Dynamics of Bubble in Dielectric Liquid in Electric Field: Mesoscopic Simulation

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***Abstract*—We investigate the dynamics of a gas-vapor bubble in a dielectric liquid placed in strong electric field using the mesoscopic lattice Boltzmann method with possible phase transitions and energy transfer [1]. In the electric field, the bubble is elongated along the field lines under the action of electrostriction forces. This leads to the increase of the field magnitude near the poles of the bubble. Since the electric strength of the gas phase is much lower than the one of the liquid phase, the electric breakdown becomes possible inside the bubble with generation of conducting substance. Electric currents produce heat, and the temperature inside and around the conducting bubble rises leading to the evaporation of liquid and further increase of conductivity. Breakdown in a cavity leads to the increase of electric field magnitude in neighbor ones, which results in the sequence of breakdowns in nearby cavities. This is the "relay-race" mechanism of breakdown. In very strong electric field, the anisotropic instability is possible leading to the decay of the dielectric fluid into a system of gas-vapor channels in a liquid oriented mostly along the field lines.**

Keywords—dielectric liquid; bubbles; lattice Boltzmann method; electric breakdown

I. Introduction

Gas or vapor bubbles which are always present in dielectric liquids can significantly influence the quality of insulation. The electric strength of gaseous phase is much lower than that of the liquid phase. Hence, the breakdown inside bubbles can occur at relatively low voltage. Such partial breakdown leads to injection of electric charge inside liquid, and the magnitude of electric field near conductive inclusions increases which can result in the breakdown of liquid itself or in neighbor inclusions. Therefore, investigation of the behavior of gas or vapor bubbles in liquid placed in the electric field is an important scientific and practical task.

The simulation of flows with possible phase transitions is complicated because phase boundaries can appear, disappear or change their topology inside the bulk. Mesoscopic methods such as the lattice Boltzmann method (LBM) are promising for such simulations being intrinsically interface-capturing. The lattice Boltzmann method was used for the simulation of electrohydrodynamic problems in the work [2] (in two-dimensional setup). Here, we extend the model to three dimensions and incorporate an accurate account for heat transfer and generation.

II. Numerical Methods

The lattice Boltzmann method with possible liquid-vapor phase transitions and simulation of internal energy transfer, pressure work and latent heat of evaporation [1] is used to model the flow of dielectric fluid. The simulation of multiphase fluid is based on the pseudopotential approach of Shan and Chen [1,3]. The method is interface-capturing, no special treatment of phase boundaries is necessary. The advection of internal energy is simulated using a second set of lattice Boltzmann distribution function (passive scalar) with special "pseudoforces" which prevent spurious diffusion at phase boundaries with large density gradients [1]. The pressure work and the latent heat release or absorption are taken into account with finite-difference method as well as the heat conduction.

The electric potential φ is calculated from the Poisson's equation

$$\nabla \cdot (\varepsilon \nabla \varphi) = -q / \varepsilon_0 .$$

Here, q is the electric charge density. This equation is solved numerically together with the equation of the electric charge transport

$$\partial q / \partial t + \nabla \cdot (q\mathbf{u}) = \nabla \cdot (\sigma \nabla \varphi) ,$$

using the time-implicit finite-difference scheme and the method of simple relaxation. Here, σ is the electric conductivity, and the electric current density is $\mathbf{j} = \sigma \mathbf{E} = -\sigma \nabla \varphi$. The advection and diffusion of electric charge is simulated using the passive scalar method [2]. The local density of Joule heating $h = \mathbf{j} \cdot \mathbf{E} = \sigma E^2$ is added to the heat source term in the LBM.

The study was supported by the Russian Science Foundation (grant No. 16-19-10229).

