailes (1981) and Thornton (1968) believe that the inability of the theory to adequately account for the effect of the electric field upon drop size results from the presence of a nonlinear field due to conductive species in the continuous phase. The same trend, however, appears to be present in gas-liquid systems, so this is probably not the reason. The fact that the nonlinear behavior appears to increase with

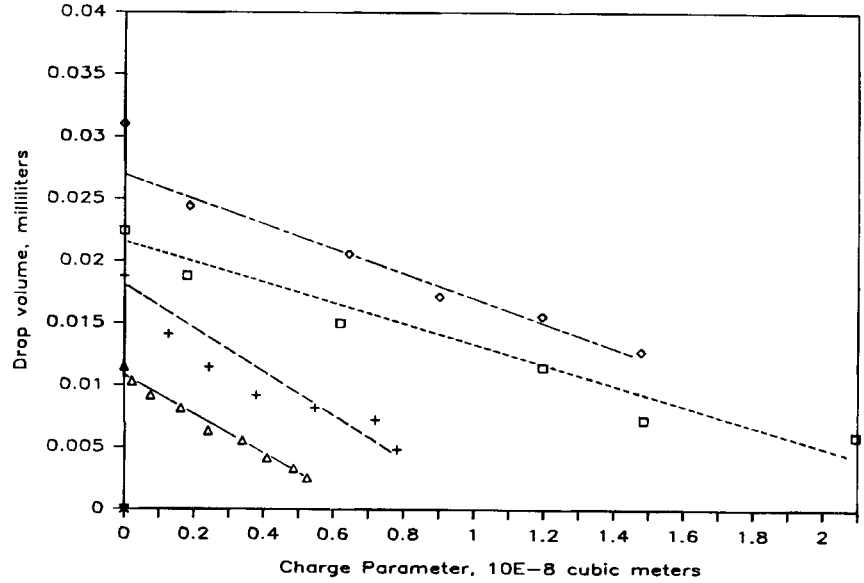

Figure 2. Drop volume vs. charge parameter.

□ Water-heptane (22 gage needle)
+ Water-pentane (22 gage needle)
◇ Water-pentane (18 gage needle)
△ Water-air (22 gage needle)
(Carleson and Berg, 1983)

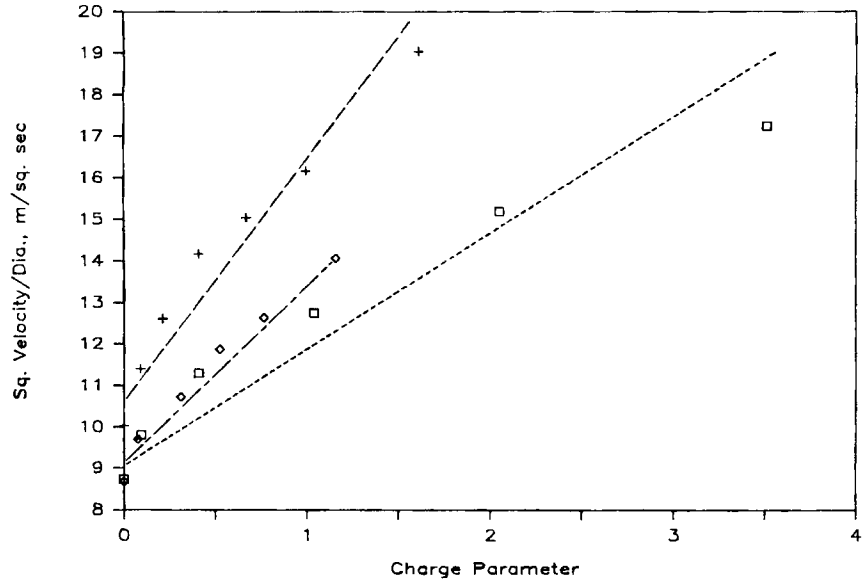

Figure 3. Sq. velocity/dia. vs. charge parameter.

