Possible reasons for the breakdown of transformer oil at low AC electric field strengths in the presence of bubbles

S.M. Korobeynikov, A.V. Ridel, A.G. Ovsyannikov
Novosibirsk State Technical University
Power Engineering Department
20, Karl Marx av., 630073, Novosibirsk, Russia

D.I. Karpov
Lavrentyev Institute of Hydrodynamics SB RAS
15, Lavrentyev Av., 630090, Novosibirsk, Russia

ABSTRACT

Three possible mechanisms of transformer oil breakdown, arising at low electric field strength values in the range from 1.3 kV / mm to 4 kV / mm, are presented. At higher values of the field, a rapid elongation of the bubble occurs the appearance of a streamer in it within one half-period and the streamer's transition to liquid in the bubble poles region. The bubble is divided in half at average values of the fields; the charged parts vibrate and drift towards the electrodes. Streamer forms between the electrode and the bubble when the bubble is approaching one of them. At low voltage in the presence of X-ray radiation, weak partial discharges repeatedly appear in the bubble for several periods of voltage action. The bubble is deformed, its poles sharpen, and streamers start from them. We emphasize that streamers always appear in pairs. One of them is directed towards the cathode and comes from the pole directed towards the cathode, the second towards the anode, and comes from the anode's pole.

Index Terms — transformer oil, partial discharge (PD), bubble, streamers, X-rays, bubble deformation, breakdown

1 INTRODUCTION

THE breakdown of transformer oil at alternating voltage has been engaged for more than 100 years. However, there are "dark spots" in this area. It is most exciting and essential in practice, under what conditions breakdown occurs at the lowest voltage. Usually, the breakdown strength of a thoroughly purified mineral oil is large enough and can take values in the interval from 0.4 to 1 MV/cm depending on breakdown conditions and the sort of the oil [1]. However, it is well known that the local electric field, which is necessary for the appearance of discharge processes (such as streamers) in the liquid phase leading to breakdown, is an order of magnitude higher. Experiments on the initiation of discharge in liquid dielectrics from very sharp points show that fields of the order from 4 to 11 MV/cm are necessary for the emergence of streamers in the liquid [2, 3]. This field strength for transformer oil was estimated as 15 MV/cm [4]. For many years, the hypothesis has been discussed that such extremely high fields occur during breakdown from flat electrodes due to the electrodes' roughness near the micro-edges and burrs on their surface. This paper shows that a breakdown is possible at much lower average values of the electric field in transformer oil than indicated above. It is essential in practice that the breakdown can occur in the oil insulation gaps at the lowest voltage under what conditions.

Manuscript received on xx Month 20yy, in final form xx Month 20yy, accepted xx Month 20yy. Corresponding author: S.M, Korobeynikov Korobeynikov@corp.nstu.ru

The authors are aware of accidents of a 500 kV power transformer [5]. In Fig.1, one can see the consequences of one from such accidents – the breakdown of the bushing of the leftmost phase from the adapter.

Fig. 1. Failure of a 500 kV block transformer after flashover of oil gap between bushing screen and adapter wall.

Fig. 2. The lower part of the 500 kV damaged bushing with traces of discharges on the external surface.

As it turned out during the investigation, the accident occurred due to the oil gap's breakdown from the electrostatic screen of the bushing (inner part) to the adapter's wall. The minimum distance between the so-called "reference points" of the power arc was 360 mm, and the breakdown occurred near the amplitude value of the voltage 429 kV. Thus, the longitudinal average field strength was 1.2 kV/mm at the time of breakdown! Such a low strength of the oil can be explained, for example, by the "gas content" of the oil in the volume of the adapter. It was in this place because oil samples taken from the transformer tank a few months before the accident showed entirely satisfactory physical and chemical analysis results. The source of gas formation in the adapter could be surface discharges, which left carbonized tracks on the lower part of the bushing (Fig. 2). The cause of discharges is beyond the scope of this research topic. However, it does not seem to require proof that discharge processes on the bushing surface led to the formation of bubbles, and partial discharges in the bubbles led to the flashover of the oil gap between the screen and adapter wall followed by the ignition of the power arc.

Usually, the electrical strength of pure, dry, and degassed mineral oil is 30 kV/mm approximately. It is known that a decrease in electrical strength occurs when the oil is contaminated with particles of mechanical impurities (both conducting and dielectric) and under humidification. The electrical strength also decreases when vapor-gas bubbles are formed for one reason or another. That is why great attention is paid to degassing the oil before filling it into the equipment and protecting the oil from contact with atmospheric air during operation.

