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ABSTRACT
The main aim of this study is to explore the role of viscoelastic properties of polymeric solutions on mode transitions in the electrospray process. By adjusting the applied electric potential between the nozzle and the collecting substrate, various electrohydrodynamic (EHD) modes were photographed by using a high-speed camera. Then, the effect of operating parameters on the droplet size in the dripping mode and the jet profile in the jet mode was investigated. By categorizing the EHD modes of each viscoelastic solution into dimensionless operating maps, it can be seen that by increasing the solution concentration, the extents of dripping mode and beads-on-a-string structure dwindle, while the jet stabilizes in a wider range of electric capillary numbers. Furthermore, contrary to deionized water, when the applied voltage escalates, the stick jet mode is observed where the jet sticks to the outer surface of the nozzle and the asymptotic thickness of the jet falls.

I. INTRODUCTION
Electrohydrodynamic (EHD) phenomena have attracted increasing attention over the past decades. Electrospraying and electrospinning are the two main EHD applications. Electrospray is a method of producing a continuous stream of monodisperse droplets in ambient air. This is achieved by exerting the potential difference between the nozzle and the collecting substrate. Various electrohydrodynamic (EHD) modes were photographed by using a high-speed camera. Then, the effect of operating parameters on the droplet size in the dripping mode and the jet profile in the jet mode was investigated. By categorizing the EHD modes of each viscoelastic solution into dimensionless operating maps, it can be seen that by increasing the solution concentration, the extents of dripping mode and beads-on-a-string structure dwindle, while the jet stabilizes in a wider range of electric capillary numbers. Furthermore, contrary to deionized water, when the applied voltage escalates, the stick jet mode is observed where the jet sticks to the outer surface of the nozzle and the asymptotic thickness of the jet falls.

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strength of the electric field lead to a higher number of jets, which in
turn implies thinner jets. The EHD modes of both Newtonian and
viscoelastic fluids are schematically depicted in Fig. 1.

Regarding viscoelastic fluids, the first EHD mode is the dripp-
ning mode even though the breakup process in these fluids is
to-完全可以品，while the frequency of droplet production is dra-
matically lower. Subsequently, due to the elastic intermolecular
forces in polymer structures and higher breakup times, the ejecting
droplets adjoin on a filament of fluid when the electric field inten-
sity increases, constituting an EHD mode called beads-on-a-string
structure. Then, by further rising the electric potential, perturbations
on the string gradually vanish and a cone-shaped jet similar to the
one from Newtonian fluids, albeit thinner and without any ramifi-
cations, is attained. Furthermore, when the electric field is escalated,
the jet becomes extremely thin and sticks to the tip of the nozzle.
This mode is called the stick jet mode and is specifically seen in vis-
coelastic fluids. Finally, further increasing the electric field strength
yields an unstable jet, moving irregularly around the tip of the no-
zle. The briefly introduced EHD modes of viscoelastic fluids are
the main focus of the current study, and their underlying physical
mechanisms will be explained in detail in Sec. IV.

Other work has explored the effects of different spraying flu-
ids,15–17 different nozzle geometries,18 and changes in the polar-
ity19,20 and direction21 of the applied electric field. Guerrero et al.22
identified and classified the different modes observed in electrically
driven co-flowing liquids. These modifications of the test circum-
cstances lead to severe changes in the EHD modes produced and
their stability domains. A complete review of electrospray and its
fundamentals was published by Ganán-Calvo.23

Many studies have examined the role of viscoelasticity on the
flow behavior. As an illustration, the atomization of polymer solu-
tions was experimentally studied,24 where the role of the physical
and rheological properties of fluid on the Sauter mean diameter of
droplets was examined. In 2010, several electrospray tests were con-
ducted for highly viscous solutions of sodium alginate, and empirical
equations were suggested for the diameter of produced droplets.25
The dispensing mechanism of polyacrylamide (PAA) Boger fluid in
the dripping mode was examined,26 where the surface tension and
gravity forces were balanced in the neck region to obtain the
diameter of the drop. Moreover, much research has been done on
viscoelastic, electrified,27–29 or free-falling30 liquid jets. Song et al.31
examined the effect of viscoelasticity on electrokinetic instabilities

