Comparative analysis of numerical simulation and PIV experimental results for a flow caused by field-enhanced dissociation

V A Chirkov, D K Komarov, Y K Stishkov and S A Vasilkov

Physics Department, St. Petersburg State University, Uljanovskaia 1, 198504 St. Petersburg, Russia

E-mail: sergeyvasilkov@yandex.ru

Abstract. The paper studies a particular electrode system, two flat parallel electrodes with a dielectric plate having a small circular hole between them. Its main feature is that the region of the strong electric field is located far from metal electrode surfaces, which permits one to preclude the injection charge formation and to observe field-enhanced dissociation (the Wien effect) leading to the emergence of electrohydrodynamic (EHD) flow. The described electrode system was studied by way of both computer simulation and experiment. The latter was conducted with the help of the particle image velocimetry (or PIV) technique. The numerical research used trusted software package COMSOL Multiphysics, which allows solving the complete set of EHD equations and obtaining the EHD flow structure. Basing on the computer simulation and the comparison with experimental investigation results, it was concluded that the Wien effect is capable of causing intense (several centimeters per second) EHD flows in low-conducting liquids and has to be taken into account when dealing with EHD devices.

1. Introduction

Specific mechanisms of high-voltage charge formation, i.e. the surface charge injection and field-enhanced dissociation (or the Wien effect), take place in low-conducting liquids under the influence of a strong electric field. Apart from their effect on the total value of the electric current passing through the cell, they can ensure the formation of space charge density inside the bulk in the case of non-uniform electric field and lead to the emergence of electrohydrodynamic (EHD) flows [1]. The field-enhanced dissociation is frequently termed as a purely theoretical phenomenon and its significance in the EHD flow formation is usually disregarded. The main problem in the context of revealing the role of field-enhanced dissociation in EHD flow formation is caused by similarities in the corresponding flow structure with that taking place in the injection model. Thus, the EHD flow formation is frequently ascribed only to the injection even if two mechanisms of charge formation are active [2, 3].

Electric field intensity can exceed $10^7$ V/m, and dissociation rate, according to [4], increases by a factor of tens. But the presence of injection from metal electrodes creates difficult conditions for experimental study of EHD flows, caused by Wien effect. Thus, to investigate EHD flows with field-enhanced dissociation charge formation mechanism, one has to exclude injection from electrode surfaces. To do this, one can use relatively weak electric fields on the order of $10^6$ V/m [5], when no injection was observed (dissociation rate increases less than twice in the case), or create a region of a strong electric field far from electrode surfaces. In the present work, the second way was chosen.
To resolve the issue, a particular setup was used: flat parallel electrodes and a dielectric plate (a barrier) having a small circular hole (figure 1) between them. The barrier surface accumulates ions, so all electric field lines pass through the hole and the intensity attains the maximum here, i.e., far from any electrode, which prevents the injection charge from forming inside the enclosure and provides favorable conditions for the Wien effect emergence. As the electric field intensity distribution and that of the increase in dissociation rate are non-uniform (figure 1a), they cause the appearance of space charge and hence EHD flow, which was studied numerically and experimentally.

**Figure 1.** (a) Schematic illustration of the electric field inside the hole and (b) computer model with marked dimensions and boundary conditions.

### 2. Simulation and experimental techniques

The present work includes computer simulation of an EHD flow with the corresponding technique being described in [6]. The computations were carried out using software package COMSOL Multiphysics® 4.2 based on the finite element method. The complete set of equations (as in [6]) was solved. The dissociation intensity, the part of the source function for transport equations, is $W_0 F(p)$ where $W_0$ is that in the absence of electric field and $F$ is the relative increase in the dissociation rate:

$$F(p) = \frac{I_1(4p)}{(2p)}, \quad p = \frac{e^2}{(2k_BT)} \sqrt{E/(4\pi\varepsilon\varepsilon_0)}$$  \hspace{1cm} (1)

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, $\varepsilon$ is the relative electric permittivity, $\varepsilon_0$ is the electric constant.

Two-dimensional model with the axial symmetry was built (figure 1b). Dimensions used in the model correspond to those of experimental setup. However, there is a difference in barrier shape: it is a circle in the case of the computer simulation and a rectangle in the case of the experiment. Nevertheless, a change in shapes of boundaries that are far from the region of interest (the hole) does not affect EHD flow near it. It is difficult to measure the fillet radius of the hole edges but the computer simulation shows that if its value is relatively small, it has little influence on velocity distribution. Figure 1b also lists boundary conditions, where $\varphi$ is the electric potential, $n$ is the ion concentration, $j$ is the ion flux density, $u$ is the fluid velocity; $N$ is the outward normal, $r$ and $z$ are coordinates; $n_{eq}$ is the equilibrium concentration. As the electrodes are far from the hole, approximate conditions for transport equations can be used. The condition $E_N=0$ was used on each dielectric surface, i.e. the total screening of electric field by accumulated surface charge was assumed. In this model, electro-osmotic effects are disregarded.