This paper discusses the physical mechanism of the formation of streamer breakdown of oil initiated by helium bubbles at the lowest electric field strengths.

2 EXPERIMENTAL SETUP

The experimental setup used in this study was described in detail earlier [6, 7]. It consisted of a high-voltage transformer, a high-speed video camera, and an experimental cell (figure 3). The interelectrode gap in all experiments is equal to 6.8 mm. The experimental cell was filled with oil grade "VG". The alternating voltage is applied to plane electrodes. Helium was fed into the experimental cell through a medical syringe mounted in the lower part of the cell. It performs to create a regular sequence of almost identical bubbles moving vertically at the same distance from each other in the absence of discharge phenomena. Bubbles floated up in the oil in the space between the electrodes. The diameter of the bubbles is 1.5 mm. The flow rate of the bubbles is the same and equal to about 12 cm/s. The camera made video recordings of processes occurring in the interelectrode gap with a recording speed of 1200 fps.

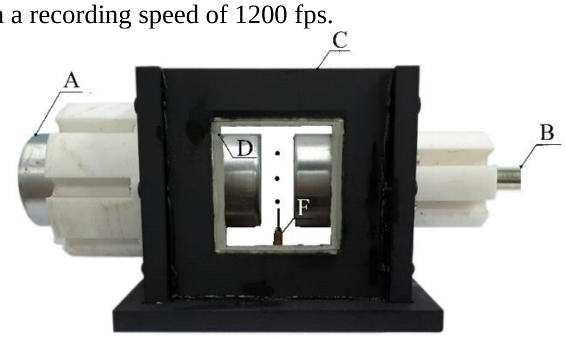
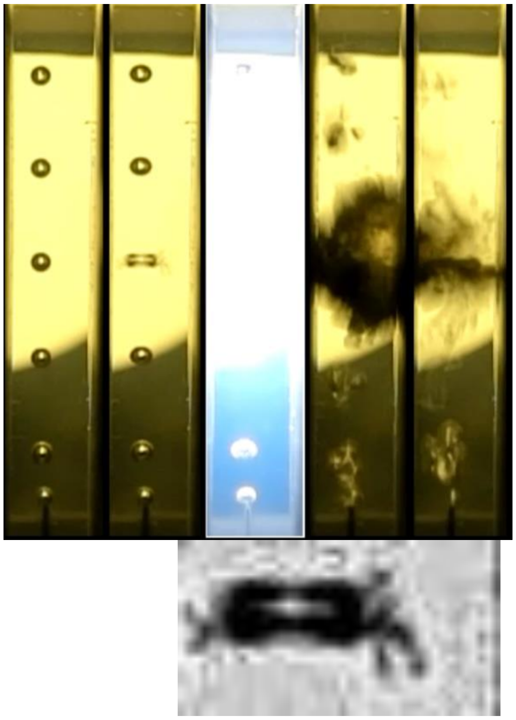


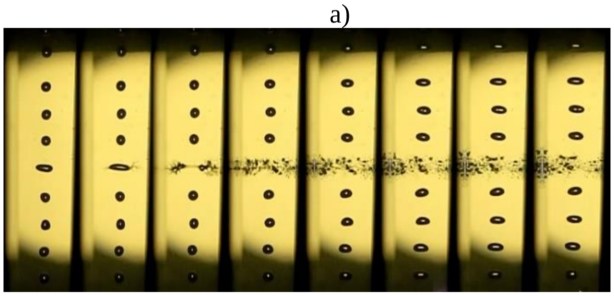
Fig. 3. Experimental cell.

3 EXPERIMENTAL RESULTS

1. When the AC voltage was switched on immediately, the following picture was observed. If the average field E_{CR} at the amplitude voltage reached a 4 kV / mm value, a partial discharge might occur in the gas bubble (figure 4). There was an elongation of the bubble along the electric field about two times its initial size (figure 4a). In many cases, the bubble was torn by Coulomb electric forces into two or smaller bubbles. Nevertheless, in some cases, instead of bubble division, we observed the development of streamers in the oil from the interface of the deformed bubble and liquid (figure 4 a, second frame). Development of streamers from the surface of the bubble deep into the oil sometimes ended with the breakdown of the oil layer between the bubble and the electrode (figure 4 a, third and subsequent frames). By the time, the entire process, starting from the moment of PD in the bubble, took about two milliseconds.



a)



b)

Fig. 4. Streamers formation from the bubble-oil interface of elongated bubble: a) E = 4.4 kV/mm (separately - enlarged fragment of streamer formation); b) E = 5.1 kV/mm. In the latter case, a thin dielectric barrier was installed at one electrode for breakdown prevention.