![FIG. 1. Schematic representation of different EHD modes of Newtonian and viscoelastic fluids.](image)
both experimentally and numerically in a T-shaped microchannel with conductivity gradients using polyethylene oxide (PEO) solutions with different concentrations. The beads-on-a-string structure, which is a rather peculiar and interesting behavior of the viscoelastic fluid, was numerically modeled by Li and Fontelos.\cite{Li2011} Recently, viscoelastic fluid’s electrospray was investigated by Yu et al.\cite{Yu2013} to optimize the fluid used in inkjet printing. They used polyethylene oxide with different molecular weights at various solution concentrations to independently control the elasticity and viscosity of the solution. Because of the different physical and rheological properties that were explored, new EHD modes were observed and operating maps for every solution were provided.

The main aim of this study is to explore the role of viscoelasticity on mode transitions of EHD. For this reason, the electrospray of a dilute PAA aqueous solution at different concentrations is examined experimentally, and transitions in modes of EHD are classified with dimensionless operating maps. Furthermore, new EHD modes for viscoelastic dilute solutions are introduced and observed with high-speed photography. The images acquired in this way are used to examine the effects of various test conditions on the droplet diameter and the viscoelastic jet profile.

The rest of this paper is organized as follows: the dimensionless numbers used in Sec. IV are introduced in Sec. II. In Secs. III and IV, the experimental setup and the results of the experiments are discussed. Finally, the paper is concluded in Sec. V.

II. DIMENSIONLESS NUMBERS

In this section, the essential dimensionless numbers controlling the electrospray process are introduced. The Weissenberg number (Wi), a dimensionless value that is regularly used in problems of viscoelastic fluids, is defined as follows:

$$Wi = \frac{l}{l}$$

where $l$, $U$, and $\lambda$ are the characteristic length of the problem, the average velocity of the ejecting fluid, and the relaxation time, respectively. Moreover, the Weber number, which describes the ratio of inertia forces to surface tension forces, is given by the following equation:

$$We = \frac{\rho U^2 l}{\gamma}$$

where $\rho$ and $\gamma$ are the density and surface tension, respectively. The electric capillary number is the ratio of the electric field force to the surface tension forces and is defined as follows:

$$CaE = \frac{\varepsilon_0 \varepsilon E^2 R_0}{\gamma}$$

where $R_0$ is the half of the characteristic length, which in our case is the outer radius of the nozzle. $\varepsilon_0$ and $E$ are the vacuum permittivity and the electric field strength, respectively. In this analytical study, the strength of the electric field at the tip of a positively charged cylinder with a semi-finite ground terminal positioned below the cylinder is calculated using a relationship originally proposed by Jones and Thong.\cite{Jones1995}

$$E = \frac{\sqrt{2\varepsilon_0}}{R_0 \ln(4z_0/R_0)}$$

where $z_0$ is the distance between the cylinder and the ground terminal and $\Phi_0$ is the applied voltage. Additionally, $\varepsilon_r$ in Eq. (3) is termed as the characteristic relative permittivity and is defined using the Lorentz model for the interaction of electromagnetic waves in dielectric materials,

$$\varepsilon_r = 1 + \frac{\sigma}{\varepsilon_0 \omega L}$$

where $\sigma$ is the electrical conductivity and $\omega$ is the characteristic frequency which is defined by the following equation:

$$\omega = \frac{c}{L}$$

In Eq. (6), $c$ is the speed of light in air and $L$ is the distance between the center of the capillary tip and the inner edge of an annular disk taken as the substrate. Last but not least, the dimensionless droplet frequency is defined as follows:

$$n^* = \frac{Q \mu \varepsilon_0 \varepsilon E^2 R_0}{L^4}$$

where $n$ is the droplet frequency and $Q$ is the volumetric flow rate. The dimensionless numbers introduced in this section are used in Sec. IV to categorize and classify the results.

