On Structure of Electrohydrodynamic Flows Caused by Field-enhanced Dissociation in Various System Configurations

Y. K. Stishkov, S. A. Vasilkov

s.vasilkov@spbu.ru

Abstract

If a dielectric liquid become charged in the external electric field, it starts moving and an electrohydrodynamic (EHD) flow emerges. There are several charge formation mechanisms that are active in the strong electric fields. Unlike the surface one (the charge injection), the volumetric mechanism (the field-enhanced dissociation) is poorly studied. The latter can take place both near metallic electrodes and solid insulation and leads to EHD flows with different structures. Thus, the present study examines a number of EHD systems and characterizes these cases by means of computer simulation. The computations are based on the complete set of electrohydrodynamic equations employing commercial software package COMSOL Multiphysics. The results show specifics of the charge formation and flow structures.

1 Introduction

Electrohydrodynamic (EHD) flows in isothermal incompressible dielectric liquids emerge under the action of the Coulomb force that takes place whenever the net electric charge exists in the presence of the electric field. The flows are typically studied in systems with inhomogeneous electric field with pointed electrodes and can correspond to several mechanisms of charge formation, namely, charge injection (the surface mechanism) and field-enhanced dissociation (the volume one, the relative increase in dissociation rate under the action of strong electric field).

Structures of the EHD flows of the injection type have been studied quite well both with the use of computer simulation and experiments in various systems [1, 2, 3, 4]. On the contrary, the flows caused by the field-enhanced dissociation [5] have been investigated only in a few works and mostly by means of computer simulation [6] or in comparatively weak electric fields [7]. However, as the work [8] has demonstrated good agreement between experimental and calculated velocity fields of the flows of the type, the simulation technique is verified and can be used for further studies.

Considering the electrode systems with pointed electrodes, for example, needle plane or blade-plane configurations, the maximum of the electric field strength and, consequently, that of the injection current or the increase in dissociation rate are located at the tip apex. The flows in the both cases have similar kinematic structures [6]: they develop from the pointed electrode towards the plane. The main difference between the two charge formation mechanisms (that the injection is the surface one and the dissociation is volumetric) does not allow for experimental identifying the dominant mechanism.

To study EHD flows caused by field-enhanced dissociation under secured absence of injection, the works [8, 9] considered original EHD system that creates the region of the strong electric field far from the electrode metal surfaces: the field is strengthened inside a cylindrical hole made in a dielectric flat barrier that is situated between two plane electrodes. In this case, the flow emerges near solid insulation and its structure differs from those observed in systems with pointed electrode. The diversity of flow localizations and structures is of interest, therefore, the present work studies and analyzes them in case of the sole action of the volumetric charge formation mechanism.

First, the paper considers a blade-plane system (Fig. 1a) in which the injection-type flows are often investigated and analyzed. Next, a system with a blade-shape barrier is examined and EHD flow is shown to emerge here (Fig. 1b). Both systems form a region of strong electric field at the tip but differ in the material of the blade. The latter sets conditions for the EHD flow with completely different structure. Further, two systems with axial symmetry are considered: the system with the hole in the barrier as discussed above (Fig. 1c) and a system with a hollow tube electrode slightly protruding from the insulating top (Fig. 1d). The latter system partially reproduces the electric field distribution in the bottom half of the former one but uses the metal electrode instead of solid insulation.

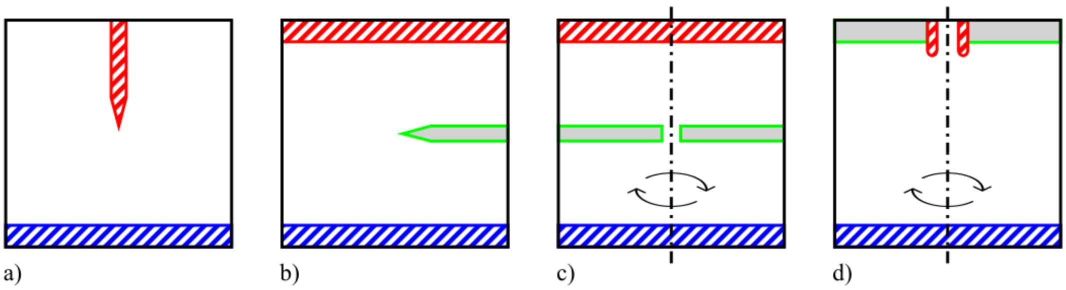


Figure 1: Schematic (not to scale) illustrations of the EHD system configurations: the blade-plane system (a), the dielectric blade system (b), the system with the hole in the barrier (c), and the slightly protruding hollow tube-plane system (d).