Fig. 5 shows enlarged frames from Fig. 4, where the formation of streamer from ~~electrode~~ bubble surface to the liquid phase is seen clearly. The contrast of the picture was enhanced, allowing us to reveal the streamers' structure (left). Streamers started from **both** poles of the bubble. Then the shapes of the streamers became more developed as the bubble disintegrated (right). The time interval between the frames was 0.833 ms.

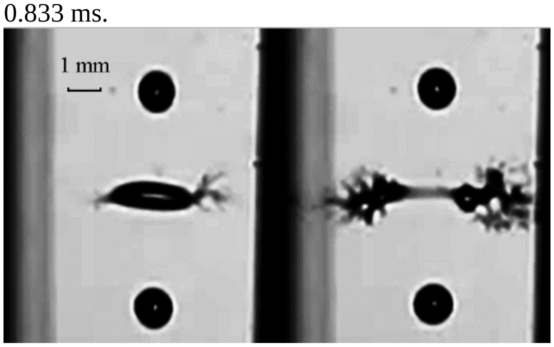


Fig. 5. The spatial structure of the streamer started from the bubble—enlarged frames from Fig. 4.

It should be noted that streamer formation from the bubble surface was observed in our experiments using carbon nanotubes in transformer oil [8]. The experiments were performed for an extremely low level of natural radiation at the deficiency of ionization events that can initiate the breakdown in gas bubbles. Fig. 6 shows two subsequent frames (with the time interval of 0.833 ms between them) where the moment of initiation of streamer in liquid (top) and the structure of developing streamer (bottom) are shown. It is seen that the bubble deformed significantly after PD in it. The bubble's size along the electric field increased two times concerning its initial size before the streamer started. Streamer branching in transformer oil was also observed. The critical difference of the process in Fig. 6 from that in Fig. 5 is the influence of agglomerated carbon nanotubes having the shape of filaments oriented along electric force lines (dark gray elongated regions from the left of the bubble in Fig. 6). It was suggested in [8] that these carbon filaments became the sources of electrons that produce PD in the floating bubbles. Another difference is the streamer's appearance from only one pole of the bubble opposite to the nanotube agglomerate location.

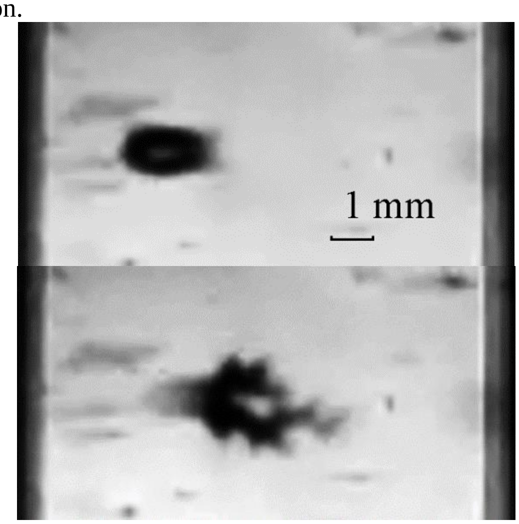


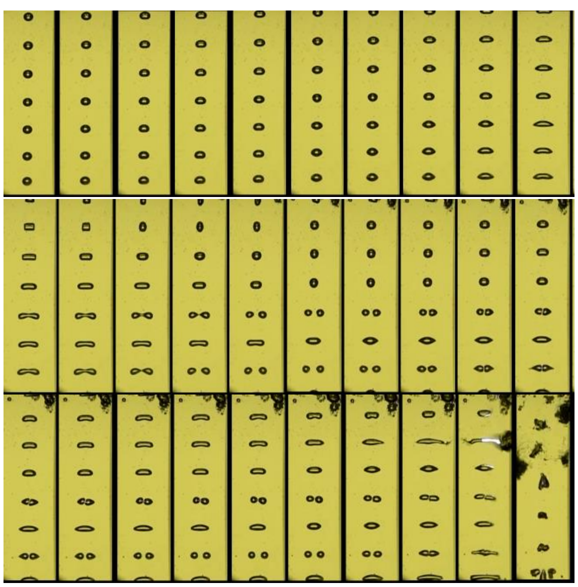
Fig. 6. Streamer formation from the bubble surface after PD in the bubble. Transformer oil contains carbon nanotubes [8].

