Registration and Simulation of Partial Discharges in Free Bubbles at AC Voltage

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ABSTRACT

Partial discharges in free bubbles in transformer oil are investigated both experimentally and theoretically. Optical, electric and optoelectronic registration are performed to obtain a picture of partial discharge. The time duration of electrical and optoelectronic signals is practically the same, 50 ns. Much longer time is needed for bubble deformation and its breaking, approximately several milliseconds. Electric properties obtained in experiments are confirmed by the simulation of the electrical field, "true" and "apparent" charges of partial discharge. Hydrodynamic behavior in experiments corresponds well to the simulation with the lattice Boltzmann method.

Index Terms — **bubbles, partial discharges, oil insulation, hydrodynamics, lattice Boltzmann method, electric field effects, simulation**

1 INTRODUCTION

A measurement of partial discharge (PD) in the high-voltage equipment is one of the most informative methods for diagnosing the high-voltage electric equipment. The most dangerous defects in the electrical insulation give rise to the lowest values of the voltage necessary for PD occurrence and to the largest values of the so-called apparent PD charge. This can be easily shown when the defects are the gas cavities in a solid insulation, because Paschen's law holds in this case and

$$E/p = f\,(pd). \tag{1}$$

Here, E is the intensity of the electric field necessary for a self-sustaining discharge, p is the pressure, and d is the cavity size. Since the pressure is usually constant and equal to the atmospheric pressure, and the field magnitude is proportional to the voltage, the voltage necessary for PD occurrence increases with the length of a cavity along the rising branch of the Paschen's curve. Note that the condition of self-sustaining is not sufficient for PD occurrence. An initial electron near the cathode wall of the cavity is necessary for developing of ionization and breakdown of gas. The delay of the PD occurrence can last up to tens of minutes or even several hours due to the small probability of the appearance of the initiating electrons in bubbles from several tenths to several millimeters in size [1].

We emphasize that the objective of the present work is the investigation of PD from floating bubbles that simulates bubble motion in an oil channel of oil-barrier insulation of a 220-500 kV power transformer or a shunt reactor [2] which confirms the practical importance of the work.

2 EXPERIMENTALSETUP

Figure 1 shows the experimental cell. The walls (1) are made of PMMA with two optical glass windows (2) for the high-speed video registration. The cell was filled with transformer oil of type Nitro (5). The gas was injected through the medical syringe (4) into the electrode region. The distance between the electrodes (3) is h=6.8 mm.

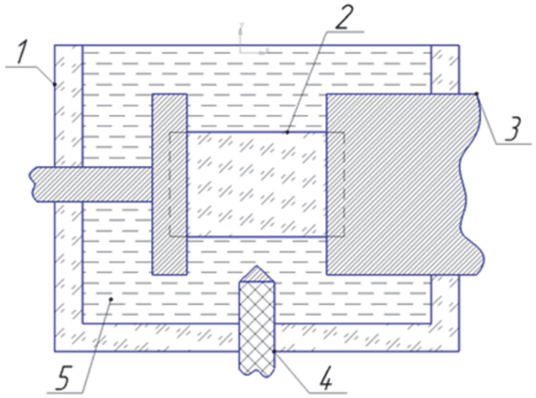

Figure 1. Experimental cell.

Electrical signals of the PD in a floating bubble is registered by two methods: 1) using the current transformer connected into the ground circuit, and 2) using the usual PD registering circuit. The electric part of the experimental setup (Figure 2) consisted of the high-voltage transformer 190 V/140 kV, the coupling capacitor SMAIV-110/3-7.33 nF, the experimental

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cell, the current transformer, the PD registering circuit, and an oscilloscope.

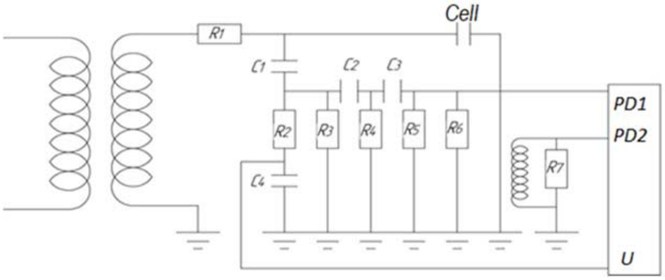

Figure 2. High-voltage circuit.

Resistor R_1 is placed at the high-voltage side of the transformer for two reasons: 1) for restricting the current after the breakdown of the inter-electrode gap, and 2) for filtering the noise from partial discharges which enters the registration system making difficult the revealing of the signal from the noise. Low-inductance resistors TVO-60 W are used. The value of this resistor is chosen experimentally. It was found, that the value of 28 kΩ provides good noise filtering.