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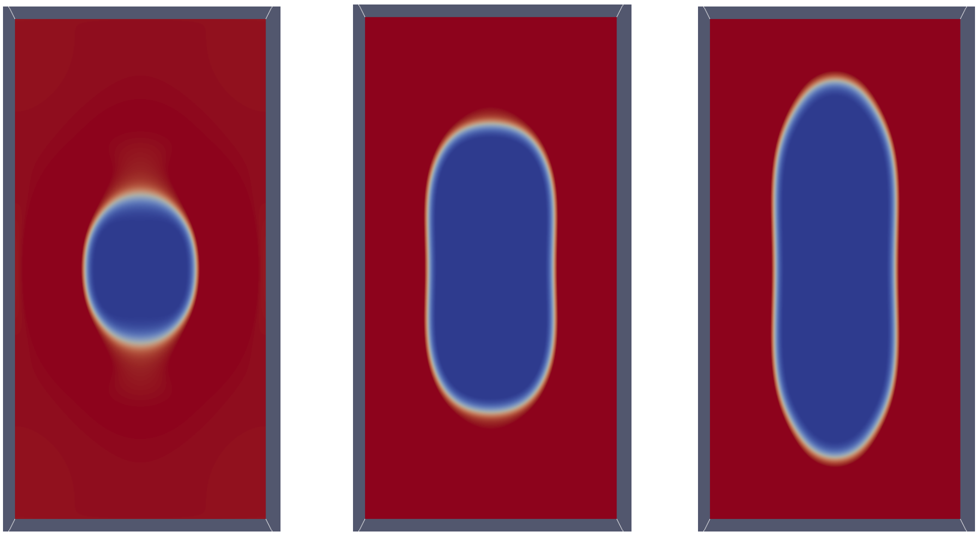

Fig. 1. Dynamics of bubble in electric field. Blue corresponds to lower density. Time left to right: $t = 200$, $t = 600$, $t = 1000$. Grid size 320×161×161.

The Helmholtz force acting on a charged fluid in an electric field is expressed by

$$\mathbf{F} = q\mathbf{E} - \frac{\varepsilon_0 E^2}{2}\nabla\varepsilon + \frac{\varepsilon_0}{2}\nabla\left[E^2\rho\left(\frac{\partial\varepsilon}{\partial\rho}\right)_T\right].$$

The second term is the force acting on inhomogeneous dielectrics; the third term corresponds to the electrostriction force. This force is taken into account in LBM together with the interparticle forces.

All quantities are expressed in non-dimensional values. Thermodynamic quantities are scaled by the values in the critical point.

III. Results and Discussion

We performed three-dimensional simulations of the evolution of a vapor bubble in a fluid under the action of electric field. Different cases are explained below.

A. Dynamics of bubble without conductivity

A vapor bubble was initially placed in the center of the calculation region. The electric field was applied in vertical direction, with the average non-dimensional magnitude $\langle E\rangle = 1$. The van der Waals equation of state (EOS) was used for the fluid with the initial temperature $T = 0.8$. This EOS is simple and gives qualitatively correct results. The specific heat is density-independent as well as in other linear in temperature EOS (e.g., Carnahan-Starling EOS). The Clausius-Mossotti formula for the electric permittivity was used with the permittivity of the initial liquid phase equal to 2. Boundary conditions were periodic in horizontal directions both for the flow and electric potential, and no-slip rigid walls with fixed electric potential were set at the top and bottom. The system was equilibrated for 5000 time steps until the bubble is in steady state before the electric field was applied.

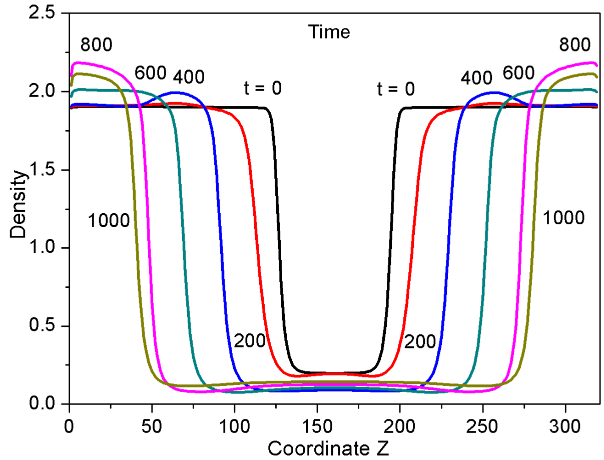

Fig. 2. Density profiles along the central line at different time.

