St. Petersburg
University

International Symposium on Electrohydrodynamics

ISEHD 2019

June 18-22, St. Petersburg

St. Petersburg State University

THE INTERNATIONAL SYMPOSIUM ON ELECTROHYDRODYNAMICS
ISEHD 2019

PROCEEDINGS

June 18–22, 2019
St. Petersburg, Russia

ORGANIZED BY

St. Petersburg State University, St. Petersburg, Russia

Dr. V.A. Chirkov

LOCAL ORGANIZING COMMITTEE

Dr. V.A. Chirkov (Conference Chair)

Dr. A.V. Samusenko, I.A. Elagin, Prof. V.A. Pavlov, Dr. O.M. Pavleino, S.A. Vasilkov, A.A. Sitnikov, A.V. Gazaryan, I.V. Gaponiuk

ISEHD COMMITTEE

Chairperson: Prof. J. Mizeraczyk (Poland)

Co-Chairperson: Prof. E. Moreau (France)

Secretary General: Dr. K. Urashima (Japan)

MEMBERS: Prof. K. Adamiak (Canada), Prof. W. Balachandran (UK), Prof. C. Ching (Canada), Dr. V. Chirkov (Russia), Prof. J. Cotton (Canada), Prof. G. Harvel (Canada), Prof. A. Jaworek (Poland), Prof. S. Kanazawa (Japan), Prof. J. Li (China), Prof. T. Kawasaki (Japan), Prof. P. Vazquez (Spain), Prof. Y. Wu (China), Prof. J. Yagoobi (USA), Prof. K. Yan (China), Dr. A. Zukeran (Japan)

HONORARY ISEHD MEMBERS

Prof. Em. P. Atten (France), Prof. A. Mizuno (Japan), Prof. T Oda (Japan), Prof. T. Ohkubo (Japan), Prof. Y. Stishkov (Russia), Prof. G. Touchard (France), Prof. T. Yamamoto (Japan)

Contact address:
Dr. Vladimir Chirkov
Email: v.chirkov@spbu.ru
Tel.: +7 911 915-26-98
St. Petersburg State University,
7–9 Universitetskaya nab.,
St. Petersburg, Russia

ISBN: 978-5-9651-1244-9

TABLE OF CONTENTS

1. Invited

2. EHD Flows and Flow Electrification

3. Ionic Wind

4. EHD in Thermal Systems

5. DBD and Plasma

6. Microfluidics and Multi-phase Media

The International Symposium on Electrohydrodynamics, ISEHD 2019
June 18–22, 2019, St. Petersburg, Russia

Numerical modeling of electrocoalescence using the arbitrary Lagrangian-Eulerian method

V.A. Chirkov, G.O. Utiugov
St. Petersburg State University, St. Petersburg, Russia

Abstract—Under the action of a strong electric field, conducting droplets suspended in a dielectric liquid attract each other and can merge after their touching. The latter is called electrocoalescence and is of great interest due to a lot of applications, including electrocleaning water-oil emulsions, joining liquid microscopic volumes for conducting biochemical analyses, etc. The suggested here is an approach to simulate electrocoalescence using so-called arbitrary Lagrangian–Eulerian method (also referred to as the moving mesh) that generally fails to describe processes of volume merging or separation (i.e., changing topology). The numerical modeling uses COMSOL Multiphysics software based on the finite-element method. The key idea of the study is to divide the simulation of the electrical coalescence into two steps: the approach of droplets and the shape change of two droplets joined into one volume via a thin bridge. The numerical results are compared with those of the experimental research into the transition between droplet coalescence and non-coalescence. The suggested approach is shown to get quite acceptable results.

Keywords—Two-phase liquid, moving mesh, ALE, water-oil emulsion, decoalescence

I. INTRODUCTION

Electrocoalescence is a process of the merger of two (or more) volumes of a conductive liquid under the action of an electric field. These volumes may be droplets of one liquid suspended in non-conductive medium, or, for example, droplets placed on a dielectric substrate. On the one hand, the investigation relevance of droplets combining under the action of an electric field is because it underlies technology of the electrocleaning of liquids from tiniest droplets of the water, as well as in other technologies. On the other hand, the numerical simulation of this process is still quite a complicated task. Existed models often lead to physically incorrect results, which, particularly, may be expressed in non-equipotentiality of the conducting media volume (for instance, [2]).