2 PRELIMINARY ESTIMATIONS

Before the experiments, expected values of voltage necessary for the PD occurrence in air bubbles of different size were determined using the classic Paschen's model of multi-avalanche discharge. The calculations are easier to make with the approximate expression from [3] which agrees sufficiently well with the experimental data on the breakdown of small air gaps,

$$U_{br} = \frac{B\cdot(pd)}{C+\ln(pd)} \tag{2}$$

Here, the pressure is to be measured in Torr, and the diameter of a bubble d in cm, B = 365 kV/(cm·Torr), $C = 1.18$. The value of U_{br} is then obtained in kV.

For atmospheric pressure and the bubble diameter of 1.5 mm, we have $U_{br} = 7$ kV. The cell voltage necessary for the PD occurrence can be calculated from the values of electric field inside and outside the bubble. The electric field inside the bubble is:

$$E_1 = \frac{U_{br}}{d} = 47\ \mathrm{kV/cm}. \tag{3}$$

For spherical bubble, the average field outside it E_0 is given by the well-known expression:

$$E_0 = E_1 \cdot \frac{2\varepsilon+1}{3\varepsilon} = 38\ \mathrm{kV/cm}. \tag{4}$$

Then the cell voltage for the PD occurrence is approximately:

$$U_{ph} = E_0 h = 26\ \mathrm{kV}. \tag{5}$$

The values of voltage necessary for PD occurrence were calculated using this expression for bubble diameters from 1 to 2 mm which are usually generated in our experiments. The results are shown in Table 1.

Table 1. Expected inception voltage for bubbles of different diameters.

d, mm	1	1.2	1.5	2
Uph, kV	28	27	26	25

3 EXPERIMENTAL RESULTS

In the experiments, PD in air bubbles were not observed even at the maximum obtained voltage of 42 kV. It was impossible to obtain higher voltage because of the large coupling capacitance (7.3 nF) and insufficient voltage of the step-up transformer.

Comparing the calculated and experimentally obtained values of U_{ph} it is worth noting that the PD in floating air bubbles can occur at a voltage much higher than the calculated one (Table 1), i.e., it appears that Paschen's law does not hold. It should be emphasized that the experiments with a continuous injection of bubbles into the cell under voltage were carried out for several hours (>20000 bubbles in one experiment, or about one bubble per second).

For this reason, the gas with the lowest electric strength, helium, was used in the experiments. There is no appropriate analytical expression for helium; hence, graphic data on the breakdown for small gaps were used for the approximate calculation. The calculated value for the PD occurrence in a helium bubble of 1.5 mm diameter is U_{br}=1.7 kV that corresponds to the electric field strength of about 1.1 kV/mm and to the cell voltage U_{ph} about 6.6 kV.

However, in the process of experiments, we obtained the voltage necessary for the PD occurrence to be equal to 15 kV which is 2.5 times higher than that obtained for the case when the voltage drop in the helium bubble was calculated with Paschen's law. Thus, the disagreement with the Paschen's law for PD in floating bubbles was revealed experimentally.

Figure 3 presents frames from the high-speed video recording of the partial discharge in helium bubbles of the 1.5 mm diameter. The frame rate was 1200 fps. It is clearly seen that all three bubbles were deformed to the third frame.

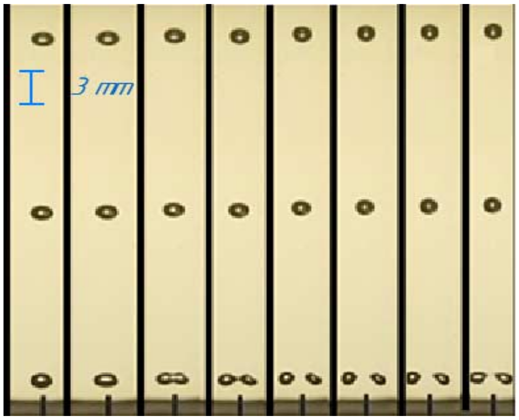

Figure 3. Development of partial discharge in transformer oil. Voltage 16 kV, plane electrodes are at left and right sides of each frame.

The bubble at the bottom of the second frame was deformed slightly more than other two that indicates to the PD occurrence in this bubble. At the next frames, the rupture of the bubble is in progress while the voltage decreased significantly. Such PD is irrelevant; this one was registered after 3.5 hours of work of the high-voltage setup with a permanent generation of bubbles. The electric signal from the PD is presented in Figure 4.