□ Water-heptane (22 gage needle)
+ Water-pentane (22 gage needle)
◇ Water-pentane (18 gage needle)

drop size indicates that it has to do with the configuration of the drop, i.e., drop distortion due to the field or gravity. Drop diameters ranged from 0.2 to 0.4 cm and resulted from release at the nozzle tip rather than jet breakup.

Figure 3 indicates how drop velocity varies with field strength and charge. The coordinates for this plot were based upon a force balance about the falling drop. This force balance is

$$C_D\pi\rho_c u^2 d^2/8 = \Delta\rho\pi d^3 g/6 + \epsilon KAE^2 \qquad (4)$$

where u = drop terminal velocity, C_D = drag coefficient, and ρ_c = continuous phase density. The plots show an approximately linear variation of u^2/d with $6\epsilon KAE^2/(g\pi d^3\Delta\rho)$. The slope of the curves ranges from 3 to 6 m/s^2, compared with a slope of 5 to 12 m/s^2 as determined from the theory. The agreement between the theory and experiment is fair.

Thus it appears that fairly simple electrostatic models of the system can be used to approximate the effect of the electric field upon the drop size and velocity. The model for drop size should be further refined to reflect the distortion from forces due to the field around the drop and plate.

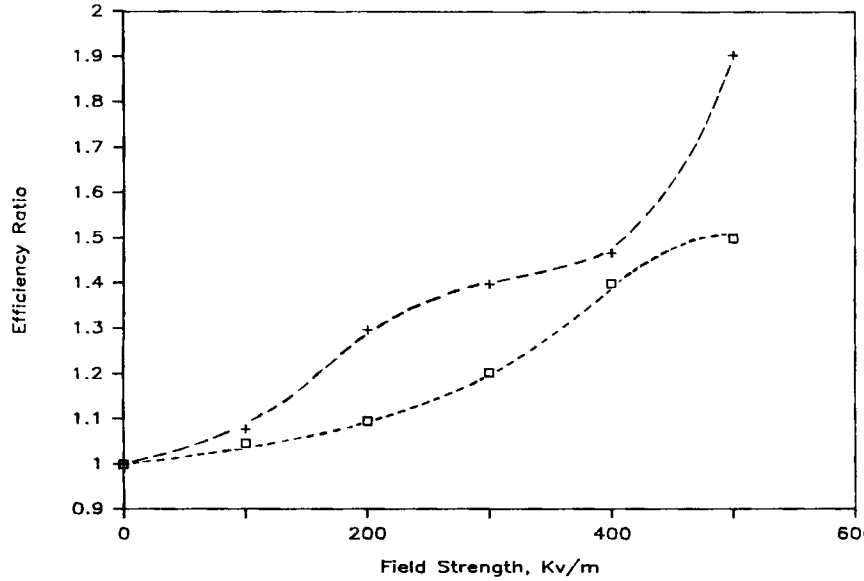

Figure 4. Efficiency ratio vs. field strength.

+ Continuous phase
□ Dispersed phase

Mass Transfer Predictions

It is of interest to look at the effect of the electric field upon mass transfer for liquid-liquid systems in light of the electric field effects upon drop size and velocity. To this end, experimental values of drop size and velocities were used in standard mass transfer correlations for circulating but not oscillating drops (Skelland, 1974; Sherwood et al., 1975) to allow prediction of the effect of electric fields upon the mass transfer coefficient and the extraction efficiency.

Figure 4 is a plot of the predicted effect of the electric field upon the extraction efficiency ratio, which is the transfer efficiency at a given field strength divided by the transfer efficiency at zero field strength, for the case of dispersed or continuous phase controlling resistances. A 50% increase in the efficiency for the dispersed-phase controlled and a 90% increase for the continuous-phase controlled resistance is seen for a field of 500 kV/m. These predictions are comparable to the experimental observations of Bailes (1981).

These results indicate that electric fields can enhance mass transfer in liquid-liquid systems and that such enhancements may be explainable by the effect of the field upon drop size and velocity.

Acknowledgment

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