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TABLE OF CONTENTS

1. Invited

F. C. Lai
EHD gas pumping – a review of recent development..... 7

S. M. Korobeynikov, A. G. Ovsyannikov, A. V. Ridel, D. I. Karpov, D. A. Medvedev, M. N. Lyutikova, Yu. A. Kuznetsova, V. B. Yassinskiy
Partial discharges in liquids 13

T. Kawasaki, K. Nishida, M. Kawaguchi, Y. Hazama, F. Mitsugi
Two kinds of liquid flows induced by plasma-jet irradiation..... 18

2. EHD Flows and Flow Electrification

A. Mizuno, G. Touchard, T. Paillat, E. Moreau
Effect of DNA molecules on streaming current..... 22

Zhihao Sun, Dexin Sun, Jinxin Hu, Hong-Liang Yi, Jian Wu
Experimental study on electrohydrodynamic flows of a dielectric liquid in a needle-plate configuration under direct/alternating current electric field..... 27

M.K. Bologa, F. P. Grosu, I. V. Kozhevnikov
Additional properties of electrohydrodynamic pump operation..... 32

F. P. Grosu, M. K. Bologa, O. V. Motorin
Derivation of hydrodynamic equations by dimensional method..... 36

M. S. Apfelbaum, R. A. Syrovatka
On the theoretical modelling and experimental investigation of the pre-breakdown transformer oil discharge ... 38

Yifei Guan, Igor Novosselov
Effect of Couette flow on electroconvective vortices..... 42

G.S. Ganchenko, N.Yu. Ganchenko, E.A. Demekhin
About features of electrokinetic instability in the electrolyte near imperfect ion-selective surfaces 46

Pedro A. Vázquez, Pablo García Sánchez, Elena Castro-Hernández, Antonio Ramos
Numerical simulation of flow-focused AC electrified jets..... 50

Yu. K. Stishkov, S. A. Vasilkov, K. D. Poluektova
Study of an electrohydrodynamic pump operating due to the field-enhanced dissociation near a dielectric barrier 54

3. Ionic Wind

J. C. Peng, S. C. Lin, F. C. Lai
Flow characteristics of an EHD gas pump in circular pipe with secondary emitting electrodes..... 58

E. Moreau, K. Bayoda, N. Benard
Effect of the high voltage electrode shape on the optical and mechanical properties of a pulsed sliding discharge..... 63

E. Defoort, E. Moreau, C. Batiot-Dupeyrat, R. Bellanger
Electrodynamic airflow produced by a point-to-plate DBD plasma reactor in presence of a water mist..... 69

Iu. Bosneaga, M. Bologa, E. Agarwal
Intensification of electro-magneto-hydrodynamic plasma effects using radionuclides 74

I.A. Elagin, P.A. Kostin, A.V. Samusenko
Computer simulation of plate cooling by ionic wind from a system of needles 79

Ravi Sankar Vaddi, Yifei Guan, Zhi yan Chen, Alexander Mamishev, Igor V Novosselov
Experimental and numerical investigation of corona discharge induced flow on a flat plate 83

Yifei Guan, Ravi Sankar Vaddi, Alberto Aliseda, Igor Novosselov
Comparison of analytical and numerical models for point to ring electro-hydrodynamic flow..... 87

4. EHD in Thermal Systems

D. Koulova, H. Romat, Ph. Traore
Effect of electric Nusselt number on electro-thermo-convection in dielectric liquid subjected to unipolar injection 94

A. Jawichian, L. Davoust, S. Siedel
Role of a non-uniform AC electric field on a buoyancy-driven flow in a differentially heated cavity 99

A.A. Safronov, V. E. Kuznetsov, V. N. Shiryaev, V. B. Kovshechnikov, O. B. Vasilieva, Yu. D. Dudnik
Investigation of physical processes in pulse-erosion injector 105

I. Kano, T. Nishina
Effects of orientation on critical heat flux enhanced by electric field during flow boiling 109

I. M. Chernica, M. K. Bologa, O. I. Mardarskii, I. V. Kozhevnikov
Action of electrohydrodynamic flow on heat transfer at boiling..... 113

