Surface Area Generation and Droplet Size Control Using Pulsed Electric Fields

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Two major problems that limit the use of solvent extraction in industrial applications are the efficient creation of mass transfer surface area and control of the area. In practice, interfacial mass transfer surface area is usually created by a form of mechanical agitation. This requires an energy input into the bulk of each of the liquid phases and therefore represents an inefficient use of energy in the system. In addition, agitation may create emulsions in the mass transfer apparatus that may prove to be hard to characterize and difficult to control during phase disengagement.

The imposition of high-intensity pulsed electric fields (>1 kV/cm) upon dispersed liquid droplets allows the creation of vast amounts of interfacial area by means of droplet rupture. The electric field stresses imposed upon droplets cause them to shatter into many daughter droplets, thereby significantly increasing the available surface area for mass transfer. Energy utilization in this process is extremely efficient because the electric field acts at the droplet-continuum interface rather than throughout the bulk of the liquid phases. Stability of droplets in a pulsing electric field is a function of field strength, droplet size, and pulse rate; therefore, this technique should allow one to control the droplet size present in the system of interest.

Description of Technique

Placing a spherical, conducting droplet that is surrounded by a nonconducting continuum in an electric field will cause stresses to develop on the droplet. As the strength of the field is increased, the droplet will deform into an ellipsoid whose major axis lies parallel to the electric field lines. If sufficient field strength is provided, the droplet will become unstable and disintegrate into a large number of smaller daughter droplets. The same effect occurs when a pulsing electric field is used. The droplet deforms when the field is on and relaxes back toward the spherical shape when the field is off; hence, the droplet is forced to oscillate about the spherical form. Augmentation of direct-contact heat transfer has been carried out using pulsing electric fields in the 2–8 Hz frequency range by Kaji et al. (1978, 1980). Results from these studies indicate that low-frequency, high-displacement pulsing of liquid droplets enhances the heat transfer process. This type of technique has also been used in our laboratory under higher frequency conditions that are near droplet natural oscillation frequencies (20–60 Hz) to study the effects of droplet oscillation on the rate of mass transfer for the case of continuous-phase control (Wham and Byers, 1987; Scott, 1986, 1987). If the proper combination of pulse rate and field strength is utilized, the droplet will shatter, thereby creating a vast amount of interfacial surface area. Initial data obtained in our laboratory indicate that one should be able to choose a drop size or range of drop sizes that will be allowed to exist in a given region of a mass transfer apparatus while creating large amounts of interfacial surface area.

The experiment in which the principle was developed is shown in Figure 1. A steadily upflowing continuous phase (2-ethyl-1-hexanol) is recirculated through a square, vertical glass channel. Water droplets formed at the top of the channel by a precision syringe are allowed to fall through the lighter organic phase. Several horizontal electrode pairs are placed along the extent of the glass channel. A horizontal, pulsed electric field can be provided across a given set of electrodes. Both the pulse rate and the strength of the horizontal electric field can be varied to study the effect upon the droplets.

Results

A series of experiments was run to determine the electric field strength required to rupture aqueous droplets as a function of pulse rate of the electric field. Figure 2 contains the results of the experiments for a single droplet size. To obtain these data, droplets of the indicated size (0.089 cm radius) were passed between the electrodes while the electric field pulse rate was maintained at a constant level. The field strength was then increased until the onset of droplet instability and rupture. The plot of the rupture field strength vs. pulse rate displays minima and maxima in the 20–60 Hz range and then shows a steady decrease as the pulse rate is increased to 120 Hz. The mode of droplet rupture also differs in these two pulse rate regions. In the 20–60 Hz range, rupture is characterized by the formation of an

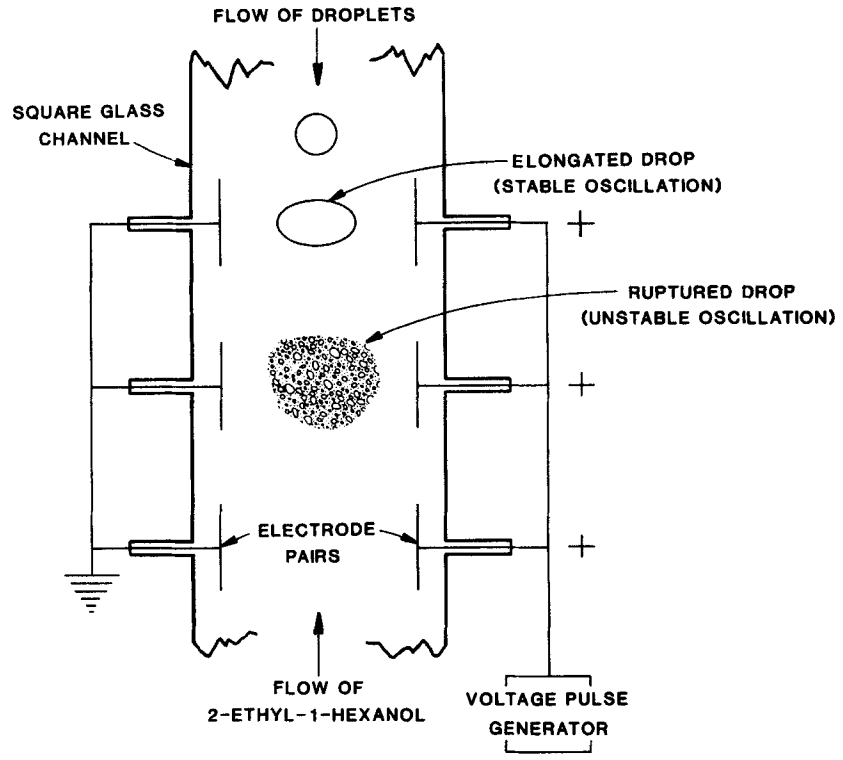

Figure 1. Experimental apparatus.