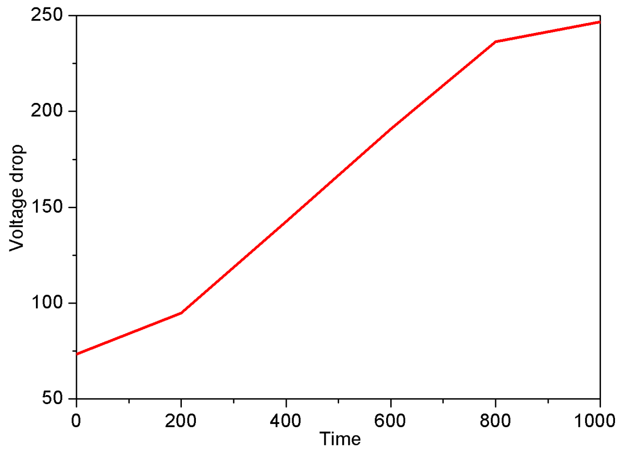

Fig. 3. Voltage drop in the bubble.

The simulation results are shown in Figs. 1–3. In the electric field, the bubble grows and elongates along the field lines under the action of electrostriction forces (Fig. 1). Evaporation at the poles occurs, and the density inside bubble decreases due to its expansion (Fig. 2). This leads to the increase of the field

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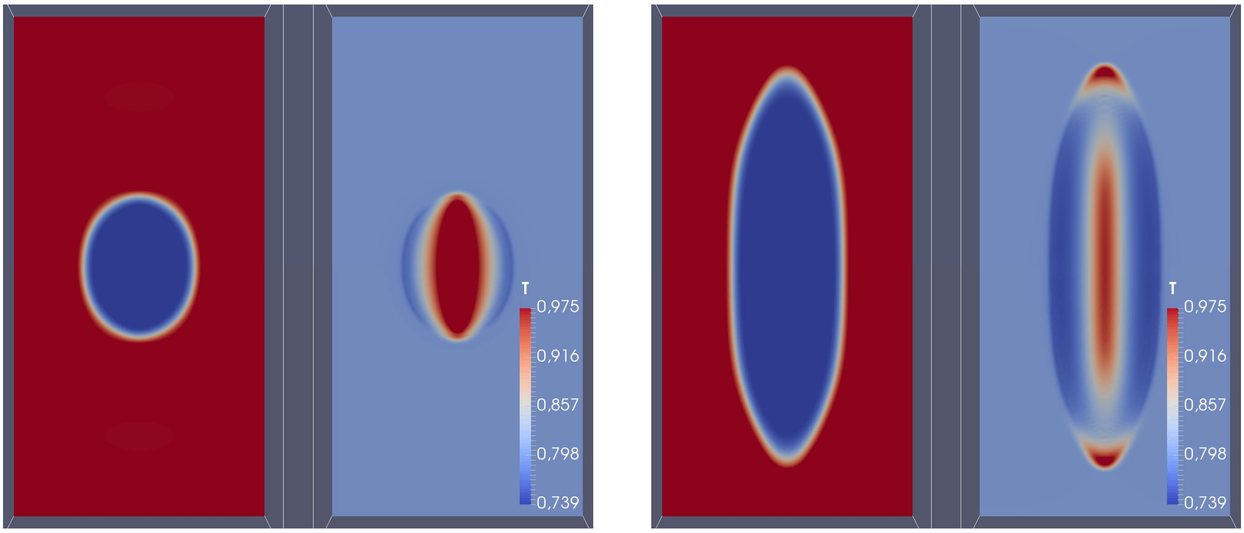

Fig. 4. Dynamics of bubble shape and temperature distribution inside the bubble with conductivity. Time $t = 400$ (left) and $t = 1000$ (right)

magnitude near the poles of the bubble. The voltage drop in the bubble also increases (Fig. 3), which increases the probability of breakdown inside the bubble. The similar deformation of air bubbles was observed experimentally in [4,5].

B. Dynamics of a bubble with conductivity inside

We assume that the matter can become conductive if the fluid density is sufficiently low ($\rho < 1.1\rho_g$), and the magnitude of electric field is high enough $\left(E > 1.05\langle E\rangle\right)$. We simulated the evolution of a bubble in the electric field with the average magnitude $\langle E\rangle = 0.6$. All other parameters were the same as in the previous simulations.