5. DBD and Plasma

Chuang Wang, Xi Chen, Wei Wang, Pengfei Li, Kai Tang
Study on discharge mechanism and electromagnetic radiation characteristics of negative corona discharge in airflow..... 120

Bangfa Peng, Jie Li, Nan Jiang, Yan Wu
Evolution of three-electrode pulsed surface dielectric barrier discharge: primary streamer, transitional streamer and secondary streamer 125

Kefeng Shang, Meiwei Wang, Jie Li, Yan Wu
Enhancement of the plasma and ozone production by a hybrid volume-surface DBD 134

M.Timshina, S.Eliseev, N.Kalinin, D. Belsky, A. Samokhvalov, K. Sergushichev, A. Smirnov, V. Burtsev
Numerical simulation of initial stage of capillary discharge 140

N. Rezazadeh, S. V. Zarifpayam, B.X.Wu
In situ momentum enhancement for heat trapped regions using plasma actuators 143

S. Kanazawa, A. Ohno, T. Furuki, K. Tachibana, R. Ichiki, A. Suzuki, K. Kuroi, K. Suzumura, T. Tanaka, K. Motegi, M. Kocik, J. Mizeraczyk
Influence of the operating pressure on pulsed positive streamer corona structure and distribution of N2(A3∑+u) metastable molecules in the needle-to-plate gap 149

Yuri Golubovskii, Aleksei Siasko, Tatyana Gurkova, Nikolay Kryukov
Direct observation of the radial temperature gradients of the neutral gas in the constricted argon glow discharge..... 155

6. Microfluidics and Multi-phase Media

Pablo S. Casas, Maria Garzon, James A. Sethian
A numerical study on electrohydrodynamic droplet interactions: coalescence and break-up..... 161

M. A. Belyaev, N. M. Zubarev, O. V. Zubareva
Conical structures on the surface of a dielectric liquid with surface ionic conductivity..... 165

O. V. Zubareva, N. B. Volkov, N. M. Zubarev
Equilibrium configurations of an uncharged liquid jet in a transverse electric field; conditions for existence 168

Kuntal Patel, Kuldip Lakhani, Nihar Thakkar, Absar M. Lakdawala
Dynamics of electro-hydrodynamic-coalescence of a sessile drop at a liquid-liquid interface 172

A. A. Nemykina, D. A. Medvedev
Behavior of a bubble in dielectric liquid in uniform and non-uniform electric field..... 178

N. Cardin, S. Siedel, J. Bonjour, S. Lips, L. Davoust
Shape of a liquid meniscus under the action of an electric field in a grooved capillary structure 182

Rochish M. Thaokar, Vikky Anand
Electrohydrodynamics of droplets: coalescence and breakup 187

Hyun-Ha Kim, Yoshiyuki Teramoto, Nozomi Takeuchi, Atsushi Ogata
EHD-induced cone-jet in gas and liquid for fine droplet generation 193

V.A. Chirkov, I.A. Dobrovolsky
Computer simulation of the droplet electrodeformation considering processes of current passage in a low-conductive dispersion medium: semi-hydrostatic approach 195

V.A. Chirkov, G.O. Utiugov
Numerical modeling of electrocoalescence using the arbitrary Lagrangian-Eulerian method 199

7. ESP and EHD Treatment

Kohei Ito, Akinori Zukeran, Yuma Mori, Yoshihiro Kawada, Tomohiro Taoka, Kenji Shibata
Simulation and measurement of charged particle trajectory with ionic flow in a wire-to-plate type electrostatic precipitator 204

Arkadiusz Świerczok, Maria Jędrusik, Dariusz Łuszkiewicz
Experimental research on removal of fine fly ash particles and Hg(p) in an electrostatic precipitator 210

K. A. Smagin, L. V. Chekalov, Yu. I. Sanaev, V. A. Guzaev, N. V. Pikulik
Computation of the collection efficiency of an electrostatic precipitator with complex electrode geometry based on a macroscale model of dust particles motion and charging 217

Ravi Sankar Vaddi, Gaurav Mahamuni, Igor V Novosselov
Development of an EHD induced wind driven personal exposure monitor and in-situ analysis for characterization of exposure..... 222

