Dynamics of bubbles in electric field

S M Korobeynikov¹², A G Ovsyannikov², A V Ridel¹² and D A Medvedev¹

¹ Lavrentyev Institute of Hydrodynamics SB RAS, 15 Lavrentyev Prosp., Novosibirsk, 630090, Russia
² Novosibirsk State Technical University, 20 Karl Marx avenue, Novosibirsk, 630073, Russia

E-mail: ridel@ngs.ru

Abstract. We consider main topic related to the behavior of rising air bubbles in transformer oil under the action of alternating electric field. The data on the degree of deformation of bubbles are provided as well as the description of the experimental apparatus. The preliminary study of the development of partial discharges in rising helium bubbles in transformer oil under the action of alternating voltage is reported. Results of mesoscopic simulation of the dynamics of a bubble are presented.

1. Introduction
Partial discharges in transformer oil are known to be one of the causes of the gradual destruction of paper-oil insulation. Bubbles in the transformer which are formed due to different reasons including non-electric ones can be transported by the cooling system to the region of strong electric field. There, they can lead to the inception of partial discharges (PDs), and they also can initiate the breakdown of insulation. Mechanisms of inception and development of partial discharges in gaseous inclusions in solid insulation were investigated earlier [1], whereas the mechanisms of partial discharges in a liquid are still poorly investigated. Therefore, the goal of this work is the investigation of the behavior of gas bubbles in transformer oil under the action of strong alternating electric field.

2. Experimental setup
Experiments were carried out in a high-voltage box (figure 1) where the high-voltage transformer (1), the linking capacitor (2), the electric and optical registration systems, and the experimental apparatus (3) were placed.
The experimental apparatus (figure 2) was assembled on the optical bench (1) in order to ensure the collinearity of the whole registration system. All elements were mounted on optical carriages (2) which allowed one to provide the exact tuning of the optical registration system based on the high-speed camera Casio EX-F1 (6). Optical magnification of the object was provided by the lens system (5). The laser pointer (3) was used as the light source. The camera and the laser pointer were placed collinearly with the experimental cell (4) in order to avoid distortions of the image of the object under investigation.

Experimental cell (figure 3) consisted of the case (1) made of PMMA, with windows (2) made of optical glass, two plane electrodes (3), and the system (4) for the injection of gas into the bulk of transformer oil. The interelectrode gap was equal to 6.8 mm.
3. Results
When attempting to inject gas to the region between electrodes, we observed the effect of the dielectrophoretic force which pushed the bubble out of the region of strong electric field. The rise of a bubble stopped at the boundary of electrodes, and later the bubble rose along the boundary of higher electric field magnitude. This problem was solved by the immediate injection of a bubble into the electrode region.

We observed in experiments the deformation of air bubbles under the action of alternating electric field. Figure 4 shows the deformation at the electric field strength (amplitude value) 4.4 kV/mm. The deformation proceeded with double frequency and without PD in accordance with the absolute value of the instant electric field magnitude. For example, a bubble of the diameter of 1.24 mm (figure 4a) elongated to 1.8 mm at the moment of maximum voltage (figure 4d). The experimentally obtained rise velocity of the bubble of this size was $V \sim 12$ cm/s.

![Figure 4. Deformation of the air bubble under the action of alternating voltage.](image)

In the investigation of the development of partial discharges in rising bubbles, helium was used as a filling gas. There are several reasons for this choice. First, the electric strength of helium is lower, hence, the partial discharge in a bubble occurs at lower magnitude of electric field. Second, the numerical simulation of the development of partial discharge is simpler in the case of individual gas than for a mixture of gases such as air. Figure 5 shows the development of PD in the helium bubble of the diameter of 1.57 mm at the magnitude of electric field equal to 1.8 kV/mm (amplitude value).

![Figure 5. Partial discharge in the helium bubble.](image)

4. Simulations of the dynamics of bubble
We investigated the dynamics of a gas-vapor bubble in a dielectric liquid placed in strong electric field. Lattice Boltzmann method (LBM) with possible phase transitions liquid-vapor and simulation of internal energy transfer, pressure work and latent heat of evaporation [2] was used to model the flow of dielectric fluid.

Electric potential $\varphi$ 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

\[
\frac{\partial q}{\partial t} + \nabla \cdot (q \mathbf{u}) = \nabla \cdot (\sigma \nabla \varphi)
\]

using the time-implicit finite-difference scheme. Here, \( \sigma \) 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 a second set of lattice Boltzmann distribution function (passive scalar) [3]. 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 Helmholtz force acting on a charged fluid in an electric field is expressed by

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

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 (scaled by values in the critical point).

A vapor bubble was initially placed in the center of the calculation region. The electric field was applied in vertical direction, van der Waals equation of state was used for the fluid with the initial temperature \( T = 0.8 \). The Clausius–Mossotti formula for the electric permittivity was used with the permittivity of the initial liquid 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 at the top and bottom. The system was equilibrated during 5000 time steps before the electric field was applied.

We assumed 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 \( (E > 1.05 E_0) \). We simulated the evolution of a bubble in the electric field with the average magnitude \( E = 0.6 \).

Distribution of fluid density and temperature is shown in figure 6 for two different time moments. Conductivity arises in the central part of the bubble leading to the heating of fluid and the enhanced evaporation. Later, the accumulated charge is advected by moving fluids 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.

![Figure 6. Distribution of density and temperature inside the bubble with conductivity. Time t = 400 (left) and t = 1000 (right).](image)

5. Discussion
Using the optical registration, we found that the inception of a PD inside bubbles always results in the breakup of them. In our opinion, this can be connected with the fact that after the generation of the
discharge plasma inside a bubble during the development of a PD, electric charges in plasma are separated, positive charges move to the negative electrode, negative charges towards the positive one. Then electric charges are deposited at the walls on the bubble. The Coulomb force acts at the walls leading to the sharp elongation of the bubble (by 2 times and more), and the instability of the elongated bubble leads to its breakup.

Note that PDs in rising bubbles do not correspond to the Paschen’s curve due to the lack of initiating electrons inside the bubble. The value of $P \cdot d$ where $P$ is the pressure inside the bubble, $d$ is the bubble diameter is about 150 Pa·m. For helium, the voltage necessary for the breakdown of a bubble according to the Paschen’s law is about 1.5 kV. The magnitude of electric field inside the bubble is about 1.2 times larger than the average field magnitude in the cell, then the average magnitude should be near 0.8 kV/mm, and the voltage necessary for the inception of PD should be 5–6 kV. This value is nearly twice lower than the voltage of PD inception observed experimentally.

Mesoscopic simulation showed that 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. The heating of fluid, enhanced evaporation and injection of electric charge into the liquid near the poles are observed.

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

References
[1] Bartnicas R 2002 Partial discharges, their mechanism, detection and measurement IEEE Trans. Dielectr. Electr. Insul. 9(5) 763–808
[2] Kupershtokh A L, Medvedev D A and Gribanov I I 2014 Modeling of thermal flows in a medium with phase transitions using the lattice Boltzmann method Numerical Methods and Programming 15 317–28 (in Russian)
[3] Kupershtokh A L and Medvedev D A 2006 Lattice Boltzmann equation method in electrohydrodynamic problems J. Electrostat. 64(7/9) 581–5