Moreover, even despite recent success in applying the phase function model [3] for the simulation of the threshold between coalescence and non-coalescence [4], corresponding models have a significant disadvantage—they are not suitable for the simulation for a long time due to the blurring of the phase function distribution. The model based on the arbitrary Lagrangian-Eulerian method or so-called the moving mesh method [5] does not have the drawback of the phase function model. However, this method does not allow one to consider the process of the object's topology changing, particularly, droplets combining. Nevertheless, the analysis of experimental data on electrocoalescence has shown that the changing object's topology—the creation of the 'bridge' between droplets—happens so fast that the geometry of the drops almost does not change during this moment (fig.1, [6]). This work is devoted to the investigation of this approach. According to this, one may conduct the process simulation of electrical droplet combining by stopping the calculation immediately before their touching, manual adding the bridge between drops and resuming the calculation.

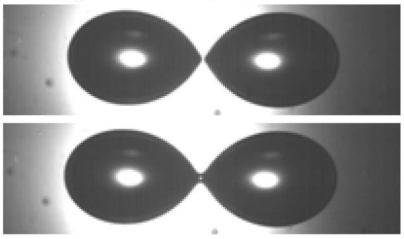


Fig 1. Water drop photos before and after the formation of the bridge (water bridge) between them; the time between frames equals 1 ms (according to data [6]).

II. NUMERICAL SIMULATION

The object being considered constitutes two parallel electrodes, space between which is filled with a liquid dielectric (oil). Drops of the conductive liquid (distilled water) were placed in the center of this cell. The following equations were calculated for the numerical simulation: Navier-Stokes, continuity, and Poisson equations. An interface displacement (finite-element mesh) occurs according to the calculated value of the liquid velocity. The system of equations describing the investigated process of electrocoalescence is denoted the following way:

$$\rho\frac{\partial v}{\partial t} + \rho(\vec{v},\nabla)\vec{v} = -\nabla p + \eta\Delta\vec{v} \tag{1}$$

$$div(\vec{v}) = 0 \tag{2}$$

$$div(\varepsilon\varepsilon_0\vec{E}) = 0 \tag{2}$$

$$\vec{E} = -\nabla V. \tag{4}$$

Here E is the electric field strength, V is the electric potential, v is the fluid velocity, p is the pressure, ε is the relative electric permittivity, ε_0 is the vacuum permittivity, ρ is the mass density, η is the dynamic viscosity, t is the time.

Corresponding author: Grigorii Utiugov
e-mail address: g.utyugov@2015.spbu.ru

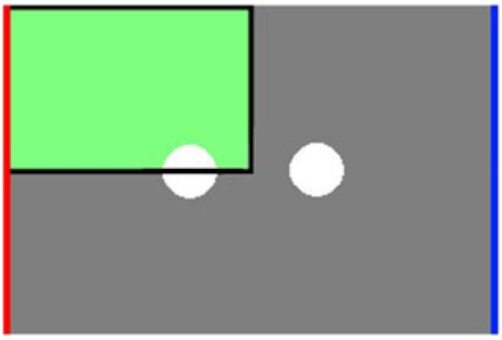


Fig. 2. Schematic picture of the model geometry with the indication of the calculated area (highlighted with the green color).

Hydrodynamic equations are calculated for both phases, equations of the electrostatics — for dielectric liquid only. The latter are not computed in the internal liquid, since the electric field does not penetrate inside it due to the high ratio of liquids conductivities, i.e., the surface of the conductive droplet equals to the equipotential surface. The electrostatics and hydrodynamics subsets are interrelated via the electric force (pressures) applied to the droplet surface [7]:

$$P_C = \frac{1}{2}\lambda E_n, \tag{5}$$

where λ is the surface charge density, E_n is the normal component of the electric field.

The surface tension force P_{st} [7] also acts on the droplet surface:

$$P_{st} = 2\gamma H \tag{6}$$

where γ is the interfacial tension coefficient, H is the mean curvature of the interface.

To account the forces mentioned above (pressures), the following boundary condition was set on the boundary of the droplet:

$$P_1 - P_2 = P_{st} + P_C,$$

where P_1 and P_2 are pressures near the interface outside and inside droplet.

The consistency of calculated hydrodynamic equations for both phases was realized through the equality of each phase velocity on the interface:

$$\upsilon_b = \upsilon_{oil} = \upsilon_{water}$$

where υ_b is the velocity of the boundary, υ_{oil}, υ_{water} are velocities of the phases.

The numerical modeling was conducted in COMSOL Multiphysics software using the finite-element method. The geometry of the computer model and boundary conditions are represented in Fig. 3.