III. EXPERIMENTAL SETUP

A schematic representation of our experimental setup is given in Fig. 2. Every electrospray test was conducted under conditions of atmospheric pressure and 25°C temperature. A stainless steel nozzle with an inner diameter of 0.31 mm and an outer diameter of 0.63 mm was connected to a syringe pump to inject fluid between the nozzle and a round aluminum disk taken as the substrate. The nozzle was positioned vertically to prevent wetting effects, and the distance between the nozzle and the substrate was 30 mm. A high voltage source was used to exert the potential difference between the nozzle and the substrate. As the voltage was varied, different EHD modes were observed. The viscoelastic solutions used in the electrospray tests were aqueous PAA solutions in three different concentrations, including 50 ppm, 100 ppm, and 150 ppm, where the molecular weight of the PAA powder was 2e4 g/mol. The fluid was pumped using an SP-100s syringe pump and photographed using high-speed photography equipment that included a PCO high-speed camera and a NIKON auto focus (AF) Micro-NIKKOR 200 mm f/4D internal focusing-extra-low dispersion (IF-ED) lens.

The measured physical properties of the PAA solutions can be found in Table I. An Anton–Paar modular compact rheometer (MCR) was used for rheometric tests, where the relaxation time of the solutions was determined with a small-amplitude oscillatory shear test (the G’G” test), and the shear-thinning behavior of solutions was examined. Negligible shear-thinning behavior was observed (the polymeric viscosity remained fairly constant for different shear rates), indicating that our PAA solutions were similar to Boger fluids representing elastic behavior in an almost constant viscosity. It should be added that glycerin was not used in the viscoelastic solution solvents, so the solvent viscosity remains low, and the fluid flows through the nozzle conveniently. Furthermore, the surface tension of the viscoelastic solutions was measured using a Dataphysics DCAT 11, following the ASTM D 1331-14 standard and using the Wilhelmy plate method, and the
solution electric conductivity was measured with a JENWAY 3540 conductometer. The physical properties of the DI water and air, which are used to calculate dimensionless numbers, are listed in Table II.

IV. RESULTS

At the beginning of every experiment, electrospray of DI water was performed to verify the repeatability of the experimental results. For this purpose, the experimental data presented by Jaworek and Krupa\textsuperscript{10} were used to analyze and validate the results. This procedure reliably ensures that the experimental conditions will lead to the same results and no new adjustments or calibrations are needed. Additionally, every test was repeated three times, and the obtained results were compared such that the authenticity of the results can be examined. High-speed photography was begun after each mode reached a steady state. The main sources of error in the experimental tests are voltage measurement (0.1 kV), flow rate measurement (1 ml/h), and image-processing algorithms (one-pixel size). In the analysis of the results, these sources of error are taken into account.

For the sake of comparison with the viscoelastic results, various EHD modes of DI water are shown in Fig. 3. As can be seen in the figure, these EHD modes include the dripping (\(Ca_E = 0–0.93\)), microdripping (\(Ca_E = 1.37\)), spindle (\(Ca_E = 1.91–2.25\)), oscillating-jet (\(Ca_E = 2.43\)), cone-jet (\(Ca_E = 2.57–6.31\)), and precession (\(Ca_E = 6.69–7.08\)) modes.

From this point forward, we concentrate on the EHD modes of viscoelastic dilute solutions. The first distinguishable characteristic in the viscoelastic solutions can be seen in the dripping mode, where a droplet is followed by a thin filament of fluid. It is clear from Fig. 4 that the detachment of the drop from the tip of the

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**TABLE I. Physical properties of dilute viscoelastic solutions.**

<table>
<thead>
<tr>
<th>Concentration (ppm)</th>
<th>Surface tension (mN/m)</th>
<th>Electrical conductivity ((\mu)S/m)</th>
<th>Density (kg/m(^3))</th>
<th>Solvent viscosity (Pa s)</th>
<th>Polymeric viscosity (Pa s)</th>
<th>Relaxation time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>70.739</td>
<td>20.3</td>
<td>1000.05</td>
<td>0.001</td>
<td>0.0047</td>
<td>0.518</td>
</tr>
<tr>
<td>100</td>
<td>71.751</td>
<td>36.6</td>
<td>1000.1</td>
<td>0.001</td>
<td>0.035</td>
<td>1.094</td>
</tr>
<tr>
<td>150</td>
<td>72.169</td>
<td>59.9</td>
<td>1000.15</td>
<td>0.001</td>
<td>0.068</td>
<td>1.709</td>
</tr>
</tbody>
</table>