The geometries of the first and the third system correspond to those used in other studies, namely, in [10] and [8]. The second system is similar to the third one but the barrier has the shape of the blade from the first system. The last one has dimensions of the bottom half of the third one. Distances from the blade tip, the barriers and the tube electrode are nearly 10 mm. The blades are 10 μm sharp, the diameters of the hole and the tube are approximately 1 mm; curvature radii of the hole edges and the tube end are 0.07 mm and 0.1 mm correspondingly. The present study focuses

mainly on the flow structures and qualitative effects; however, certain quantitative results are of interest too but can differ since the sizes are different.
Analysis of all these cases, on the one hand, allows us to emphasize the variety of possible structures of EHD flows caused by field-enhanced dissociation and, on the other hand, to reveal their general regularities.

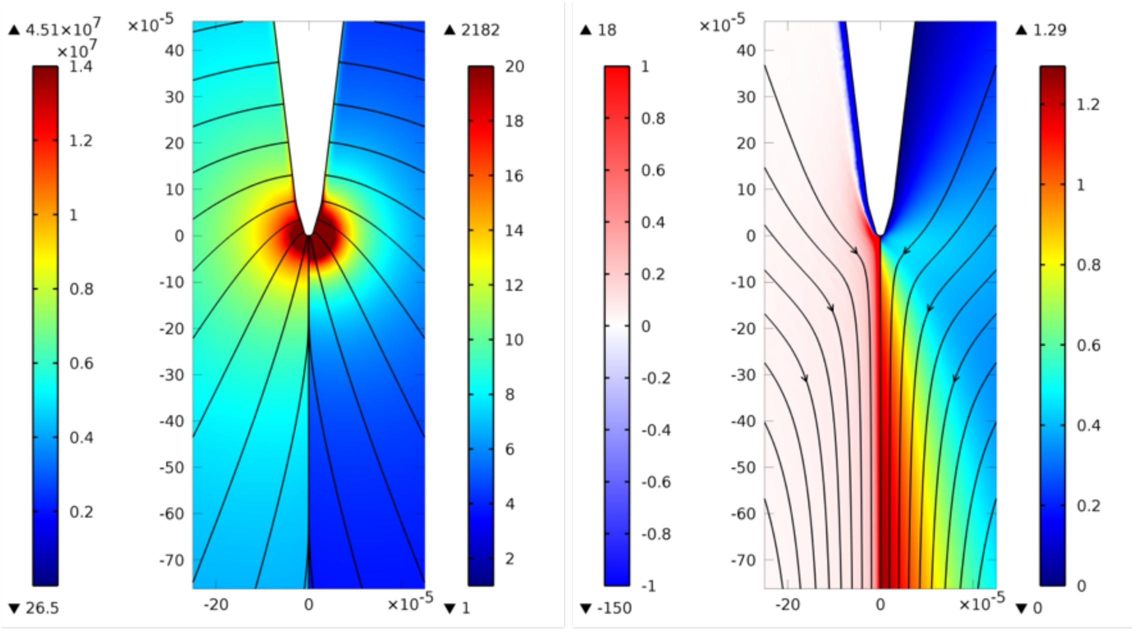
2 Simulation technique

The present work includes computer simulation of an EHD flow with the corresponding technique described in [6]. The computations were carried out using software package COMSOL Multiphysics based on the finite element method. The complete set of equations (as in [6]) was solved for the case of the two species of univalent ions with equal mobility and diffusion coefficient values. The dissociation intensity, the part of the source function for transport equations, is $W_0F(p)$ where W_0 is that in the absence of electric field and F is the relative increase in the dissociation rate [5]:
$F(p) = \frac{I_1(4p)}{2p}, p = \frac{e^2}{2k_BT}\sqrt{\frac{E}{4\pi\varepsilon\varepsilon_0 e}}$
Here I_1 is the modified Bessel function of the first kind, e is the elementary electric charge, k_B is the Boltzmann constant, T is the temperature, E is the electric field strength, ε is the relative electric permittivity, ε_0 is the electric constant.