T. Miichi
Influence of solution circulation on water treatment using corona discharge 226

J. Mizeraczyk, M. Tański, A. Berendt
A proposal of a SDBD-driven two-stage electrostatic precipitator 230

8. Electrostatics

Bing Sun, Penghui Zhan, Xiaomei Zhu, Yanbin Xin, Zhiyu Yan, Tonghui Zhu
The organics degradation of concentrated wastewater with electro-catalytic oxidation method 239

D. I. Karpov, S. M. Korobeynikov, A. G. Ovsyannikov, A. V. Ridel, M. B. Meredova
Numerical simulation of partial discharges in deformed bubbles in transformer oil 243

M. N. Lyutikova, S. M. Korobeynikov
Influence of water on liquid insulation electrical strength of large power transformers 248

Korobeynikov S.M., Kuznetsova Yu.A., Yassinskiy V.B.
Simulation and analysis of prebreakdown processes in liquids 254

A. A. Tikhonov, A. B. Yakovlev
On dependence of equilibrium characteristics of the space tethered system on environmental parameters 257

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June 18–22, 2019, St. Petersburg, Russia

Computer Simulation of the Droplet Electrodeformation Considering Processes of Current Passage in a Low-conductive Dispersion Medium: Semi-hydrostatic Approach

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Abstract—Under the effect of the electric field, the shape of a conducting droplet suspended in low-conducting liquid changes until the forces acting on its surface—the surface tension forces and the Coulomb force—balance each other. Since the external fluid (dispersed medium) is a low-conducting one, the application of the electric field can lead to the emergence of non-equilibrium dissociation-recombination layers, which can affect the steady-state value of the droplet deformation significantly. The paper numerically investigates the effect of the electric field strength distortion due to charged layer formation on the electrodeformation process. It is shown that results are dependent on the value of the dimensionless parameter that determines the structure of the space charge distribution. The emergence of charged layers can increase the deformation up to several times.

Keywords—two-phase liquid, dissociation-recombination charged layers, arbitrary Lagrangian-Eulerian method, water-oil emulsion

I. Introduction

Under the effect of a strong electric field, low-conducting liquids can be set into motion, which is called electrohydrodynamic or electrically-induced one. The latter is a specific class of flows caused by the volume force and is actively explored in several last decades. The basis of the phenomenon is the process of the medium electrization, i.e., the emergence of an electric charge in it. In the case of single-phase liquids, the space charge may emerge, e.g., due to a disturbance under the action of the electric field of equilibrium between the dissociation reactions of molecules and the recombination of ions [1]. In turn, in two-phase immiscible liquids, a charge may emerge at the interface between two media if their electrophysical properties differ. One example of this phenomenon is the so-called electro-deformation of a droplet of a relatively conducting liquid suspended in a liquid dielectric [2]. Under the effect of the electric field, the shape of such a droplet changes until the forces acting on its surface—the surface tension forces and the Coulomb force—balance each other [3], if, of course, this balance can be achieved under specific conditions.

Since in the latter process, the external fluid (dispersed medium) is a low-conducting one, the application of the electric field can lead to the emergence of two types of electrically-induced flows at once, which will manifest simultaneously and mutually influence each other. Even though there are many papers devoted individually either to electroconvection in single-phase liquids or to EHD processes in two-phase liquids, the study of this complex phenomenon can hardly be found in the literature.

At the current stage of the study, electrodeformation of a conductive liquid droplet suspended in a low-conducting oil is considered in a "semi-hydrostatic" approach, in which the problem of electrical deformation is supplemented by taking into account the distortion of the electric field distribution due to the volume electrification, but disregarding the convective current transfer and EHD flows in the bulk. The goal of the study is to determine the degree of influence of the electric field distortion near the surface of a conducting droplet due to the formation of hetero-charged layers on the degree of the droplet electrodeformation. In addition to academic interest, this work is of undoubted practical importance due to the wide occurrence of two-phase liquid EHD devices, in particular, electrohydrators.

II. Mathematical and Numerical Model

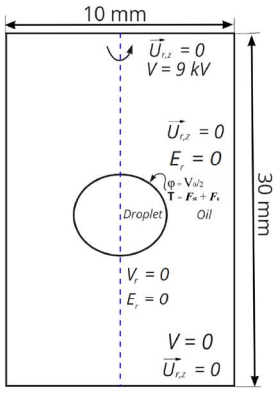

Fig. 1. Schematic of the model and boundary conditions.

