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Volume-charged cones on a liquid interface in an electric field

A. V. Subbotin[+*1)], *A. N. Semenov*[×]

[+] *A.V. Topchiev Institute of Petrochemical Synthesis, Russian Academy of Sciences, 119991 Moscow, Russia*

[*] *A.N. Frumkin Institute of Physical Chemistry and Electrochemistry, Russian Academy of Sciences, 119071 Moscow, Russia*

[×] *Institut Charles Sadron, CNRS-UPR 22, Universite de Strasbourg, BP 84047, 67034 Strasbourg Cedex 2, France*

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It is well known that in high electric field liquid meniscus adopts a cone-like shape which is also known as a Taylor cone whose apex emits a fine jet or droplets. Taylor was the first who showed that perfectly conducting liquid forms conical shape with apex half-angle $\theta = \theta_T = 49.3°$ due to a balance between the electrostatic and capillary forces [1]. The conical surfaces have also been predicted for the ideal dielectric liquids whose dielectric constant ε exceeds some critical value $\varepsilon > \varepsilon_c \approx 17.6$ [2, 3]. The cone half-angle θ depends on ε and varies in the range $0 < \theta < 49.3°$. The surface of the dielectric cone carries only the polarization charge and emanation of jet from the cone apex is impossible just like for the case of the perfectly conducting liquid. Recently we proposed a different class of self-similar conical solutions (micro-cones) arisen in the leaky dielectric model which carry both the polarization and conductive surface charge [4, 5]. By contrast with the hydrostatic Taylor cone and dielectric cones these new conical features have finite size and conduct the surface electric current which depends on the cone apex angle. It was shown that both the electric current and the angle θ are the functions of ε, but do not depend on the applied voltage.

In this paper we reveal and study a qualitatively novel type of electrically driven conical meniscus which carries both the surface and net bulk charges. Our consideration is based on the experimental scheme shown in Fig. 1. The conductive liquid is pumped through a nozzle of the needle micro-electrode with the flow rate Q (see Fig. 1). The electrode is at a high positive voltage Φ_0 which generates an electric field of strength E_0 directed along the z-axis due to a positive charge of the needle. When the flow rate is small enough the effluent liquid adopts a slender conical shape, while it becomes atomized beyond the cone apex region (cf. Fig. 1).

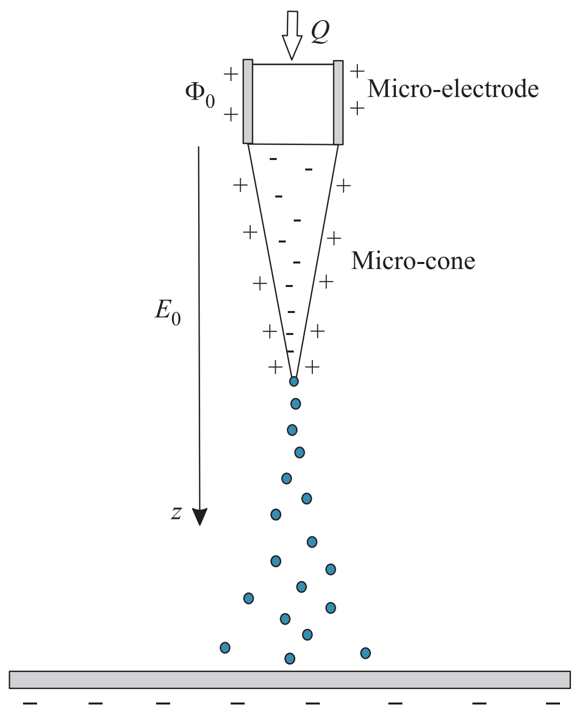

Fig. 1. Schematic picture of a conical meniscus formed on micro-electrode

When a high voltage is applied, the cations move towards the cone apex being localized at the surface, whereas the anions move to the electrode. The cations are generated at the micro-electrode and transported downstream. In what follows we assume additional generation of ions at the cone apex. We distinguish two generation mechanisms. The first mechanism is connected with dissociation and separation of cations and anions by the tangential electric field. Here we do not discuss dissociation enhanced by the strong electric field since the corresponding electric field strength is too high. Another possible mechanism is based on the corona discharge in the surrounding gas medium. We assume that electrons of the corona after having attained the inter-

1)e-mail: subbotin@ips.ac.ru

face get absorbed by the molecules of the liquid and trigger their dissociation.

Based on the above model and electrohydrodynamic equations we elucidated the effect of the physical parameters of the liquid on the micro-cone structure and show that the electric current is the only unknown parameter defining the cone half-angle θ. When the cone half-angle tends to $\theta = \theta^* = 2/\sqrt{\lambda\varepsilon}$ where $\lambda = \ln(1/\theta) \simeq 0.5 \ln \varepsilon$, the electric current tends to infinity. The above conclusion is valid only for an ideal infinitely long cone. In reality the cone base size is always limited by the size of the micro-electrode. In this case the current is limited by the electric field near the base, hence it must depend on the applied potential Φ_0. The obtained scaling relation between the electric current inside the cone and the applied voltage reads $I_0 \propto \Phi_0^2$. Note, that this scaling is quite natural for the cases where the volume charge of one sign dominates in the system.

To summarize, in this paper we discover a novel type of slender liquid conical emitters of charged droplets. The predicted conical dissipative structures arise when the dissociation/association processes in the liquid are governed by the applied voltage, while the stabilization of the cone is ensured by the capillary and electrostatic forces. The predicted micro-cones carry both surface and net bulk charges and are similar to those described in Ref. [5], however due to the anions generated at the cone apex in the present case, the electric current can become very large and tend to infinity when the half-angle approaches the critical value θ^*. Generally, the micro-cones are characterized by a finite-size base a_b where they touch the positive micro-electrode or transform into a meniscus of a classical Taylor-cone shape. We show that the electric current passing through the cone is likely to be proportional to the square of the applied potential. Presumably, the predicted volume-charged micro-cones can be identified with micro-cones or micro-jets observed in experiments on electrospraying [6, 7].

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