All the considered configurations can be simulated using 2D models with axial or plane symmetry. The following assumptions and approximations are used thought all the models: all the system are closed, consist of electrodes (the shaded regions in Fig. 1) and dielectric surfaces (the remaining ones). Boundary conditions on the surfaces of the electrodes are the voltage (0 or 30 kV), zero velocity, zero flux for the ions of the same polarity (no injection current) and the free passage of the ions of opposite polarity (complete neutralization). Dielectric surfaces use condition $E_N = 0$, zero velocity, and no flux of ions conditions.
Since there is no injection on the electrodes, the only mechanism of charge formation is the dissociation enhanced by the field. The working liquid properties correspond to those of the mixture of transformer oil and cyclohexanol (see [11]) with the low-voltage conductivity of $0.92 \cdot 10^{-8}$ S/m.

3 Results and Discussion

3.1 Metallic blade

To start with, consider blade-plane electrode system that is frequently used to study EHD flows of injection type. Now, the case of field-enhanced dissociation is examined. The curvature radius of the blade tip is as small as 10 μm and thus produces strong electric field. As it can be seen from the simulation results (Fig. 2), the electric field strength exceeds $4{\cdot}10^{-7}$ V/m and the relative increase in the dissociation rate is higher than 10 at a distance of 0.1 mm from the blade (the maximum is greater than 2000).



a) b)

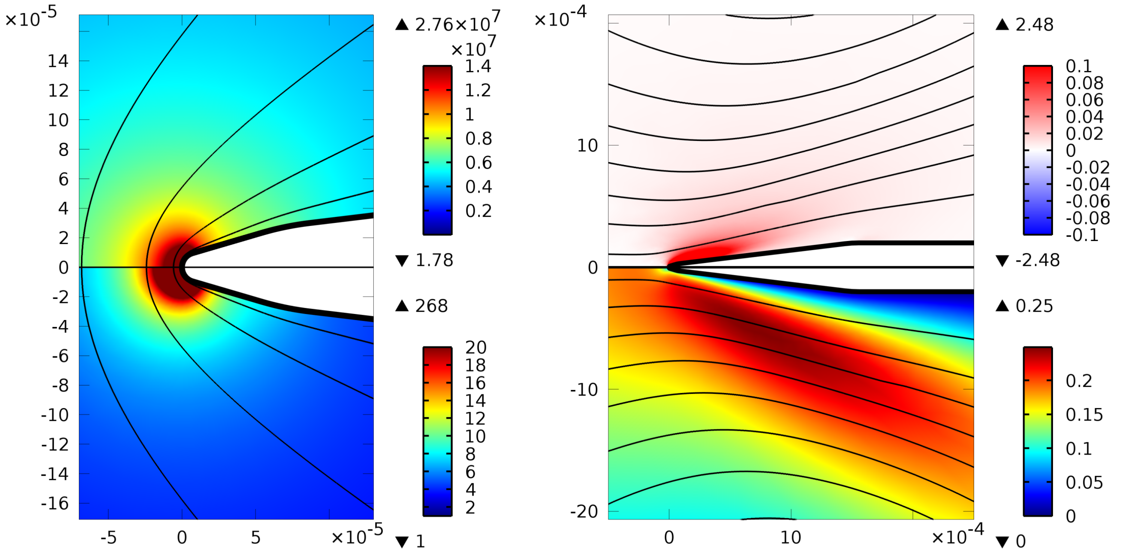
Figure 2: Distribution of quantities near the tip of the metallic blade: (a)п»„the electric field strenght (left) and the relative increase in the dissociation rate (right) near the tip of the blade, and the electric field lines; (b)п»„the distribution of the space charge density (left) and that of EHD flow velocity (right) near the tip of the blade and the streamlines.