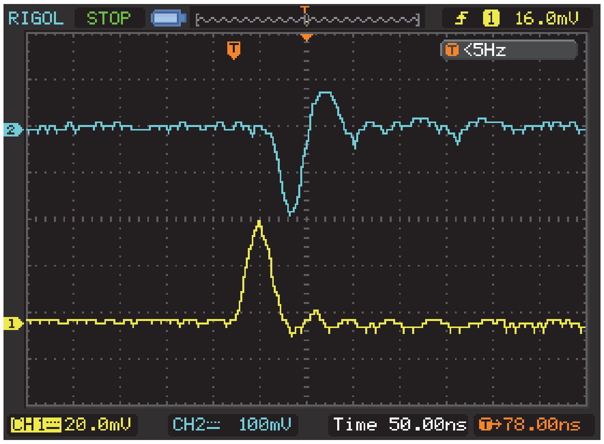

Figure 4. Signal from the partial discharge in a bubble of 1.7 mm diameter. Lower curve is the signal from the current transformer; upper one is from the registering circuit.

Based on the signal from the registering circuit, we determined the duration of the pulse and the current as well. In this case, the maximum current was 3.3 mA, the time duration was 50 ns. Overall, 16 events were registered with PD inside bubbles. The averaged over these measurements "apparent" charge was 80±3 pC. However, the systematic error may exist because of the oscillations at the tail of the current signal (upper curve in Figure 7). This error is estimated to be about 10%. Hence, we can state that the measured value of the "apparent" charge is between 70 and 90 pC.

After the development of the PD in a bubble, the subsequent discharge between one of the bubbles and the electrode was observed in most cases. Figure 5 shows the secondary discharge caused by the PD in a bubble presented in Figure 3.

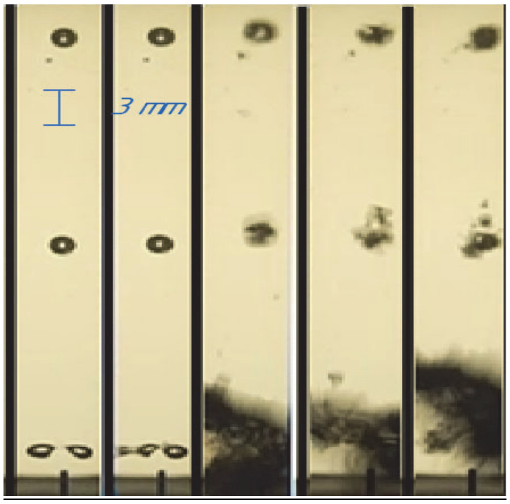

Figure 5. Secondary partial discharge after a partial discharge in the bubble.

The oscillogram of this PD is shown in Figure 6, the recording was started by the signal from the current transformer.

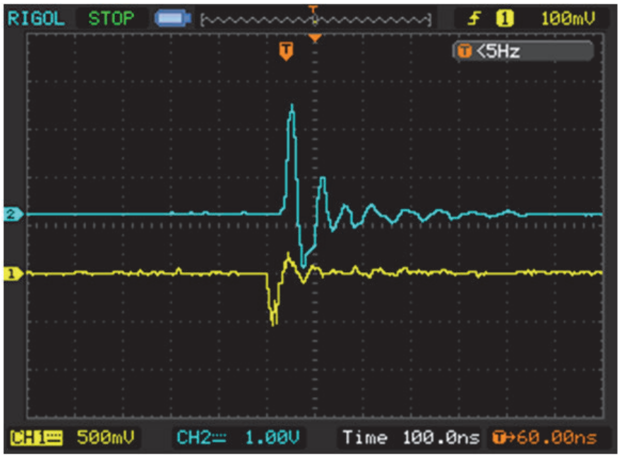

Figure 6. Signal from secondary PD. Lower curve is the signal from the transformer; upper one from registering circuit.

In this case, the maximum current was 56 mA, and the pulse duration was 40 ns. The "apparent" charge was 1.1 nC.

In Figures 6 and 7, the oscillations in the registering circuit induced by the discharge occurrence are clearly seen. In order to improve the quality of our results, we performed the optoelectronic registration of PD events by the photomultiplier FEU-97. Simultaneous use of three different registration methods allows us to be confident that the partial discharge in a floating bubble was indeed observed.

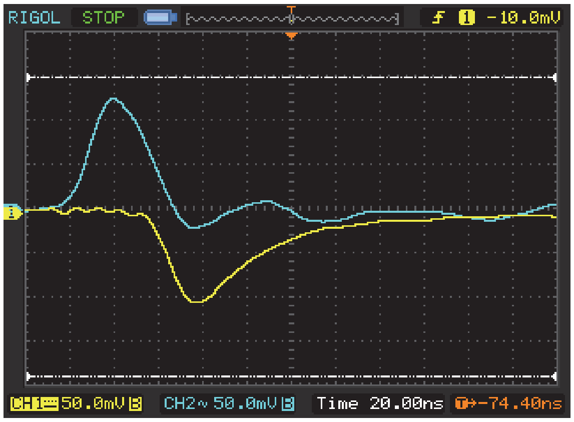

Figure 7. Oscillograms from the partial discharge in floating bubble of 1.6 mm diameter. Lower curve is the signal from the photomultiplier; upper one from the registering circuit.

