Drop Formation from an Orifice in an Electric Field

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The formation of dispersed phases at needle tips and orifice plates has generated considerable practical interest in various separation processes. The influence of applied electric fields in reducing and controlling drop volume has already found use in electropainting and ink-jet printing. These applications are examples of electrohydrodynamic atomization in which the electric field is so intense that the liquid is disrupted into a spray of charged drops. In contrast, the present study concerns the formation of droplets in an immiscible liquid phase at charges well below the Rayleigh stability limit. Here the results could be of importance in a broad range of liquid-liquid processes such as liquid-liquid extraction, where energy in the form of mechanical agitation is expended in the production of surface area.

As a research area the behavior of charged drops in an electric field has received considerable investigation. Studies of drop shape and size, velocity of translation, and mass transfer with surrounding fluid have been published. Possible mass-transfer applications are suggested by the production of smaller drops and the promotion of internal circulation (Wham and Byers, 1987).

Many investigators have found that drop volume decreases as a result of electric-field-application to drop formation at nozzles from syringe needles (e.g., Vu and Carleson, 1986). In this investigation, drops were formed from an orifice plate with a geometry that is more commonly encountered in industry. Experiments were carried out with low fluid velocities at the orifices, described by previous investigators as the "prejetting" or "single-drop" regime. The charged orifice plate produced an axisymmetric, nonuniform field. Because the field is significantly influenced by the radius of the orifice plate, it was used as an experimental variable to help control the formation of drops in a field.

To allow prediction of the electrostatic force on a drop, a theoretical model based on an ellipsoidal shape was developed. The model provided a good prediction of drop sizes over the ranges of variables for which its assumptions apply.

Experimental

Water drops were formed from an orifice enclosed in a glass column filled with cyclohexane. The charged orifice plate, 0.952 cm in diameter, was oriented horizontally and the water drops that formed fell downward toward a grounded stainless steel screen, Figures 1 and 2. The distance between the orifice plate and the screen was 5 cm and remained constant throughout the study. Plates were used with orifice diameters of 0.03175, 0.06350, 0.09525 and 0.1524 cm.

A static DC field was applied using a Hipotronics power supply with a range of 0 to 30 kV. A Tritronics Model PC5600, high-speed shuttered video camera was used to record the experiments. Shutter speed was varied from 4 to 0.1 ms, with framing rates of 60 to 300 frames per second. A Sony VO-5800 video recorder recorded the video image for playback and analysis of the results, while a FOR.A video timer VTG-33 recorded the date and time (to within 0.1 s) on the videotape during each experiment. A VPA-100 position analyzer was used for determining droplet size and shape from the video image. A Sony microcomputer with Genlocking capability allowed an overlay of microcomputer graphics on the video image, while on Apple IIe microcomputer analyzed the digitized images.

In each experiment, a steady flow of water was established through the orifices. Because of complexities associated with jetting at higher flow rates, this study was confined to the prejetting or single-drop flow regime. The extent of this regime was determined for each orifice size by preliminary experiments in the absence of an electric field, which showed that the prejetting regime for the water-cyclohexane system occurs for flow velocities less than ~0.05 to 0.1 m/s for these orifices. Drop volumes were calculated using the volumetric flow rate of water to the orifice and the number of drops produced per unit of time (obtained by inspection of the videotape).

These preliminary experiments were followed by a series of experiments in which the flow was held steady and the applied

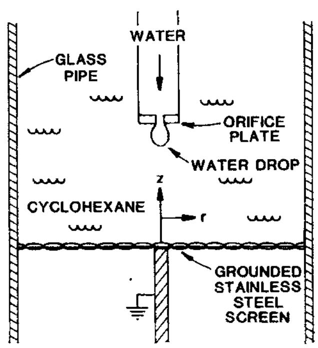

Figure 1. Simplified schematic of drop formation.

potential was increased. As the field strength increased, the drop eccentricity also increased and the drop volume decreased. Although the drops are not perfectly elliptical, a quantitative index of length to width may be calculated using eccentricity as defined for ellipses:

$$e = \sqrt{1 - \frac{b^2}{a^2}}, \tag{1}$$

with a as the drop length and b as the maximum drop diameter. A plot of eccentricity vs. applied voltage for the 0.09525-cm orifice is shown in Figure 3.