The EHD flow in Fig. 2 is directed from the blade towards the plane and has typical structure that qualitatively coincides with that of the already studied injection EHD flows [10].The reason for this is the following: In the region of non-uniform and strong electric field, the counter ions move to the surface of the electrode whereas the ions of the same polarity escape into the bulk. This causes a layer of homocharge to form outside the heterocharge layer (that of the deficit of the ions of the same polarity where the dissociation and recombination rates are unbalanced). Therefore, the Coulomb force pulls the liquid downward just as in the case of injection and forms the observed flow. The space charge density exceeds 10 C/m^3 within approximately 10 μm thin charged jet and becomes much smaller but nonzero in the neighbor regions. The velocity profile is much wider (Fig. 2b) due to the effect viscosity; and the speed exceeds 1 m/s.

3.2 Dielectric blade

To isolate the field-enhanced dissociation from the injection, the works [8, 9] use the dielectric barrier of special design and shows the EHD flow to exist near the barrier. The key feature of the system is the location of the region of the strong electric field far from electrode surfaces, which makes the injection charge formation in the region impossible. The way how the solid insulation changes the electric field distribution is the accumulation of the electric charge on its surface, which results in screening the normal component of the electric field. Therefore, the present simulation technique uses condition $E_N = 0$ (the component has been screened) on dielectric surfaces.

Consider a blade of the same shape as in previous section but made from solid dielectric. It has the greatest impact on the electric field if it is placed horizontally in the middle of the gap. The electric field lines go around its surface, and a region of the strong electric field (up to $2 \cdot 10^{-7}$ V/m) and enhanced dissociation emerges near the tip (Fig. 3a). The distributions of |E| and F are very similar to those observed in the case of the metal blade but the direction of the field is completely different: electric field lines are perpendicular to the metal surface and are parallel to that of solid insulation. The positive and negative ions move along the electric field lines away from the region of enhanced dissociation and, in the contrast to the case of metal electrode, form the positive net charge above the dielectric blade (Fig. 3b) and the negative net charge bellow it (not shown in Fig. 3). The Coulomb force acts along the field lines and causes the liquid to flow from the tip along the surface of the blade towards its body. Compared with the previous case, the flow has the opposite direction.



a) b)

Figure 3: Distribution of quantities near the tip of the dielectric blade: (a)п»„the electric field strength (top) and the relative increase in the dissociation rate (bottom) and the electric field lines; (b)п»„the density of the space charge (top) and the velocity magnitude (bottom) and the streamlines.

Similar space charge distributions and flow structures can be generally expected near the sharp edges of solid insulation when the local increase of the electric field strength is produced by the accumulated charge. The latter can happen if the initial (when the dielectric surfaces are uncharged) electric field lines pass through the insulation. This means it should be placed between the electrodes.

3.3 Barrier with the hole

Next, consider and analyze the flow structure in the more complicated system used in [8]. The system consists of two flat parallel electrodes and a dielectric plate (barrier) having a small circular hole. The barrier is placed between the plates and splits the chamber filled with a dielectric liquid into two equal parts, with the hole remaining the only link to connect them. The charge accumulates on the barrier surface, screens the normal component of the electric field, and moves the electric field lines to the hole (the only available way). As a result, a region of the strong electric field emerges inside the hole (Fig. 4) that enhances the dissociation rate and provides EHD flow formation. The work [8] confirmed experimentally that the EHD flow (Fig. 4) does form in this system and has the following structure: the liquid spreads out radially along the barrier and then comes to the hole from the bulk along the cell axis. Let us examine what is happening taking into account the features noted for the system with the dielectric blade.