4 SIMULATIONS OF PD IN A BUBBLE

4.1 SIMULATION OF ELECTRIC FIELD, TRUE CHARGES, AND APPARENT CHARGES

The computer simulations of the charge relaxation during PD in a void in dielectrics were performed in order to calculate the true and apparent charges in our experiments. The similar calculations were performed earlier in [4], but two-dimensional model was used, and the conductance of the bubble during PD was modeled with the very high dielectric permittivity of the bubble. We performed the simulation of PDs in voids in a condensed dielectrics for two- and three-dimensional formulations taking into account the conductivity of the substance in void. We used regular lattices 128×128×128 and 256×256×256, and 200×200 in the two-dimensional case. The graphic processing units (GPU) with 2880 computing cores were used for high performance parallel computations that shorten the simulation time by two orders of magnitude.

The gap between two parallel plane electrodes was filled with a dielectric layer with the dielectric permittivity 2.2. A void with the dielectric permittivity 1 was put to the gap so that the void center was located on the middle line connecting the electrodes. The potential field distribution in the gap during PD in the void was calculated using Gauss' theorem

$$\nabla \cdot (\varepsilon \nabla \varphi) = -q/\varepsilon_0, \qquad (6)$$

where φ is the electric field potential, q is the density of the electric charges. The transport of the electric charges is calculated with the continuity equation

$$\partial q/\partial t + \nabla \cdot \mathbf{j} = 0. \qquad (7)$$

Here, the density of electric current is $\mathbf{j} = \sigma \mathbf{E} = -\sigma \nabla \varphi$ and σ is the conductivity.

First, we calculated the initial distribution of the electric field in the gap, and then switched on the conductivity inside the void. It is well known from the experiments (e.g., see [5]) that the discharge can occur both in the whole volume of a cavity and in the form of conducting filaments depending on the size of the cavity. We used the model of the conductivity that was fixed in time and had the same value in all the lattice sites belonging to the void. We took the value of $\sigma = 0.0177$ Sm/cm in order to get the charge relaxation time ~ 50 ns that was observed in our experiments on PD in gas bubble in transformer oil.

The development of the electron avalanches in a bubble takes the time of the order of 10 ns while the characteristic time scale of hydrodynamics processes during PD in a bubble of size of ~ 1 mm is more than several hundreds of nanoseconds. Thus, the process of charge relaxation finishes long before the development of hydrodynamic processes due to the bubble deformation. From this point of view, the detailed model of charge relaxation is not of great importance. Therefore, we considered that the conductivity in a void providing charge transfer to the void walls arose instantly. The calculations showed that we needed the relative accuracy of the potential calculation not worse than 10^{-10} for the satisfactory calculations of the current peak shape (first derivative of the circuit charge).

The effect of the position of the spherical void with respect of the electrode on the PD current was investigated. If the cavity is at the electrode surface, the amplitude of the PD current is higher by the order of magnitude than if the cavity is inside the gap (the cavity is not in contact with the electrode surface). The reduced current of PD is presented in Figure 8. Reduced time is the time divided on Maxwellian relaxation time $\tau_M = \varepsilon_0 \cdot \varepsilon / \sigma$ and reduced current is current divided on $i_0 = U_{ph} h / \tau_M$. It gives us the possibility to scale the results of the calculations to different values of the applied voltage. The apparent charge is approximately eight times larger for the void on the electrode surface than for the void in the gap center. At the same cases, the "true" charge in the void on the electrode is only 10 percent larger the true charge in the void in the center of dielectric layer.

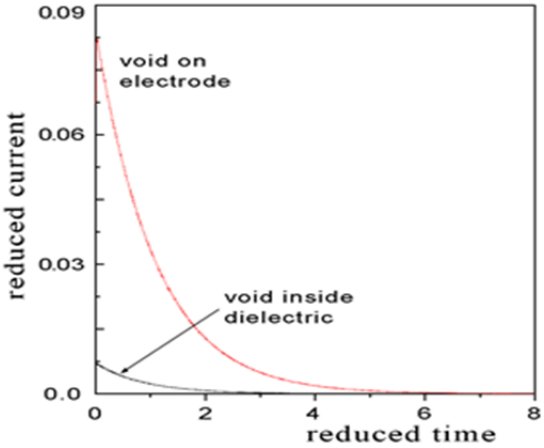

Figure 8. PD current in the circuit. Time is in units of Maxwellian relaxation time.