The schematic of the model is shown in Fig. 1. A small droplet of water is placed in the center of the cell between two flat electrodes. The conductivity of water is

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so large that the interface between the two phases can be considered as an equipotential surface.

The computation used software package COMSOL Multiphysics® based on the finite element method to solve the set of EHD equations for isothermal incompressible liquid dielectrics [4]:

$$div(\vec{E}) = \frac{q}{\varepsilon\varepsilon_0} \quad (1)$$

$$\frac{\partial n_i}{\partial t} + div(\vec{j_i}) = W - \alpha_r n_1 n_2 \quad (2)$$

$$\rho\frac{\partial u}{\partial t} + \rho(\vec{u}, V)\vec{u} = -\nabla p + \eta\Delta\vec{u} + q\vec{E} \quad (3)$$

$$div(\vec{u}) = 0 \quad (4)$$

supplemented with the following definitions and expressions:

$$\vec{E} = -\nabla V \quad (5)$$

$$\vec{j_i} = n_i sign(Z_i) b_i \vec{E} - d_i \nabla n_i + n_i u \quad (6)$$

$$q = \sum_i Z_i e n_i \quad (7)$$

$$d_i = \frac{k_B T}{|Z_i| e} b_i \quad (8)$$

$$W = \frac{\sigma_0^2}{2eb\varepsilon\varepsilon_0} \quad (9)$$

$$\alpha_r = \frac{2eb}{\varepsilon\varepsilon_0}. \quad (10)$$

Here $\vec{E}$ is the electric field strength, q is the space charge density, ε is the relative electric permittivity, ε_0 is the vacuum permittivity, V is the electric potential, n is the ion concentration, $\vec{j}$ is the ion flux density, b is the ion mobility, d is the diffusion coefficient, u is the fluid velocity, p is the pressure, e is the elementary electric charge, ρ is the mass density, η is the dynamic viscosity, Z is the ion charge number, T is the temperature, k_B is the Boltzmann constant, σ_0 is the low-voltage conductivity, t is the time; subscript i indicates the ion species. Ions are assumed to be univalent ($Z_1 = 1$, $Z_2 = -1$) and are believed to have equal values of ion mobility ($b_1 = b_2 \equiv b$) as well as diffusion coefficients ($d_1 = d_2 \equiv d$).

The following simplifications were made at the present stage of research according to the introduced above semi-hydrostatic approach: the third term in the right-hand side of (3) was excluded from the consideration as well as that in the right-hand side of (6). Besides, the movement of fluid inside the droplet is not calculated, and gravity is not considered. Thanks to the latter, the droplet does not experience translational motion, thus remaining centrally located between the electrodes, which allows one to consider the problem in a two-dimensional axisymmetric formulation.

The two-phase medium is described using the so-called arbitrary Lagrangian-Eulerian (ALE) method, also called the moving boundary method (or moving mesh). In this approach, the boundary between the two phases is represented by a line of geometry that throughout the entire solution of the problem moves by the calculated value of the fluid velocity. At the same time, due to the actual change in the geometry, the drawing or rebuilding of the mesh occurs at each time step.

The boundary conditions are partially presented in Fig. 1. At the interface of the two phases, the surface tension force (F_{ST}) and the Coulomb force (F_C) acting per unit area are specified:

$$F_{st} = 2\gamma H \quad (11)$$

$$F_C = \frac{1}{2}\varepsilon_0\varepsilon E_n^2, \quad (12)$$

where γ is the interfacial tension, H is the mean curvature of interface, and E_n is the normal component of the electric field strength at the interface.

Special attention should be paid to the boundary conditions for the ion transfer equation: the charge loss condition is set at the oppositely charged (concerning the ion) part of the droplet and the electrode, whereas zero ion concentration is set at the homo-charged half of the droplet and the electrode.