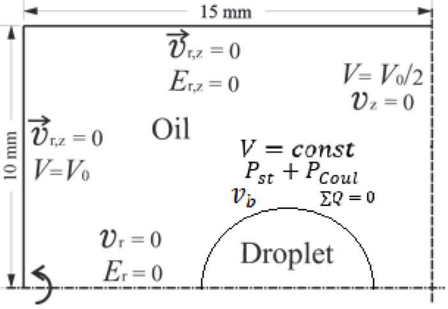


Fig. 3. Geometry and boundary conditions.

The moving mesh method does not allow one to describe an electrocoalescence directly due to object topology changing during the process. The key idea of applying this method is to divide the original task into two. At first, to consider the drops deformation under the action of an electric field and their convergence, then to add the 'bridge' between droplets and to resume the calculation using the final result of the first solution step as the initial conditions for the second step. One may define the outcome of the process—coalescence or non-coalescence—by further deformation of the received combined droplet.

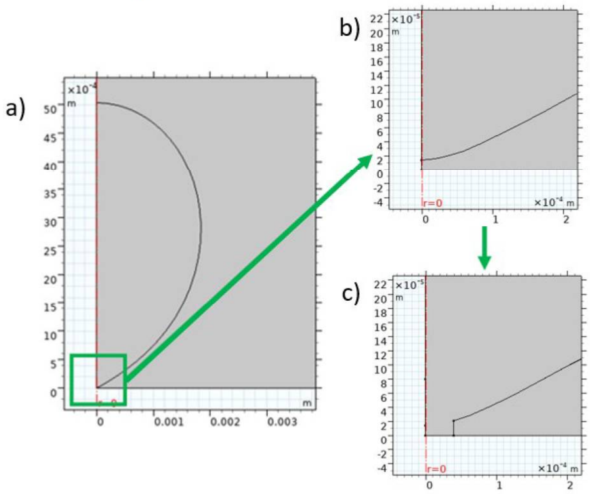


Fig. 4. Process of adding the "bridge": a—droplet before adding the "bridge," b and c—droplet pole before and after adding the "bridge."

Further process result after adding the "bridge" is defined by the relation of the Coulomb force and the surface tension force.

III. RESULTS

The modeling was conducted for liquids corresponding to olive oil (as a dispersion medium) and water (as dispersed phase): $\gamma = 0.016\ N/m$, $\varepsilon_{oil} = 2.85$, $\varepsilon_{water} = 80$, $\rho_{oil} = 910\ kg/m^3$, $\rho_{water} = 1000\ kg/m^3$, $\eta_{oil} = 0.065\ Pa \cdot s$, $\eta_{water} = 0.001\ Pa \cdot s$.

A. Comparison with the Experiment

The simulation of electrocoalescence (droplets with radius *r* = 1.97±0.01 mm, voltage *V* = 4950 V, interelectrode distance 3 cm) and non-coalescence (droplets with radius *r* = 2.09±0.01 mm, voltage *V* = 5950 V, interelectrode distance 3 cm) was conducted in accordance with available experimental data [6]. The results obtained in modeling (tables 1 and 2) are in a good agreement with the experimental data.

TABLE I
Experimental video frames and modeling results of the electrocoalescence for droplets with radius $r = 1.97 \pm 0.01$ mm and applied voltage $V = 4950$ V.

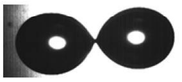
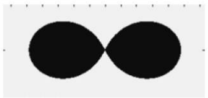
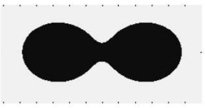
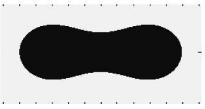
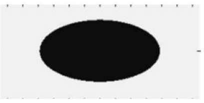
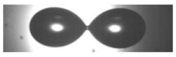
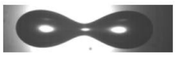
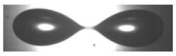
Time, ms	Experiment	Simulation
0		
8.5		
35.5		
109		

TABLE II
Experimental video frames and modeling results of the non-coalescence for droplets with radius $r = 2.09 \pm 0.01$ mm and applied voltage $V = 5950$ V.

Time, ms	Experiment	Simulation
0		
56		
77		
95		

Moreover, in case of electrocoalescence, high level of the accordance with droplet shapes obtained in the experiment and the simulation is observed throughout the whole transient process, however, in case of non-coalescence, there is some delay.