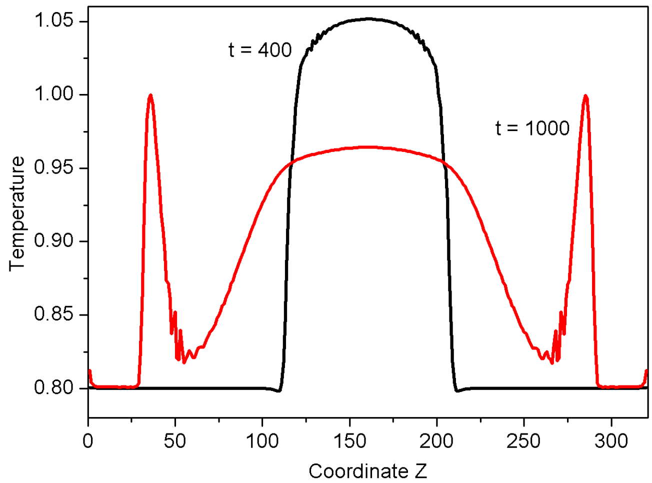

Fig. 5. Temperature profiles along the central line at different time.

The dynamics of the bubble shape and the distribution of fluid temperature are shown in Fig. 4 for two different time moments. The temperature profiles are shown in Fig. 5 for the same time moments. The conductivity arises in the central part of the bubble leading to the heating of fluid and the enhanced evaporation. The electric charges are accumulated at the poles, and the electric force acting on the charge increases the elongation of the bubble comparing with non-conductive case (Fig. 1, note that the average electric field magnitude there is higher).

Later, the accumulated charge is advected by the moving fluid which results in the injection of charge into liquid near the poles of the bubble. The motion of charge also produces the electric current in outer circuit.

C. Breakdown in a chain of cavities

When several bubbles are close to each other in electric field, the breakdown in one bubble leads to the increase of electric field magnitude in nearby ones, increasing the probability of breakdown there [6].

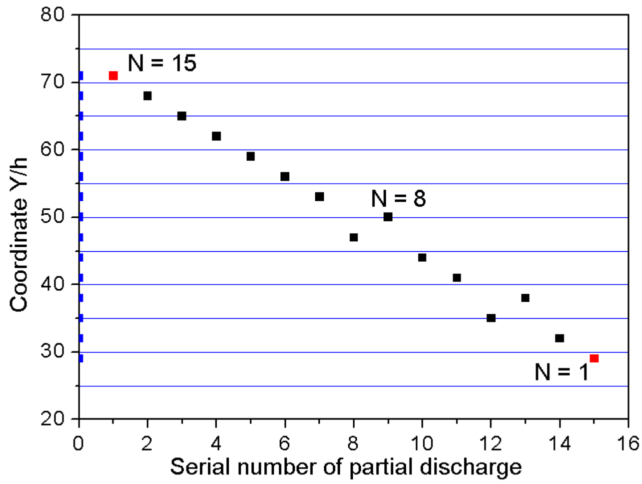

Fig. 6. “Relay-race” propagation of a wave of partial discharges along the chain of gas inclusions [8].

Under the certain conditions, the wave of partial discharges can arise in a chain of cavities oriented along the electric field [7,8]. Such “relay-race” mechanism of propagation of partial discharges was observed (Fig. 6) in stochastic simulations of microdischarges in a chain of 15 cavities [8]. The dashed line

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at the left shows the positions of cavities. Here, N is the serial number of cavity where partial discharge occurs.

D. Anisotropic decay

In sufficiently strong uniform electric field, a dielectric fluid can undergo instability leading to the decay of initially homogeneous state into a two-phase system of vapor channels in a liquid if the density dependence of electric permittivity is nonlinear [9]. This decay is anisotropic; vapor channels are mainly oriented along the field lines.

When solute gas is present in dielectric liquid, the action of electric field can lead to release of gas, which also forms channels along field lines. The presence of gas can decrease the threshold magnitude of electric field necessary for the anisotropic decay [10]. In some places, the branching of channels can be observed (Fig. 7). The electric strength inside channels is lower than inside the bulk of a liquid, therefore these channels can serve as the possible paths for initiation of streamers.