It is shown that the values of both the «apparent» charge and the «true» charge depend on the size of the spherical void. For the cavity in the center of the electrode gap, the increase of the radius of the void by 4 times (the void diameters changed from $0.077h$ to $0.3h$), caused the increase of the «true» charge in 17 times and the "apparent" charge in about 75 times. The current magnitude increased the same way. The results of these calculations are presented in Table 2.

Table 2. The dependence of «true» and «apparent» charges on the size of spherical cavity of the diameter d.

d, mm	0.53	0.85	1.06	1.59	2.13
Qtrue, pC	35	87.2	142.7	334.9	611.2
Qapp, pC	1.87	8.57	16.4	63.2	140.6

One can see some discrepancy in the measured and calculated values of the "apparent" charge. For the bubble of the radius about 1.6 mm, experiments gave the values from 70 to 90 pC while the calculations for spherical cavity of the diameter 1.59 mm gave about 63 pC. This difference of 25 percent cannot be considered as significant one since we cannot consider the real cavity as a sphere before PD. Moreover, it will be shown below that taking the deformation into account will result in values of the "apparent" charge closer to the experimental values.

A gas cavity in a dielectric liquid elongates under the action of the electric field stress along the electric force lines that influences the PD magnitude as the experiments show. The influence of the void deformation on the PD characteristics was investigated numerically. The cavity was approximated with the elliptical region of the lower dielectric permittivity $\varepsilon = 1$ and constant conductivity of $\sigma = 0.0177\frac{\text{Sm}}{\text{cm}}$ in a dielectric with $\varepsilon = 2.2$. The semiaxes of the ellipse were $b > a$, and the deformation coefficient was $k = b / a$. The simulations were performed for the values of k from 1 to 2 that corresponds to the different degrees of deformation observed in the experiments. The values of the true charge and the "apparent" charge change significantly with the cavity volume. Nevertheless, the value of the apparent charge reduced to the volume depends on the cavity shape only. Table 3 and Figure 9 represent the dependence of the value of the "apparent" charge due to the PD in the elliptic cavity placed to the center of the gap on the deformation coefficient k.

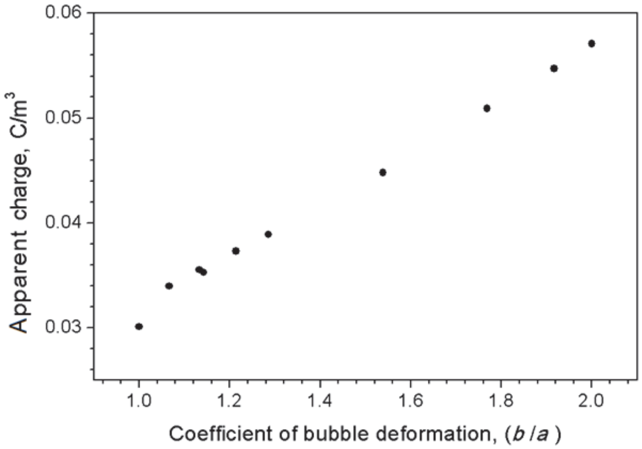

Figure 9. Values of the apparent charge vs deformation coefficient of the cavity.

Table 3. Dependence of the «apparent» charge reduced to the cavitv volume Q_{app}, mC/m^{3}on the deformation coefficient of the cavity $k = b / a$

k	1	1.1	1.13	1.2	1.3	1.54	1.77	1.92	2
Q_{app}	30	34	35	37	39	45	51	55	57

A significant deformation of a bubble under electric field k~1.5 at the moment of PD (see Figure 3, and [6] for more details) takes place. That gave us the increase of the possible value of the apparent charge by 1.5 times too in accordance with Table 3 and Figure 9. Thus, the registered "apparent" charge value in 16 measurements 80±3 pC is close to computed one ~ 90 pC. So one may conclude that the calculated values of the apparent charges are in a good agreement with the values measured in our experiments.

4.2 SIMULATION OF HYDRODYNAMIC PROCESSES AT THE PD IN A BUBBLE

The model for calculating the dynamics of a bubble in a liquid under the action of electric field was developed taking into account the electric conductivity, the advection of electric charge, and the heat released by the electric current (Joule heating). The model was based on the thermal multiphase lattice Boltzmann method (LBM) with heat and mass transfer (see [4] for the detailed description). For simplicity, it was assumed that the bubble contains pure vapor.

The electric potential was calculated by solving Poissons's Equation (1) together with the equation of charge transport

$$\partial q/\partial t + \nabla \cdot (q\mathbf{u}) + \nabla \cdot \mathbf{j} = 0 \tag{8}$$

using the time-implicit numerical scheme. Here, $\mathbf{u}$ is the fluid velocity, and the density of electric current is $\mathbf{j} = \sigma\mathbf{E} = -\sigma\nabla\varphi$. Thus, the convective charge transport was added to the equation (7) in the hydrodynamic model. The advection and diffusion of electric charge were simulated using an additional set of LBE distribution function (passive scalar transport similar to the transport of internal energy). The local rate of Joule heating $N = \mathbf{j} \cdot \mathbf{E} = \sigma E^2$is included into the heat source term in the LBM.