**TABLE II. Physical properties of DI water and air.**

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Surface tension (mN/m)</th>
<th>Electrical conductivity ((\mu)S/m)</th>
<th>Density (kg/m(^3))</th>
<th>Solvent viscosity (Pa s)</th>
<th>Polymeric viscosity (Pa s)</th>
<th>Relaxation time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DI water</td>
<td>72</td>
<td>5.5</td>
<td>1000</td>
<td>0.001</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Air</td>
<td>...</td>
<td>(8 \times 10^{-9})</td>
<td>1.225</td>
<td>(1.18 \times 10^{-5})</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>
FIG. 3. Observed DI water EHD modes for a 108 ml/h flow rate (We = 1.382), categorized according to the electric capillary number: (a)–(c) dripping mode, (d) microdripping mode, (e) and (f) spindle mode, (g) oscillating-jet mode, (h)–(j) cone-jet mode, and (k) and (l) precession mode.

nozzle varies significantly for viscoelastic solutions. Generally speaking, Newtonian droplets detach instantly from the nozzle, or in some cases, they are followed by a small satellite droplet. Viscoelastic droplets, on the other hand, are known for depicting strong elastic behavior upon detachment. The thin filament formed in viscoelastic fluids is stretched, and its thickness plummets as the drop moves further away from the nozzle. Consequently, the filament becomes extremely thin, until it breaks.

In Fig. 5, every viscoelastic EHD mode is illustrated in an increasing sequence of the electric capillary number for a 108 ml/h flow rate and a 100 ppm PAA aqueous solution. The first mode observed in viscoelastic solutions is the dripping mode, where the droplet size falls, while the frequency increases as the voltage increases (Ca_E = 0–0.79). In this mode, the gravity force on the accumulated fluid at the tip of the nozzle and electrostatic forces balance with the surface tension and viscoelastic molecular forces. The elongation of drops transforms the originally coiled configuration of polymer molecules to the stretched conformation of these molecules in the elongated fluid filament. This stretching in polymer networks increases the extensional viscosity, resulting in the more robust elastic forces in polymer chains. Acting like viscoelastic springs, these chains extend in the direction of the flow movement in liquid filaments, delaying the breakup process markedly. The next identifiable mode is the beads-on-a-string structure (Ca_E = 1.05–1.6), which has been observed and reported in previous publications. Additionally, a transition mode is observed between the dripping mode and the beads-on-a-string structure, where the two modes can be observed intermittently. In the beads-on-a-string structure, which is only observed in viscoelastic fluids, the electric field tends to deform the pendant drop into a cone jet. On the other hand, the elongated chains of polymer molecules act as springs and develop back stress which helps the surface tension force to overcome the electric deforming force; as a result, some parts of the jet recover their initial shape as beads. By further increasing the electric capillary number, beads gradually diminish in size, and the string is transformed into a cone-shaped jet (Ca_E = 2.03–4.16). This mode is acquired under the effect of an intense electric field, where the polymer molecules do not have enough time to rearrange, and in the absence of spring...
effects, the droplet is deformed into a cone jet. For viscoelastic solutions, the cone-jet mode is stable across a wider range of potential differences than DI water. Furthermore, as the electric field is augmented, the cone angle increases and the asymptotic thickness of the jet falls. The cone angle surges until the jet sticks to the annular section of the nozzle ($C_{aE} = 7.84–10.35$), which is why this mode was termed as the stick jet mode. In DI water, the jet usually ramifies in the downstream of the flow. By intensifying the strength of the electric field, this ramification moves upstream until the multijet mode is reached, while in the viscoelastic solutions, no ramification is observed downstream of the flow. Finally, if the electric capillary number reaches an instability threshold, the thin jet produced begins to oscillate and shows erratic behavior ($C_{aE} = 11.03$). The crucial result that can be derived from this part is that viscoelasticity stabilizes the jet and escalates the stability limit. To avoid redundancy, in Fig. 6, the EHD modes of other concentrations and flow rates are classified according to their dimensionless numbers, where the observed range for every mode is specified.