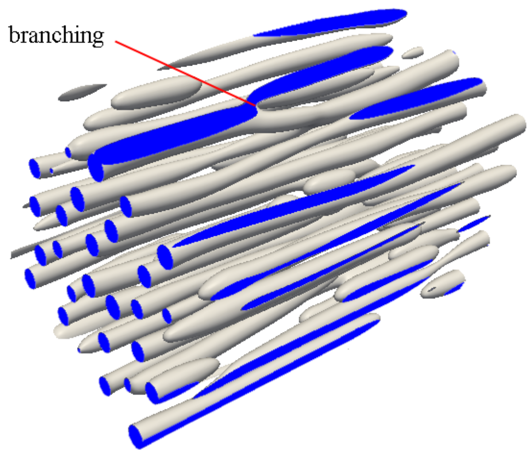

Fig. 7. The decay of a dielectric liquid with solute gas in the three-dimensional strong electric field. Only the gas-vapor channels are shown. [10].

IV. Conclusions

We investigated the behavior of a single vapor bubble in dielectric liquid placed in the electric field taking into account the transfer of internal energy, the latent heat of phase transition, and the action of electric forces on the fluid. After the application of voltage, the bubble elongates, and the density inside decreases. The voltage drop along the bubble increases leading to higher probability of a breakdown. When conductivity inside the bubble is possible, the heating of fluid, enhanced evaporation and injection of electric charge near the poles are observed. The elongation is more pronounced than in non-conductive case even with lower electric field magnitude.

The sequence of breakdowns in a chain of bubbles spaced in the electric field can occur as the “relay-race” mechanism of partial discharges propagation.

In very strong electric field, the anisotropic instability is possible leading to the decay of the dielectric fluid into a system of gas-vapor channels in a liquid oriented mostly along the field lines.

References

[1] A.L. Kupershtokh, D.A. Medvedev, and I.I. Gribanov, “Modeling of thermal flows in a medium with phase transitions using the lattice Boltzmann method,” Numerical Methods and Programming, vol. 15, pp. 317–328, 2014. (in Russian).

[2] A.L. Kupershtokh and D.A. Medvedev, “Lattice Boltzmann equation method in electrohydrodynamic problems,” J. Electrostat., vol. 64, no. 7/9, pp. 581–585, 2006.

[3] X. Shan and H. Chen, “Lattice Boltzmann model for simulating flows with multiple phases and components,” Phys. Rev. E, vol. 47, no. 3, pp. 1815–1819, 1993.

[4] M. Talaat and A. El-Zein, “Analysis of air bubble deformation subjected to uniform electric field in liquid dielectric,” Int. J. Electromagnetics and Applications, vol. 2, no. 1, pp. 4–10, 2012.

[5] C.G. Garton and Z. Krasucki, “Bubbles in insulating liquids: stability in an electric field,” Proc. Roy. Soc., vol. 280, no. 1381, pp. 211–226, 1964.

[6] A.L. Kupershtokh, C.P. Stamatelatos, and D.P. Agoris, “Simulation of partial discharge activity in solid dielectrics under AC voltage,” Tech. Phys. Lett., vol. 32, no. 8, pp. 680–683, 2006.

[7] N.Yu. Babaeva, D.V. Tereshonok, G.V. Naidis, and B.V. Smirnov, “Initiation of breakdown in strings of bubbles immersed in transformer oil and water: String orientation and proximity of bubbles,” J. Phys. D: Appl. Phys., vol. 49, no. 2, p. 025202, 2016.

[8] A.L. Kupershtokh and D.I. Karpov, “Simulation of waves of partial discharges in a chain of gas inclusions located in condensed dielectrics,” J. Phys.: Conf. Ser., vol. 754, no. 10, p. 102006, 2016.

[9] A.L. Kupershtokh and D.A. Medvedev, “Anisotropic instability of a dielectric liquid in a strong uniform electric field: Decay into a two-phase system of vapor filaments in a liquid,” Phys. Rev. E, vol. 74, no. 2, p. 021505, 2006.

[10] A.L. Kupershtokh, “Three-dimensional LBE simulations of a decay of liquid dielectrics with a solute gas into the system of gas-vapor channels under the action of strong electric fields,” Computers and Mathematics with Applications, vol. 67, no. 2, pp. 340–349, 2014.