The Helmholtz force acting on a dielectric fluid in an electric field $\mathbf{E}$ was calculated from:

$$\mathbf{F} = q\mathbf{E} - \frac{\varepsilon_0 E^2}{2}\nabla\varepsilon + \frac{\varepsilon_0}{2}\nabla\left[E^2\rho\left(\frac{\partial\varepsilon}{\partial\rho}\right)_T\right]. \tag{9}$$

The bubble was initially placed in the center of the calculation area. Van der Waals equation of state was used for the liquid with the dimensionless temperature $T = 0.7$. The Clausius–Mossotti expression for the density dependence of the dielectric permittivity was used with the value of permittivity for the initial liquid equal to 2.2.

The size of the calculation area was 161×161×320 nodes. Boundary conditions were periodic in horizontal directions for both the flow and electric potential, and no-slip rigid walls with fixed electric potential at the top and bottom. After the initial relaxation during 10000time steps, the electric field was applied along the vertical direction. The conductivity inside the bubble was assumed constant $\sigma = \sigma_0$ when the fluid density was lower than the threshold one ($\rho < 1.1\rho_g$, ρ_g is the equilibrium density of the gas phase), otherwise the conductivity was set to zero. The dynamics of a bubble was simulated for the average non-dimensional value of electric field equal to $\langle E \rangle = 0.169$ which corresponded to the experimental value of 20 kV/cm. The electric capillary number Ca is equal to

$$\mathrm{Ca} = \frac{\varepsilon_0(\varepsilon - 1)E^2 r}{\gamma} = 10. \tag{10}$$

Here, r is the initial radius of the bubble, γ is the surface tension. Let us evaluate the energy release in a bubble during PD. For the bubble of the size about 1.6 mm, the true charge transferred with the current to the bubble walls is $Q_t = 335$ pC in accordance with Table 2. The maximal voltage drop in the bubble is $V_b = 1.7$ kV for helium bubble as was mentioned above. The work of the electric field does not exceed $W = Q_t V_b = 0.6$ μJ. Let us imagine that all this energy is released in the form of heat $W = \frac{3PV}{2T}\Delta T$, where $P = 100$ kPa is the pressure, $V = 2.15 \cdot 10^{-9}$ m^3, $T = 300$ K is the temperature. In this case, the temperature increase is $\Delta T = 0.6$ K. Thus, the Joule heating of the fluid inside the bubble is small so it was neglected in the calculations.

Figure 10 shows the distribution of the fluid density in a central plane of the bubble for three moments of time. Conductivity arises in the central part of the bubble leading to the conductive charge transport and the appearance of electric forces that stretch the bubble. Later, the accumulated charge is transferred together with the fluid to the poles of the bubble. The motion of charge also produces the electric current in outer circuit. Then electric forces acting on the accumulated charge lead to the rupture of the initial bubble into two smaller ones.

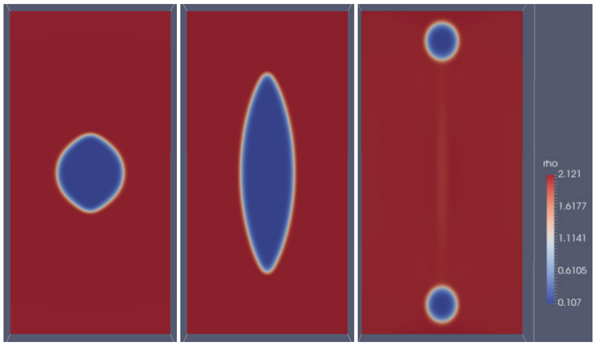

Figure 10. Distribution of fluid density in the conductive bubble. Time (left to right) t = 2 ms, 6 ms, 14 ms.

5 DISCUSSION

Comparison of the experimental data and the simulation results show that the LBM-based model can reproduce semi-quantitatively the main features of the hydrodynamics of a bubble up to the rupture after the PD. The electric field value of 20 kV/cm which produces the rupture of bubbles of the radius ~ 1 mm was close to the experimental data.

Calculated values of the apparent charge were very close to the experimental ones especially when the bubble deformation was taken into account. This indicates that a full relaxation of the electric field takes place at the PD, i.e., the bubble discharges completely in the experiments.