The extent to which each EHD mode is produced in a nondimensionalized operating map is depicted in Fig. 6. This graph clearly shows that by increasing the concentration of the viscoelastic solution, regions pertinent to the dripping and transition modes dwindle, so the beads-on-a-string structure is obtained for lower electric capillary numbers. At higher solution concentrations, the beads-on-a-string structure and the cone-jet mode are observed in a narrower range of the electric capillary number, while the stick jet mode shows a reverse trend. This result is in contrast with our expectation that due to the more vigorous elastic properties and stronger bonding between polymer molecules in higher solution concentrations, the beads-on-a-string structure and the cone-jet mode should appear at higher and wider ranges of the electric capillary number. The contradiction can be explained by the fact that although the spring effects become stronger at higher polymer concentrations, the electric deforming forces are also increased considerably since the electric conductivity of the solution is almost tripled, as is shown in Table I. As the solution concentration increases, the stick jet mode stabilizes in a wider range of electric capillary numbers. This behavior can be attributed to two simultaneous reasons, namely, the onset voltage for stick jet formation falls, while the stability threshold surges. This is because electric repulsion is neutralized by viscoelastic stresses; therefore, the threshold of thin jet stability is increased and the stick jet mode, a mode initially formed...
FIG. 5. Snapshots of the viscoelastic EHD modes for a 100 ppm PAA solution \((\text{Wi} = 690.2)\) and a 108 ml/h flow rate \((\text{We} = 1.387)\): (a)–(c) dripping mode, (d)–(f) beads-on-a-string structure, (g)–(i) cone-jet mode, (j) and (k) stick jet mode, and (l) unstable jet.

through the action of tangential viscoelastic volume forces on the interface, is observed at a lower electric field strength. It is noteworthy that the dimensionless maps are separated according to the solution concentration rather than the Weissenberg number because the Weissenberg number depends on both relaxation time, which is directly affected by the solution concentration, and the velocity, which is directly dependable on the flow rate; therefore, each map encompasses a range of Weissenberg numbers, and a single Weissenberg number cannot be assigned to a single map.

To determine the influence of different parameters on the droplet size, images of droplets acquired by high-speed photography were processed using image-processing codes. First, noise on the surface of the droplets and its circumference was eliminated. Using the outer diameter of the nozzle, the size of each pixel was obtained, and the mean diameter of the droplets was calculated using the Riemann sum method. The formation of a thin filament of fluid in the breakup led to the calculation of the diameter of every droplet at the onset of neck formation. The calculated diameters are plotted vs the potential difference for each flow rate and solution concentration in Fig. 7. Possible error in voltage measurement and the standard deviation for the diameters of the droplets are plotted in Fig. 7. It is inferred from the figure that when the flow rate or solution concentration is increased, the droplet size also grows, while increased voltage reduces the diameter of the drops. A similar trend has also been observed for DI water\(^{10}\) and nanosuspension droplets in previous studies although these were obtained with different nozzle diameters.

In Fig. 8, the same results are depicted in terms of nondimensional quantities. The droplet diameter in the figure is nondimensionalized by the diameter of the same case in the absence of the electric field. The plotting of the results to a single curve shows that the non-dimensionalized droplet diameter only depends on the electric capillary number, and it is independent of the concentration and flow rate of the solution. This is due to the fact that among the main forces influencing the breakup process, namely, the surface tension, electric repulsion, and gravity forces, only electric forces are affected by the alterations in the solution concentration since surface tension, solvent viscosity, and density change negligibly between different solution concentrations whereas electrical conductivity alters considerably. In addition, the trend given in Fig. 8 is curve-fitted to
FIG. 6. Operating range of various viscoelastic EHD modes plotted according to the electric capillary and Weber numbers for PAA solutions at three concentrations: (a) 50 ppm solution, (b) 100 ppm solution, and (c) 150 ppm solution.

FIG. 7. Droplet size vs applied voltage for every tested case.

For each histogram to produce a better view of the standard deviation and the symmetry of the distribution of droplet sizes. In Fig. 9, it can be explicitly seen that although the average droplet size falls with increasing electric field strength, the size distribution markedly broadens. This result stems from the fact that when the voltage is increased, the repulsion between the polarized droplets produces minor deviations of droplet ejection from the vertex of the cone. This phenomenon causes increased irregular behavior during the breakup. The results shown in Figs. 8 and 9 have also been found for nanosuspension droplets.