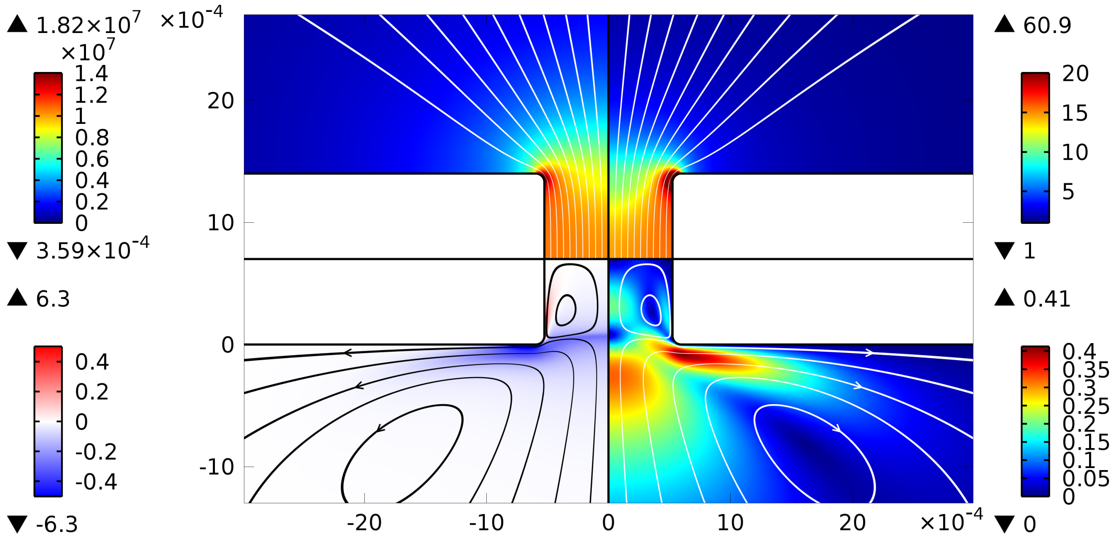


Figure 4: Computed distribution near the hole: the electric field strength and lines (upper left quarter), the relative increase in the dissociation rate with and field lines (upper right quarter), the space charge density and the streamlines (lower left quarter), the velocity magnitude and the streamlines (lower right quarter).

As can be seen from Fig. 4 (where a small area near the hole is shown), the electric field strength is increased in the entire hole, but the maximum values are observed at its edges. The dissociation intensity is distributed in a similar way. Drawing an analogy with the dielectric blade, it is worth noting that the edge of the barrier (the scale of the order of 1 mm) in Fig. 4 plays the role of the end of the blade in Fig. 3. However, it is not sharpened like a blade but blunted (taking into account axial symmetry, the barrier edge forms the hole). In turn, the edges of the hole at the top and bottom surfaces of the barrier (the scale of the order of 0.1 mm) are pointed, and physical processes in close proximity to them are also similar to those at the tip of the dielectric blade. This means there are two "edges" of different scales in the systemп»„the edge of the barrier as a whole and the sharp corners at the edges of

the hole.
The electrical charge moves apart at the both scales. On the scale of the whole hole, a region of positive charge appears above it (not shown in Fig. 4) and that of the negative charge – bellow (Fig. 4). On the scale of the edges of the hole, the two oppositely charged regions appear on different sides of the sharp corner. A small area of positive charge can be seen in Fig.4 at the bottom corner that contributes to the formation of a vortex inside the hole. The complementary region of negative charge enhances the effect of charge separation on the scale of the hole and contributes to the onset of the flow outside the hole.
It should be noted that both the maximum field strength and relative increase in the dissociation rate are smaller than those in the system with the dielectric blade, however, the flow is more intense.

3.4 Slightly protruding hollow tube electrode

Finally, consider a system close to the dielectric barrier with the hole when a slightly (0.1 mm) protruding hollow tube electrode is inserted into the hole. In this case, the electric field distribution is configured mostly by the metal electrode rather than by accumulated charge on the barier.