emulsion as the daughter droplets formed in the initial rupture continue to disintegrate into extremely small droplets (typical diameter ~5 μm). At higher frequencies, rupture is characterized by a single breakup of the droplet into several relatively large, stable daughter droplets.

The most interesting behavior is found to occur when the electric field pulse rate is in the vicinity of the natural oscillation frequency of the droplet (as defined in Lamb, 1945). Near this natural frequency, a significant increase in field strength is required for droplet rupture; hence, this implies that this is the condition of maximum stability for the droplet. In addition, stability of the droplet drastically decreases on either side of the natural oscillation frequency. It is this phenomenon that should allow one to control droplet size by choosing a field strength and

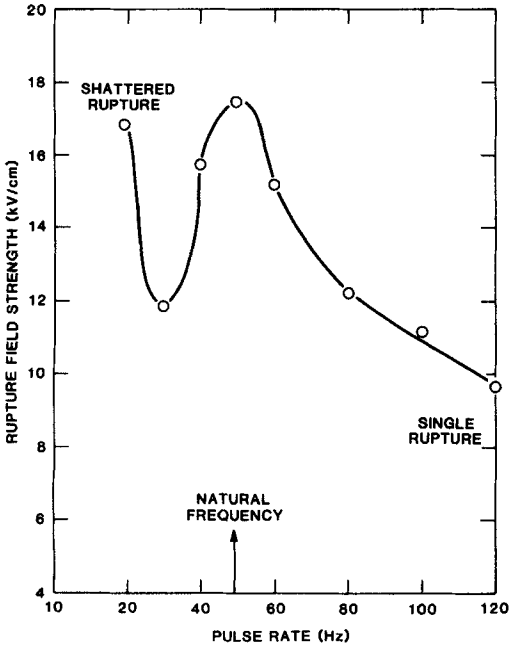

Figure 2. Typical rupture behavior of 0.089 cm radius H_2O drops in 2-ethyl-1-hexanol medium.

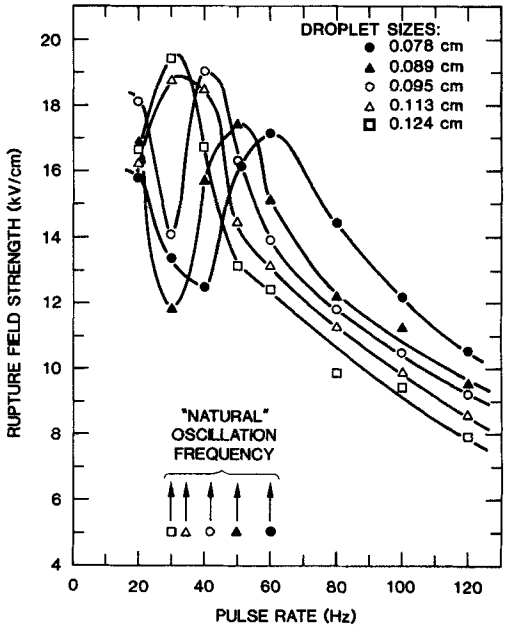

Figure 3. Rupture behavior for several droplet sizes.

a pulse frequency. All droplet sizes that are significantly removed from their respective natural oscillation frequency should become unstable and rupture.

Figure 3 contains a plot of the droplet rupture data obtained for five droplet sizes. For each droplet size, there is a maximum in rupture field strength near the natural oscillation frequency, accompanied by a drastic decrease in required field strength for rupture on either side of the natural frequency. These data lend an explanation as to why emulsion formation takes place in the 20–60 Hz range. The daughter droplets formed in the initial rupture have natural oscillation frequencies that are removed from the parent droplet and therefore are unstable in the electric field. This plot also illustrates an interesting phenomenon that is a consequence of using pulsing electric fields. In the 20–60 Hz range, under certain conditions, larger droplets are stable in the pulsing field while smaller droplets rupture and form an emulsion. In the 60–120 Hz range, smaller droplets are more stable in the pulsing fields, so a single split occurs to form several smaller daughter droplets that are stable in the field. Similar results have been obtained using the water/1-hexanol and water/*n*-octanol systems.

Remarks

While there appears to be a satisfactory explanation for the maxima in droplet stability, the existence of the minima (regions on either side of the natural oscillation frequency) does not lend itself to a straightforward interpretation. It is believed that this behavior is due to the contributions of viscous dissipation in the liquid droplet to the dynamics of the oscillation. Indications are that conditions exist under which the combination of inertial, viscous, and stability contributions cause a maximum deformation for a given disturbing force imposed on the droplet. This hypothesis, as well as more extensive data sets containing droplet size distributions and energy input information, will be presented and discussed in forthcoming publications.

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