In order to explain deviations from the Paschen's law, we considered that the lack of initiating electrons plays significant role increasing the delay time of discharge. Indeed, Paschen's law states the conditions for a self-sustaining discharge in gases and gives the breakdown voltage provided that an initiating electron is present near the cathode. This electron produces the first avalanche. The Paschen's law thus states the necessary conditions for the breakdown of a gas gap, and the presence of an initiating electron is usually taken for granted. In our experiments, however, the problem of an initiating electron could play an important role leading to an apparent deviation from the Paschen's law.

The delay time of discharge can be defined as [7]

$$t_d = 1/(wP_0), \tag{11}$$

where P_0 is the number of initiating electrons generated in one second near the cathode, and $w$is the probability of an electron to generate an avalanche leading to the breakdown of the gap.

There are different mechanisms for the generation of primary electrons.

The most frequently, the cosmic radiation and the gamma-background from the Earth's interior are mentioned. The cosmic radiation produces 4-10 ion pairs per second in a cubic centimeter of air at the sea level [8]. Even if we set $w = 1$ in (11), the delay time of the PD inception in bubbles in a liquid or in cavities in a solid would be very large because of the small volume of such bubbles or cavities. The estimations for the delay time of the PD occurrence are given in [1]. The calculated delay time increases from 11 minutes to 178 hours if the cavity diameter decreases from 1 to 0.1 mm. The same paper shows that the delay time of PD increases dramatically when metal walls screen the outside radiation. This makes it difficult to register PDs in compact switchgears and cables.

Note that the experiments were performed in the completely screened chamber made of steel 2 mm thick, and the test laboratory is located in the basement 4 m below the ground level. It is evident that almost no outside radiation can enter the experimental cell. This can be the reason of the apparent deviation of the voltage necessary for the PD occurrence from values determined by the Paschen's law. An additional factor decreasing the probability of the PD occurrence is the small time of the rise of a bubble in the interelectrode gap (several tens of milliseconds).

In order to avoid the problem of initiating electrons, an exposition by UV or other ionizing radiation is usually used. Some manufacturers apply the x-ray exposition of the inner volume of compact switchgears during high-voltage tests [9]. This allows one to detect microcavities in insulator in which no PDs are incepted in standard test methods.

The researchers of the laser breakdown in gases also discussed the problem of the initiating electron [10]. Such breakdown incepts in very small volumes of the gas. Experimental results showed that the initiating electrons are detached from the outer electron shell of atoms under the action of electric field of the laser radiation which has the magnitude of $E \geq 10^{10}$V/m. Such strong electric fields are not present either before or during the PD.

The tunneling probability of the initiating electrons from the bulk of the dielectric can be estimated as:

$$W_e = \exp\left[\frac{-\pi^2\sqrt{2m_e}(\Delta\varepsilon)^{1,5}}{2eE\hbar}\right], \tag{12}$$

where $\Delta\varepsilon$ is the width of the band gap, e, m_e are the charge and the mass of electron, and $\hbar$ is the Planck's constant.

Substituting the typical value of the electric field into (12) and integrating the probability over the number of atoms, we can see the lack of initiating electrons necessary to explain the observed delay times of PD.

For PDs in air cavities in solid dielectrics, the mechanism was proposed in [11] for the generation of initiating electrons by the decay of negative ions. Negative ions can be generated inside the cavity under the action of radiation or by other events in pre-history of the PD process. These ions could drift in the cavity and settle at the surface where they are held by the electrostatic image forces [12].

Unfortunately, the data on the equilibrium ion density at the surface of dielectrics do not exist. At the same time, it is known that outer surfaces of insulating constructions contain water layers several molecules thick (the thickness depends on the wetting angle) and a layer of oxygen molecules [13]. We can suppose that there is also a certain amount of oxygen molecules at the surface of a cavity in dielectrics. Taking into account the electronegativity of oxygen, we can presume the existence of a certain amount of negative ions at the surface of dielectrics. These ions can provide the initiating electrons.

The decay energy of a negative ion is determined by the electron affinity that is equal to 0.4-1 eV for the oxygen, according to different sources. The decay of negative ions in air is observed at $E/P \geq 90\ \mathrm{V/(cm \cdot mmHg)}$ (for atmospheric pressure, $E/N \geq 270\ \mathrm{Td}$) [7]. At PDs in cavities smaller than 1 mm, this criterion is satisfied, and this mechanism for the generation of initial electrons is realistic.

The possibility of such mechanism was later discussed in [1] with reference to PD, and in [14] at the explanation of the mechanism of air breakdown under the action of a microwave radiation.

This could possibly influence the methods for determining the voltage of the PD inception in electric equipment. The inception of a PD is observed at the second voltage increase because PDs occurred at the first voltage increase leave behind a large number of negative ions, the decay of that provides the generation of initiating electrons necessary for the subsequent breakdown of the gas in a cavity, i.e., the PD at the next voltage increase.