Next, in Fig. 10, the frequency of droplet generation is plotted against the voltage for every tested case. It is observed that the droplet frequency shows an upsurge when the applied voltage or flow rate is increased; however, the effect of rising solution concentration on the droplet frequency is nonsignificant. This is
because surface tension, the main parameter determining the time of droplet generation, is relatively constant for every solution concentration, while polymeric viscosity alters the severity of elastic behavior during the breakup process. The general trend of the data plotted in Fig. 10 is similar to the corresponding trends depicted for DI water and nanosuspensions; nevertheless, the frequency of droplet generation in viscoelastic solutions is substantially lower than that in Newtonian fluids because of the increased total viscosity and delayed breakup. For every flow rate, the data plotted in Fig. 10 are curve-fitted with a third-order polynomial, and the corresponding equations of curve-fitted diagrams can be found in the figure.

When the data in Fig. 10 are rearranged in terms of the electric capillary number and dimensionless droplet frequency, as seen in Fig. 11, we recognize that the dimensionless droplet frequency increases almost linearly with the electric capillary number, but it is barely affected by the solution concentration or flow rate. Moreover, the electric capillary number, affected by the electric field strength and surface tension with the latter being almost constant among different concentrations, directly determines the severity of charge repulsion in the cone. On the other hand, the effect of increased droplet-generation frequency in higher flow rates is neutralized when the frequency number is divided to the volumetric flow rate in the dimensionless droplet frequency definition [refer to Eq. (7)]. The two aforesaid reasons cause the changes in the dimensionless droplet frequency with the electric capillary number to be independent of the flow rate or solution concentration. Thus, the intensity of electric volume forces is the sole criterion influencing the alterations in the dimensionless droplet frequency.

As in the algorithms used for droplet image processing, the images pertinent to the cone-jet and stick jet modes were processed and the noise from the captured pictures was eliminated. Afterward, every jet profile was curve-fitted with a power-law relationship of an arbitrary power. The effects of the operating parameters on the
stable jet profile are shown in Figs. 12–14. First, we examine the effect of electric field strength on the final diameter of the jet in Fig. 12. It is clear from the figure that the final thickness of the jet plummets when the electric field strength is increased. Because the jet mode is initially formed by the action of tangential electric stresses on the interface, it is expected that the increased electric forces diminish the asymptotic thickness of the jet. On the contrary, Fig. 13 indicates that when the flow rate is increased, a monotonic increase in the diameter of the jet appears for a constant strength of the electric field and solution concentration. By contrast with electrostatic effects, in higher flow rates, the initial thinning of the jet is slower, which leads to an increased cross-sectional area and lower jet velocities. As shown in Fig. 14, although the behavior of the stick jet becomes more evident in higher Weissenberg numbers, the parameters of viscoelasticity have little influence on the asymptotic jet thickness. The alterations in the jet profile are caused by enhanced stretching at the beginning, which is harness by tangential electrostatic forces further downstream.

In Fig. 15, the cone angles, calculated from the slope of the tangential lines on each jet profile, are plotted against the electric capillary number. It is evident from the figure that the cone angle alterations within each mode are rather small, while a jump in the cone angle is seen in the transition from one EHD mode to another. The first jump occurs when the ellipsoidal meniscus in the beads-on-a-string structure changes to a conical meniscus in the cone-jet mode. Subsequently, by further increasing the electric field strength, the cone-shaped jet sticks to the outer surface of the nozzle, making the apex angle of the cone wider. These alterations are curve-fitted
with a third-order polynomial, and the corresponding equation for this diagram can be found in the figure.

V. CONCLUSION

In this study, the influence of viscoelasticity on EHD modes was examined in detail. The change in the mechanical behavior of fluid caused by viscoelastic stresses leads to the observation of new EHD modes. The results of every electrospray test were classified in dimensionless operating maps, where the effects of different parameters on the operating range of each mode were examined. By increasing the flow rate or solution concentration, the region of the stable jet, especially the region of the stick jet mode, enlarges and the fluid stability threshold grows considerably. On the other hand, the regions pertinent to other EHD modes diminish when the flow rate or solution concentration increases. It can also be deduced that the breakup process in viscoelastic solutions is entirely different from that of Newtonian fluids. Additionally, it is noted that the dimensionless droplet diameter and the dimensionless droplet frequency vary almost linearly with the electric capillary number. Although increasing the electric capillary number reduces the average droplet diameter, the distribution of the droplet size broadens significantly. If the electric capillary number increases, the asymptotic thickness of the jet diminishes, while increasing the flow rate thickens the jet. Changing marginally in every mode, the cone angle steeply increases during mode transitions.

REFERENCES