Effect of Electric Field in Drop Formation

In analyzing the influence of electrostatic forces applied in the same general direction as gravity and opposing surface forces, we anticipated the significant reduction in drop volume observed experimentally. A rigorous analysis of calculating the drop shape from the balance of forces required the solution of coupled nonlinear equations. To simplify the analysis, we used the observed fact that the droplets are approximately ellipsoidal in shape, and we assumed them to be ellipsoids of varying eccentricities.

$$F_s = F_g + F_e. \tag{2}$$

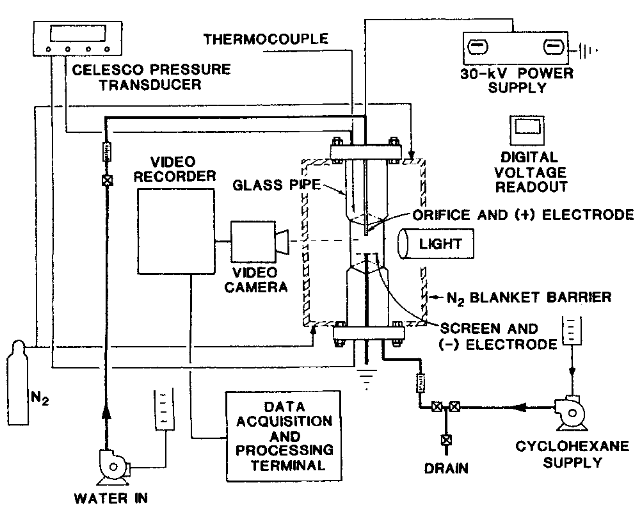

Figure 2. Experimental apparatus used in drop formation studies.

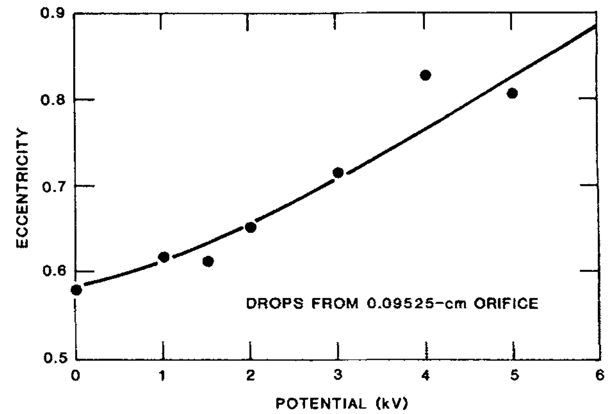

Figure 3. Experimental data for field intensity effects on drop eccentricities.

The interfacial tension force, F_s, does not depend on the drop volume and may be expressed as:

$$F_s = \pi D_o \sigma. \tag{3}$$

The Harkins-Brown factor has not been included in Eq. 3. This empirical factor, which is intended to account for the fraction of the liquid volume which remains attached to a nozzle after the drop breaks off, may not be accurate for the present application. The gravitational force, F_g, which does depend on drop volume, v, is:

$$F_g = (\rho_w - \rho_c) v g. \tag{4}$$

The addition of the electrostatic force, F_e, causes the force balance to be satisfied with smaller drops.

Experimental drop volumes were obtained for a range of electric-field-strengths in the prejetting regime, Figure 4. Drop sizes decreased significantly as voltages ranged to 4 kV. This effect is most pronounced with the larger orifices, which produce larger drops in the absence of an electric field.

Theoretical Model

The electric field is developed between the disk-shaped orifice plate and the metal screen positioned 5 cm below it. The orifice plate diameter is small compared to that of the screen.

To approximate the experimental system, the orifice plate may be represented as a disk electrode at the surface of an infinite medium bounded by two parallel planes. The mathematical problem is more easily solved if there are two disk electrodes, one in each parallel plane, in opposing positions, and of opposite charge. The potential field for the present application is that between one of the disk electrodes and the midplane of the system, where the charge is zero. This model requires the assumption that the presence of the water drop does not affect the potential field.

This potential field problem was solved by Gray and Matthews (1931). The solution is

$$V = \frac{s}{2\pi k R} \int_0^\infty \frac{\sinh(\lambda z)}{\cosh(\lambda d)} [\sin(\lambda R)]\,[J_o(\lambda r)] \frac{d\lambda}{\lambda}, \tag{5}$$

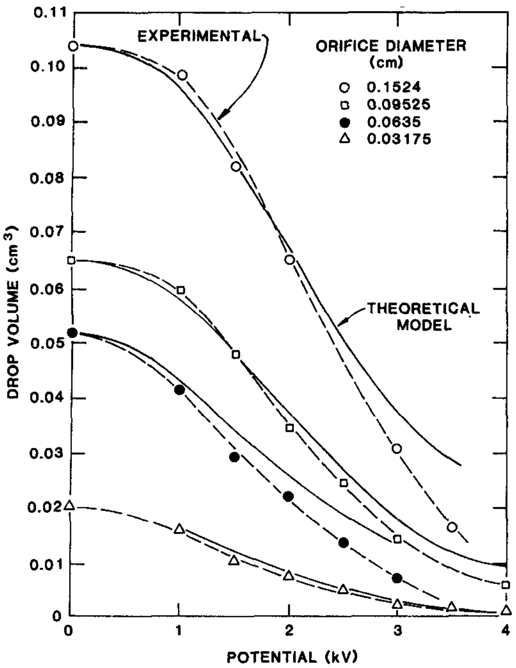

Figure 4. Experimental and model-predicted values for drop volumes in electric fields of varying intensity.

where

R = radius of disk
z = distance in normal direction from midplane
d = distance from disk to midplane
r = radial distance from center of disk

The field intensity may be obtained as

$$\left(\frac{\partial V}{\partial z}\right)_{r,z} = E_z = \frac{S}{2\pi kR}\int_0^{\infty}\frac{\cosh(\lambda z)}{\cosh(\lambda d)}\sin(\lambda R)J_o(\lambda r)\,d\lambda. \quad (6)$$

The electrostatic force, F_e, is given by

$$F_e = \frac{1}{2}\int \epsilon E_z^2\,dA. \quad (7)$$

When a value for voltage is selected, Eq. 5 may be solved to evaluate the group preceding the integral for a point in the field. Equation 6 may then be solved for the field intensity at that point.