It should be noted concerning the process of the PD occurrence in gas bubbles in oil that the long-time retention of negative ions at the bubble surface is not possible because the conductivity of oil is higher than that of solid dielectrics. Moreover, the action of the electrostatic image forces should lead to the injection of ions from the near-surface region of the bubble [15]. Accordingly, the above described mechanism for the generation of initiating electrons by the decay of negative ions is not operable. The mechanism of field emission is practically excluded even taking into account the tunneling.

At the same time, it is necessary for helium bubbles to analyze further the effect of the metastable excited states of helium mentioned by Bartnikas [1]. The discharge of the excitation is explained, in particular, by the Penning mechanism of discharges in a mixture of gases. It is possible to suppose that the decay of an excitation can initiate the ionization of impurities and, accordingly, the appearance of initial electrons.

6 CONCLUSIONS

The experimental investigations and the computer simulations of the PDs in floating bubbles were performed. The deformation of floating bubbles in the external electric field, PD currents, breaking of the bubbles into two bubbles after PD and subsequent secondary breakdown from the bubble wall to the electrode were registered. Numerical calculations of the PD in spherical and elliptical voids gave the values of the “apparent” charge which agree well with the experimental measurements. The simulation of the hydrodynamic evolution of the bubble after the PD demonstrated not only the bubble elongation due to the electric forces but also the breaking of the bubble into two smaller bubbles that corresponds to the experimental observations.

The rare events of PD and apparent violation of Pashen’s law is due to the absence of initiating electrons. The reason is in experimental conditions: completely screened chamber and absence of negative ions at the surface of moving bubbles.

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REFERENCES

[1] R. Bartnikas, “A Comment Concerning the Rise Times of Partial Discharge Pulses,” IEEE Trans. Dielectr. Electr. Insul, vol. 12, no.2, pp. 196–202, 2005.

[2] S. D. Lizunov and A. K. Lokhanin, *Power Transformers. Reference book*, Moscow, Energoizdat, 2004. (in Russian)

[3] Yu. P. Raizer, *Gas Discharge Physics*, Springer, Berlin, New York, 1997.

[4] A. G. Ovsyannikov, S. M. Korobeynikov and D. V. Vagin, “Simulation of Apparent and True Charges of Partial Discharges,” IEEE Trans. Dielectr. Electr. Insul, vol. 24, no. 6, pp. 3687–3693, 2017

[5] A. L. Zanin, A. W. Liehr, A. S. Moskalenko and H.-G. Purwins, “Voronoi Diagrams in Barrier Gas Discharge,” Appl. Phys. Lett, vol. 81, no. 18, pp. 3338–3340, 2002.

[6] S. M. Korobeynikov, A. V. Ridel, D. A. Medvedev, “Deformation of Bubbles in Transformer Oil at the Action of Alternating Electric Field”, European Journal of Mechanics/B Fluids, vol. 75, pp. 105–109, 2019

[7] J. M. Meek and D. Craggs, *Electrical Breakdown of Gases*, Oxford, Clarendon press, 1953.

[8] L. B. Loeb, *Fundamental Processes of Electrical Discharge in Gases,* John Wiley & Sons, 1939.

[9] H. Fuhrmann, U. Riechert, and A. Troger, “Pulsed X-ray Induced Partial Discharge Measurements - a New Testing Technique for HV Insulation” *Proc. of the CIGRE Session*, Paris, 2010. – Report D1 – 206.

[10] J. F. Ready, *Effects of High-power Laser Radiation*, Academic Press, New York – London, 1971.

[11] A. G. Ovsyannikov, “Spatio-temporal and Energy Properties of Partial Discharges in Cavities in Solid Dielectrics,” PhD theses, Siberian Research Institute of Power Engineering, Novosibirsk, 1977. (in Russian)

[12] R. M. Schaffert, *Electrophotography*, The Local Press, London – New York, 1965.

[13] D. Vajda, “*Investigation of i\Insulation Damages*,” Energia, Moscow, 1968 (in Russian).

[14] N. I. Busleev, V. L. Bychkov, L. P. Grachev, I. I. Esakov and A. A. Ravaev, “Detachment of Electrons from Atmospheric Oxygen Molecules in a High Electric Field,” Technical Physics, vol. 62, no 9, pp.1332–1336,2017.

[15] S. M. Korobeynikov, A. V. Melekhov, G. G. Furin, D. P. Agoris, and V. P. Charalambakos, “Mechanism of Surface Charge Creation Due to Image Forces,” J. Phys. D: Appl. Phys., vol. 35,no. 11, pp.1193–1196, 2002.

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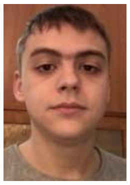

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