To obtain the velocity distribution, the particle image velocimetry (or PIV) technique was used. This requires seeding the flow with small tracer particles that are illuminated during the measurement by pulsed laser sheet (for more details, see [7]). Two consecutive recorded frames are used by the DaVis software to compute the velocity distribution. Working liquid was chosen to be transformer oil mixed with 5% of butanol. Its conductivity was $3.3 \cdot 10^{-10}$ S/m, with other properties being chosen typical for the transformer oil [1].
3. Results and discussion
Consider results for 15 kV. Figure 2a shows all electric field lines to pass through the hole. So, the electric field intensity increases inside the hole and has the values from $0.6 \times 10^7$ to $1.1 \times 10^7$ V/m (with the maximum observed on the hole edges). At the same time, the electric field intensity has the value of order $10^4$ V/m near the electrode surfaces. According to equation (1), at the hole center, the dissociation rate increases by the factor of eight, while near the edges — more than by the factor of twenty (figure 2b). The non-uniform dissociation rate distribution results in space charge emergence. The distributions of the space charge (figure 2c) and the velocity field (figure 2d) are highly interrelated: the former governs the latter via the Coulomb force, and the latter deforms the former. The velocity magnitude is of the order of several centimeters per second, and the flow has following structure: liquid comes to the hole from the bulk and then spreads radially along the barrier.

![Figure 2](image_url)

*Figure 2.* Distributions of (a) the electric field intensity ($10^7$ V/m) with electric field lines, (b) the relative increase in the dissociation rate (1), (c) space charge density (C/m$^3$) with streamlines, (d) velocity magnitude (cm/s) with streamlines.

The PIV technique was applied to study the velocity distribution below the barrier. Figure 3 shows the comparison of computer simulation and experiment results. It is noteworthy here that the experimental results have no symmetry in contrast to simulation, but the flow structure is quite similar: liquid spreads (but non-uniformly) from the gap center to the edges (figure 3b). Besides, it is worth noting that barrier perimeter was pressurized during the enclosure assembly and zero mass flux thought the hole was guaranteed.

![Figure 3](image_url)

*Figure 3.* Velocity contours (cm/s) and streamlines (a) in the computer model, (b) in the experiment, and (c) velocity vectors and streamlines near the hole.

At distances closer to the barrier than 0.5 mm, the velocity values are underestimated (and are incorrect) due to the data processing specifics. As far as 1 mm from the hole, the velocity in both computer simulation and experimental study has values on order of 3 cm/s, but the values in the latter case decrease slower with growing distance from the barrier. This happens because a stream coming to the hole remains relatively thin far from the barrier surface compared to simulation. Also, after passing the hole most liquid moves to the left, but there also exists a flow directed to the right, with its size agreeing to that from simulation.
As it was noted above, the computer model disregards electro-osmotic effects. In the case of pure electro-osmosis, the flow should be directed in the opposite direction [8]. But indeed, such flow was observed at 5kV, when the field-enhanced dissociation effect is insignificant.

In addition, the local heating of the liquid inside the hole can theoretically lead to the observed flow structure (the temperature gradient is frequently used to create the space charge inside induction pumps [9]). But the computer simulation shows that in the case of considered liquid, the overheat is less than 0.01 K inside the hole so that the temperature gradient is negligible.

This means that the observed flow structure can be explained only by the Wien effect. The absence of symmetry of experimental data precludes the accurate quantitative comparison (but the flow proves to be more intensive far from the hole).

4. Conclusions
A particular experimental setup was arranged to create a strong electric field far from the electrode surfaces and to study EHD flows caused by the Wien effect. The system was investigated by means of computer simulation: the velocity values of order of several centimeters per second were obtained, the flow structure was described. It was demonstrated by the experiment that the Wien effect actually causes such flow, since other charge formation mechanisms are excluded or negligible. This means that the Wien effect should be taken into account when EHD flows are investigated as its role in EHD flow formation can be comparable with that of injection and it can affect dissociation-recombination layers (and hence conduction pump performance [10]).

Acknowledgments
The authors acknowledge St. Petersburg State University for a research grant 11.0.65.2010. Research was carried out using computer resources provided by Resource Center "Computer Center of SPbU" (http://cc.spbu.ru) and Resource Center "Geomodel".

References
[1] Stishkov Y and Chirkov V 2011 Dependence of the electrohydrodynamic flows structure in very non-uniform electric field on the charge formation mechanism Proc. Int. Conf. on Dielectric Liquids, ICDL (Trondheim, Norway, 2014)
[2] Atten P and Seyed-Yagoobi J 2003 Electrohydrodynamically Induced Dielectric Liquid Flow Through Pure Conduction in Point/Plane Geometry IEEE Trans. Dielectr. Electr. Insul. 10 27–36
[3] Daaboul M, Louste C and Romat H 2009 PIV measurements on charged plumes – influence of SiO2 seeding particles on the electrical behavior IEEE Trans. Dielectr. Electr. Insul., special issue ‘‘EHD & Flow Electrification’’.
[4] Onsager L 1934 Deviations from Ohm’s law in weak electrolytes J. Chem. Phys. 2 599–615.
[5] Suh Y K, Baek K H and Cho D S 2013 Asymptotic and numerical analysis of electrohydrodynamic flows of dielectric liquid Phys. Rev.E 88 023003.
[6] Chirkov V A, Stishkov Yu K 2013 Current-time characteristic of the transient regime of electrohydrodynamic flow formation J. Electrostat. 71 484–488.
[7] Willert C E, Gharib M 1991 Digital particle image velocimetry Exps. Fluids 10 181–193.
[8] Squires T M and Bazant M Z 2004 Induced-charge electro-osmosis J Fluid Mech 509 217–252.
[9] Seyed-Yagoobi J 2005 Electrohydrodynamic pumping of dielectric liquids J. Electrostat. 63 861–869.
[10] Stishkov Y, Chirkov V and Vasilkov S 2015 Characteristics of electrohydrodynamic pump of the dissociation type: low- and high-voltage ranges IEEE Trans. Dielectr. Electr. Insul., in press.