B. Determination of the Boundary between Processes

Changing the voltage, which is applied to electrodes, one may control the outcome of the process and thus define the threshold voltage between electrocoalescence and non-coalescence. This procedure was carried out for several droplet radii. At the same time, the size of added 'bridge' approximately corresponds to the experimental size obtained with the analysis of experimental video frames referred to the process of electrocoalescence (the ratio of the 'bridge' height to its width was about $h{:}w{=}1{:}2$). The threshold between coalescence and non-coalescence was being found with the error ±100 V. The results obtained were compared with experimental data. The results are represented in Fig. 5. One may see that, with the increasing of the droplet radius, the less applied voltage is necessary to break the droplet.

One may also see that the results obtained from the model with the application of the moving mesh method have rather good agreement with experimental data and approximating line lies between two areas corresponding to electrocoalescence and non-coalescence.

V. CONCLUSION

The created model of electrocoalescence enables one to obtain results on the threshold between coalescence and non-coalescence, as well as qualitative analysis of the process, including the dynamics of an internal liquid. The results obtained for calculated droplet radii coincide with experimental data within the available sample of the latter and experimental error.

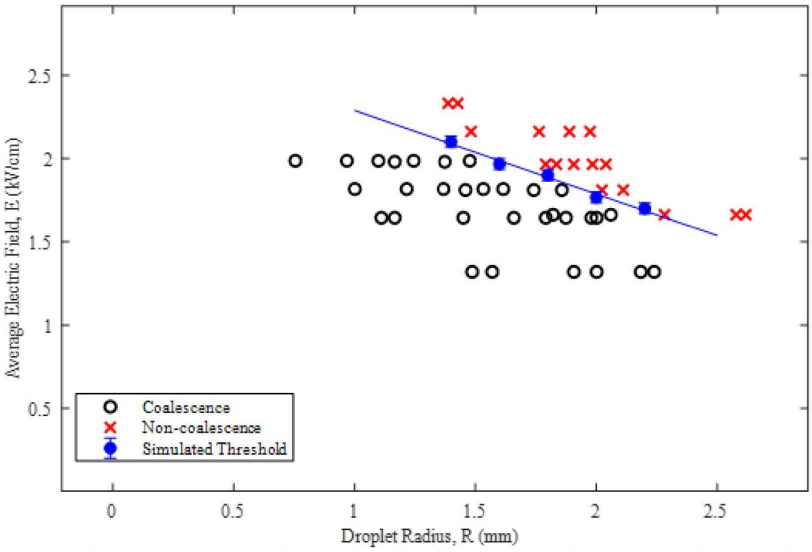


Fig. 5. The experimental statistical data on coalescence and non-coalescence (black circles and red crosses) ([4]) and the simulated dependence of the threshold electric field value on the droplet radius.

ACKNOWLEDGMENT

Research was carried out using resources provided by the Computer Center of SPbU and Center for Diagnostics of Functional Materials for Medicine, Pharmacology and Nanoelectronics of Research park of St. Petersburg State University.

REFERENCES

[1] P. Atten, “Electrohydrodynamics of dispersed drops of conducting liquid: From drops deformation and interaction to emulsion evolution,” *Int. J. Plasma Environ. Sci. Technol.*, vol. 7, no. 1, pp. 2–12, 2013.

[2] K. V. Tarantsev, “Modeling of the processes of coagulation and dispersion of water in low-conductive fluids in an electric field,” *Surf. Eng. Appl. Electrochem.*, vol. 49, no. 5, pp. 414–422, Sep. 2013.

[3] E. Olsson and G. Kreiss, “A conservative level set method for two phase flow,” *J. Comput. Phys.*, vol. 210, no. 1, pp. 225–246, Nov. 2005.

[4] V. Chirkov, A. Lashko, M. Reznikova, and A. Gazaryan “Numerical and Experimental Investigation of Water Droplet Electrical Coalescence and Non-coalescence,” in *Proc. Electrostatics Joint Conf.*, 2018, pp. 1–8.

[5] C. Hirt, A. Amsden, and J. Cook, “An arbitrary Lagrangian-Eulerian computing method for all flow speeds,” *J. Comput. Phys.*, vol. 14, no. 3, pp. 227–253, Mar. 1974.

[6] V. Chirkov, A. Lashko, and M. Reznikova “The Investigation of the Transition From Electrical Coalescence to Non-coalescence of Two Water Droplets,” in *Proc. Annual Meeting of the Electrostatics of America.*, 2017, pp. 1–9.

[7] J. Raisin, J.-L. Reboud, and P. Atten, “Electrically induced deformations of water–air and water–oil interfaces in relation with electrocoalescence,” J. Electrostat., vol. 69, no. 4, pp. 275–283, Aug. 2011.