The electric current passage through low-conducting liquids depends both on the properties of these liquids and on the configuration of the electrodes and the applied voltage. In the case of homogeneous (and weakly inhomogeneous) electric field distributions, it turns out that there is one key dimensionless parameter that determines the structure of the space charge distribution [5]:

$$P = \frac{\sigma_0 L^2}{bV_0\varepsilon\varepsilon_0},$$

where V_0 is the applied voltage and L is the interelectrode distance.

In this paper, various cases are considered based on a change in this parameter, and the base value of the properties is selected by the properties of olive oil (Table 1). Droplet radius (R_d) is 0.8 mm and voltage (V_0) is 9 kV. The change in the value of the parameter P is achieved by varying the electrical conductivity of the medium.

TABLE I
Properties of the working liquid (olive oil)

ε	2.85
ρ	910 kg/m^3
γ	16 mN/m
η	0.065 Pa×s
b	$1\cdot10^{-9}$ m^2/(V×s)
σ_0	$1.9\cdot10^{-11}$ [S/m]
d	$2.5\cdot10^{-10}$ m^2/s

III. Results and Discussion

The degree of deformation, according to the conventional approach (e.g., [6, 7]), is described by parameter:

$$D = (\alpha - \beta)/(\alpha + \beta), \qquad (13)$$

where α and β are the width and height of the droplet.

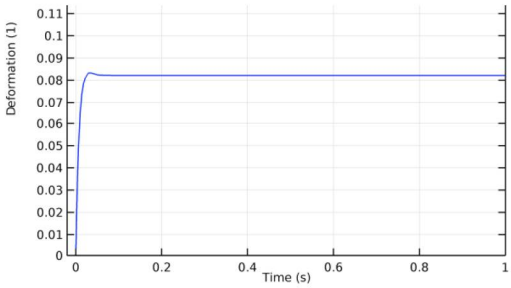

Fig. 2. The time dependence of the degree of deformation $D(t)$ in the case when charged layers are disregarded ($P = 75$).

Fig. 2 shows the time dependence of the degree of deformation $D(t)$ in the case when charged layers are disregarded. The droplet deforms quickly and reaches the steady-state shape within less than 0.05 s. However, the situation changes greatly when the distortion of the electric field strength is accounted for.

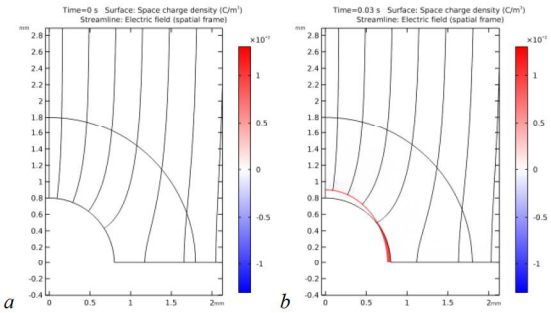

Fig. 3. Space charge density distributions and electric field lines at the initial state (a) and at the end of the primary process of electrodeformation (b) ($P = 75$).

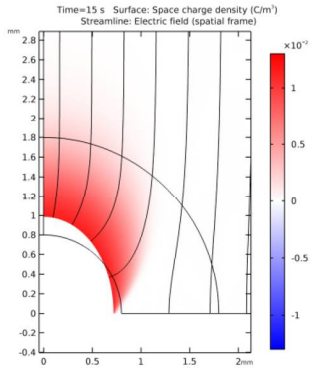

Fig. 4. The steady-state distribution of space charge density and electric field lines ($P = 75$).

Fig. 3 presents the surface plot of space charge density distribution near the droplet surface. Initially, there is no non-equilibrium dissociation-recombination layer near the interface; thus, droplet deforms like in the case when there is no charged layer. After 0.03 s, the deformation reaches nearly the same value as in the previous case (approximately 8.2 %). Further on, space charge emerges near the droplet surface (Fig. 3*a* and Fig. 4) and forces the droplet to continue to change its shape. Fig. 5 demonstrates that the second stage of the deformation lasts approximately several seconds and leads to the nearly doubled value of D.

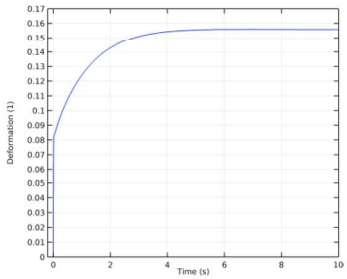

Fig. 5. The time dependence of the degree of deformation $D(t)$ in the case when charged layers are accounted for in the model ($P = 75$).