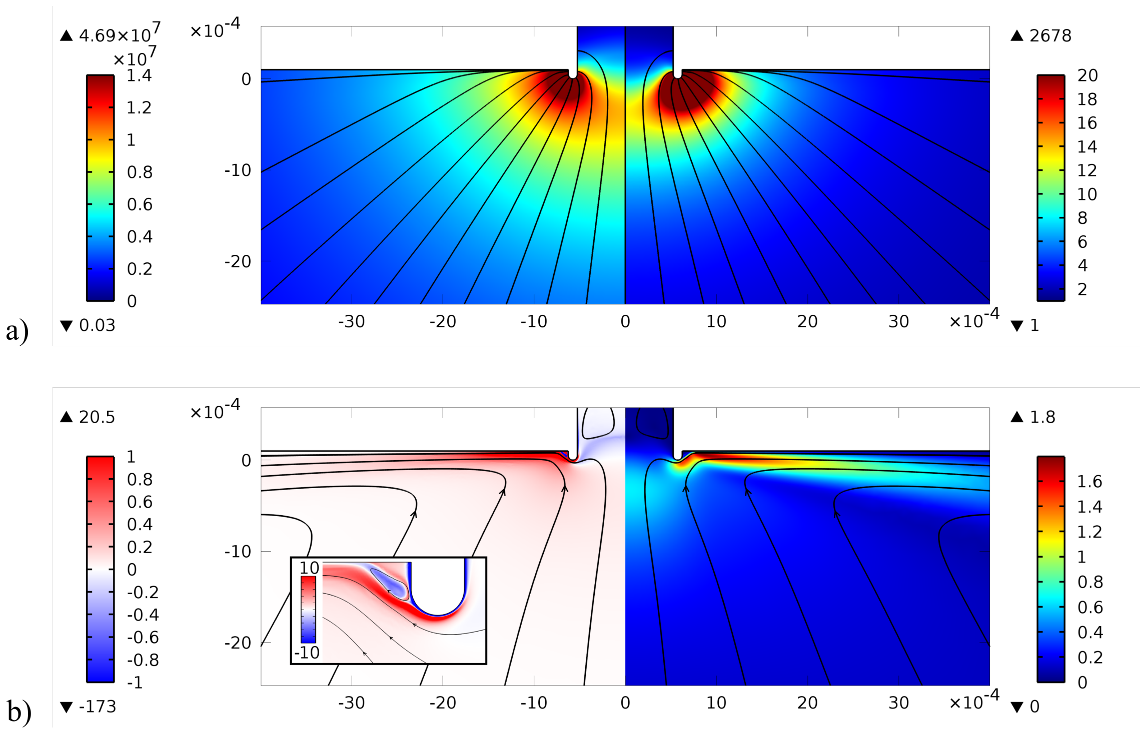


Figure 5: Distribution of quantities near the tube end: (a)п»„the electric field strength (left) and the dissociation intensity enhancement (right) near the end of the tube and the electric field lines; (b)п»„space charge density (left) and velocity magnitude (right) near the end of the tube and the streamlines; (b) also shows an enlarged fragment of the space charge distribution near the in the immediate vicinity to the electrode.

The edges of the tube play the role of sharp dielectric corners in the previous system; the maximum electric field strength and the increase in the dissociation rate are close to those observed in the system with the metal blade. The electric field lines start on the electrode surface at a right angle; they go downward from the very end of the tube (where the field is strongest) and radially along the barrier from its sidewall (where the field is slightly weaker). It would be difficult to predict the direction of the EHD flow if one studied electric field distribution only. Figure 5 shows the flow to be directed along the surface of the barrier right as in the case of the previous system.

As can be seen from the enlarged part of near-electrode region in Fig. 5, there appear a bipolar structure, heterocharge and homocharge layers, and the highest space charge density is produced at the bottom of the electrode. The Coulomb force acts downward here whereas the liquid actually moves to the left in Fig. 5 (away from the axis). Charged bellow the electrode, the liquid shifts and then accelerates radially along the dielectric surface. The EHD flow has the structure as in the system with the hole in the barrier but the specifics of the charge formation and flow intensity (more than 1 m/s) is as in the system with the metal blade.

If the hollow tube is extended from the barrier at a considerable distance, one should expect the system as a whole to be similar to that of needle-plane and the liquid to move toward the counter electrode through the bulk. The simulation results show that the dielectric barrier plays the key role in the present system configuration and changes the flow direction. The possible mechanisms how the barrier influences the flow include the following. First, if the liquid starts moving at some angle to the surface of the barrier under the action of the resultant Coulomb force, the hydrodynamic effects (as the Coanda effect) can redirect the flow along the surface. Second, if the liquid starts moving along the barrier away from the electrode, it transports the charge in the same direction, which enhances the tangential component of the net Coulomb force (a kind of positive feedback takes place). This shows that both electrostatic and hydrodynamic effects contribute to the formation of the EHD flow along the barrier.