Examples of field strengths (E_z^2) are shown in Figure 5 for a drop volume of 0.020 cm³ with a potential of 1,000 V on the orifice plate. Field strengths are plotted at ten peripheral points for two drops with eccentricities of 0.2 and 0.9. The field strength decreases sharply as the distance from the orifice plate increases.

A computer program was written to evaluate the integrals in Eqs. 5 and 6 by Simpson's rule. The field intensity at the surface of each drop was calculated for ten points around the drop periphery. The force on the drop was calculated using a summation approximation to Eq. 7 for the ten area segments.

Using the model, calculations of electrostatic force were made to explore the effects of eccentricity. In this model the drops were represented as prolate ellipsoids. For the range of

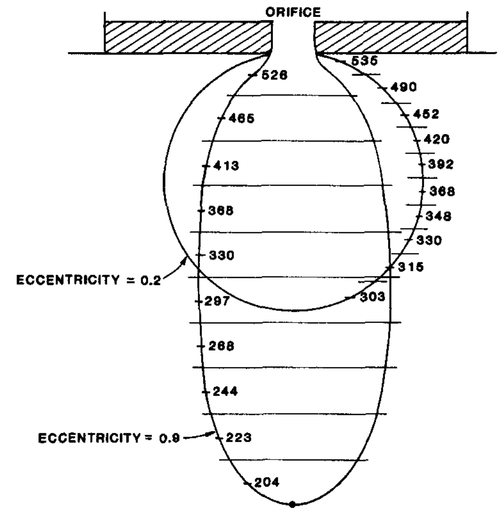

Figure 5. Field strength trends with varying radial and longitudinal distances for droplets with eccentricities of 0.2 and 0.9 at 1,000 V.

Field strengths (E_z^2) are in units of $(N/C)^2 \times 10^{-8}$.

drop sizes encountered in the experiments, which are shown in Figure 4, the effect of eccentricity was quite small. Typical model calculation results for a 0.02 cm³ drop volume in a 1,000-V field are:

Eccentricity	Electrostatic Force, N
0.6	1.22 E-5
0.7	1.21 E-5
0.8	1.19 E-5

This variation is within the precision of the experiments. The trend is surprising in that the force increases as the drop becomes more nearly spherical. Apparently, the greater surface area of the drops with higher eccentricity and the decline of field intensity with a radius are more than compensated for by the decrease in field intensity with a distance away from the orifice plate.

Force calculations utilizing Eqs. 5 to 7 were made for a number of voltages and drop sizes. Since the eccentricity appears to be a less important factor than at first anticipated, a correlation was sought to empirically predict the electrostatic force as a function of drop volume and applied voltage. The following empirical equation for the force (in Newtons) on the drop represents the model-generated results quite well.

$$F_e = 9.80\ 10^{-5}\left(\frac{V}{1{,}000}\right)^2 v^{0.54}, \quad (8)$$

where V is the applied voltage and v is the drop volume in cm³.

It should be emphasized that Eq. 8 applies only to the particular experimental system tested. It was utilized in the force balance equation (Eq. 2) to predict drop volumes produced with the four orifice sizes tested experimentally. The results of these calculations are shown in Figure 4.

The model set out in this study is quite simple, ignoring such effects as:

1 Presence of the water drop on the local electric field strength

2 Electric field on the interfacial tension

3 Harkins-Brown effect

Even so, the agreement between experimental results and model predictions is fairly good up to 2,500–3,000 V. An explanation for the significant deviations at higher voltages may lie in these effects.

Acknowledgment

This research was sponsored by the Office of Basic Energy Sciences, U.S. Department of Energy, under contract DE-AC05-840R21400 with Martin Marietta Energy Systems, Inc.

Notation

a = major dimension of ellipse
A = surface area of drop
b = minor dimension of ellipse
d = gap between disk and plane
D_o = orifice diameter
e = eccentricity defined by Eq. 1
E_z = field intensity
F_e = electrostatic force
F_g = gravitational force
F_s = surface force
g = gravitational constant
k = conductivity of medium
r = radial distance from axis of disk
R = radius of disk
s = current
v = drop volume
V = potential
z = normal distance from plane

Greek letters

ϵ = electrical permittivity of cyclohexane
σ = interfacial tension
ρ_w = density of water
ρ_c = density of cyclohexane

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Manuscript received Sept. 14, 1987, and revision received Apr. 5, 1988.