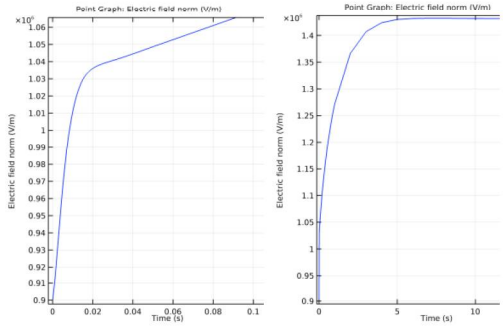

Fig. 6. The time dependence of the electric field strength at the top point of the droplet ($P = 75$).

The key reason for the deformation increase is the rise in the electric field strength (Fig. 6): the hetero-charged layer enlarges the strength and raises the Coulomb force that acts at the interface. Besides, the droplet curvature grows during the process, thus providing an additional gain in the electric field.

According to the features of the electric current passage in a low-conducting liquid [5], the results are to be dependent on the dimensionless parameter P. Fig. 7 presents the change in the steady-state value of the deformation with the variation of the parameter. When $P \approx 0$, the distortion of the electric field is of negligible value; thus, the computed value is the same as for the base model discussed in the beginning of this section. In turn, when $P \gg 1$, the deformation is enhanced up to several times (like in the above case). However, when $P \approx 1$, the deformation lessens, which is quite an unexpected outcome.

The latter result can be explained on the base of the axial distribution of the electric field strength (Fig. 8). There are two areas where hetero-charged layers emerge: near the conducting droplet and near electrodes. Thus, the electric field strength is affected by two non-equilibrium layers with the latter one being larger. It appears that for moderate values of P ($P \approx 1$) the strong

growth of the strength near the electrode leads to some decrease in it near the droplet since the integral value of the electric field is to be constant and equal to the applied voltage.

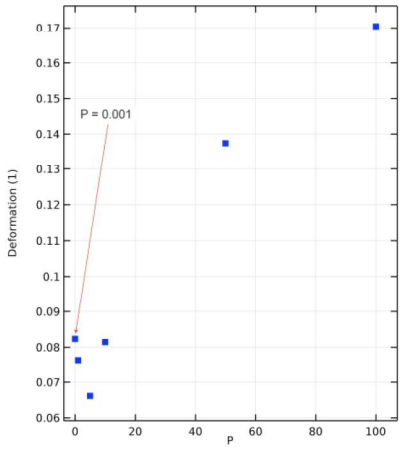

Fig. 7. The dependence of the steady-state value of the deformation on dimensionless parameter P ($P = 0.001,1,5,10,50,100$).

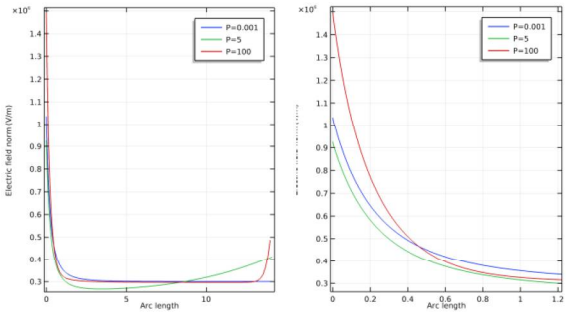

Fig. 8. The axial distribution of the electric field strength in the interelectrode gap (on the left) and the same in the area near the droplet surface (on the right).

IV. Conclusion

The distortion of the electric field at the surface of a conducting liquid droplet due to the formation of non-equilibrium dissociation-recombination layers affects the stationary value of the degree of electrical deformation strongly. Depending on the value of the dimensionless parameter P, three cases can be realized:

- the role of charged layers is negligible ($P \ll 1$);
- the degree of deformation is reduced by several tens of percent ($P \approx 1$);
- deformation increases up to several times ($P \gg 1$).

The further extensions of the research are the accounting for EHD flows and convective charge transfer in the bulk of the dispersion medium, simulating the fluid inside the droplet, and studying similar processes for different values of the radius of the droplet.

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