4 Conclusions

The paper has studied numerically EHD flows caused by the field-enhanced dissociation in slightly conducting liquids. A number of EHD system configurations have been examined and allow concluding the following:

EHD flows of the dissociation type can emerge near both pointed electrodes and dielectric barriers. The latter additionally requires the accumulated charge to form a localized region of the strengthened electric field. Practically, almost every configuration of dielectric barriers that partially splits the interelectrode gap could lead to the formation of EHD flows of the dissociation type. The flow is always directed away from the region of the enhanced dissociation and follows the electric field lines. In the case of п»„classicalп»„ metal electrodes protruding considerably from any insulation walls, EHD flows are directed toward the counter electrode through the bulk and their structures is qualitatively similar to those of injection EHD flows. If the dielectric barrier edges cause the flows, the same high-voltage processes result in different space charge distribution and flow structure: the Coulomb force acts upon the oppositely charged regions at the both sides of the edge and accelerates the liquid along the insulation surface away from this edge. If a pointed metal electrode is situated near an insulation surface, a number of electrostatic and hydrodynamic effects can cause the EHD flow to develop along the surface; the direction of the flow can be at a right angle to the direction towards the counter electrode.

Acknowledgements

Research was carried out using computer resources provided by Resource Center "Computer Center of SPbU" (http://cc.spbu.ru).

References

[1] Y. K. Stishkov, A.A. Ostapenko, п»„Electrohydrodynamic Flows in Liquid Dielectricsп»„, Leningrad: Izdatelп»„stvo Leningradskogo universiteta, 1989.

[2] Y. K. Stishkov and V. A. Chirkov, п»„Features of electrohydrodynamic flows in needle-plane electrode system,п»„ 2008 IEEE Int. Conf. Dielectr. Liq., pp. 1п»„3, Jun. 2008.

[3] I. Ashikhmin, Y. K. Stishkov, Y. Donskov, п»„Experimental study of EHD flows in symmetric electrode system in wide range of low-voltage conductivitiesп»„, International Journal of Plasma Environmental Science and Technology, 10 (1), pp. 1-5, 2016.

[4] J. Shrimpton, Charge Injection Systems. Berlin, Heidelberg: Springer Berlin Heidelberg, 2009.

[5] L. Onsager, п»„Deviations from Ohmп»„s Law in Weak Electrolytes,п»„ J. Chem. Phys., vol. 2, no. 9, pp. 599п»„615, 1934.

[6] Y. K. Stishkov and V. A. Chirkov, п»„Formation of electrohydrodynamic flows in strongly nonuniform electric fields for two charge-formation modes,п»„ Tech. Phys., vol. 57, no. 1, pp. 1п»„11, Jan. 2012.

[7] Y. Suh and K. Baek, п»„Competition between the bulk and the dissociation layer in electrohydrodynamic flow of dielectric liquid around coplanar electrodes,п»„ Phys. Rev. E, vol. 87, no. 2, p. 23009, Feb. 2013.

[8] V. A. Chirkov, Y. K. Stishkov, and S. A. Vasilkov, п»„PIV Investigation of EHD Flow Caused by Field-enhanced Dissociation,п»„ in Proc. of 10th Conf. French Soc. Electrost. SFE 2016, pp. 1п»„4, 2016.

[9] V. Chirkov, D. Komarov, Y. Stishkov, and S. Vasilkov, п»„Numerical and experimental study of an EHD flow near solid-dielectric surface,п»„ Proc. 11-th Int. Conf. Mod. Probl. Electrophysics Electrohydrodynamics, pp. 122п»„126, 2015.

[10] A. Gazaryan, A. Sitnikov, V. Chirkov, Y. Stishkov, п»„A Method for Estimation of Functional Dependence of Injection Charge Formation on Electric Field Strengthп»„, in Proc. Electrostatics Joint Conference, pp.1п»„8, 2016.

[11] S. A. Vasilkov, V. A. Chirkov, Y. K. Stishkov, п»„Study on high-voltage conductivity provided solely by field-enhanced dissociation in liquid dielectricsп»„, Journal of Electrostatics, 88, pp. 81-87, 2017.

Y. K. Stishkov, St. Petersburg State University, St. Petersburg, Russia
S. A. Vasilkov, St. Petersburg State University, St. Petersburg, Russia