2. With a gradual voltage increase, the PD in the bubbles were recorded at lower average values of the field strength, at 2.4 kV/mm < E_{CR} < 4 kV/mm. In some cases, there was also a breakdown in the electrical insulation gap. Video recording of the process is shown in figure 7. It can be seen that after the necessary voltage was established, a partial discharge developed in one of the floating up bubbles. It is indicated by the deformation of the bubble along the electric field's direction (figure 7, fourth and fifth frames). The bubble began to lengthen rapidly (figure 7, sixth and following frames), which is why it split into two smaller bubbles. They begin to move towards the electrodes. Near the electrode, there was a breakdown between one of the bubbles and the electrode, which then passed into the gap breakdown. The process took eight milliseconds, starting from the PD in the bubble.

Fig. 7. Bubble dividing and following breakdown between bubble and electrode at E=3.3 kV/mm.

An estimate of the growth rate can be made using considerations similar to the explanation of electrohydrodynamic flows, namely, converting a part of electrical energy into hydrodynamic energy. Then the deformation time will be several milliseconds.

3. In [6], it was shown that under conditions of the low radiation background, PD in floating up bubbles almost did not occur, even if the voltage drop on the bubbles noticeably exceeded the voltage level of the gas discharge, according to Paschen's law. In the case of exposure to X-ray radiation with a gradual increase in voltage amplitude, the breakdown occurs at the lowest field values close to those defined by Pashen's law. The X-ray radiation-initiated PD in the bubbles at amplitude values of the field strength in the range $1.3 < E_{CR} < 2$ kV/mm. Sometimes it was found that at the specified electric field strengths, an electrical insulation gap was broken. Unfortunately, the PD's electrical signal was not recorded because of the powerful high-frequency noise when the pulsed X-ray unit was triggered. The occurrence of PD after the X-ray pulse was registered by the elongation of the bubble along the electric field (figure 8). After the first PD, the deformation was small. Further, when the polarity of external voltage was changed, a repeated partial discharge occurred in the deformed bubble (in reality, up to 5 consecutive partial discharges were registered in one bubble). The bubble elongated after each PD.



Fig, 8. Multiple PDs in bubbles when exposed to X-ray at E =1.4 kV/mm.

It is evidenced by the sharply increasing deformation of the bubble along the electric field's direction (figure 8). After the next PD (figure 8, 27-29 frames, second row), streamers began to develop from the bubble's poles into the transformer oil (before the penultimate frame). It should also be noted that the bubble at the same time near the poles had a conical shape and the angle of the cone decreased with each subsequent PD.

Common to all three cases was the occurrence of a breakdown at relatively low electric field strength.

4 DISCUSSION

Typically, the breakdown mechanism is determined by three key stages: the ignition of the discharge leading to the appearance of a streamer in the liquid, the stage of development of the streamer from the nucleation site to the opposite electrode, and the stage of breakdown along the streamer channel. A partial discharge provided the ignition of the discharge in our experiments in the bubble. However, the second stage could be different. For a streamer to appear in a liquid, as indicated above, a field strength of about 10 MV/cm is required. We assume that three possible mechanisms for a breakdown of transformer oil occur at low average electric field strengths in the range of $1.3 < E_{CR} < 5$ kV / mm.

4.1. ELECTRIC FIELD ≥4 KV/MM.

In this case, the bubble was lengthened. We are judging by frames 1 and 2 in Figs. 4a and b, the bubble length was doubled in approximately the duration of one frame, i.e., in 1 ms. It means a growth rate not less than 1.5 m/s. In our opinion, the conditions for the development of streamers in oil with the voltage switching on by a push were achieved because a streamer initially developed in the gas phase in the bubble. Clear, the appearance of the streamer in the gas phase begins with the development of electronic avalanches. In [9], it was shown that when the condition $\alpha x d \geq 20$ is fulfilled, electronic avalanches are converted to a streamer, that is, the local electric field at the avalanche front exceeds the average initial field in the gas, and the field determines the further development of ionization at the top of the streamer. Here α is the ionization coefficient, and **d** is the size of the bubble along the electric field strength line. In our case, this condition is held. The streamer's growth inside the bubble is accompanied by a significant redistribution of the field strength because the charge density at the streamer's tip is very high. Due to this, conditions were created at the boundary of the bubble, under which the tip of the streamer in it becomes similar in its role to a sharp electrode during a breakdown in a sharply inhomogeneous field. It is well known that the field strength at the tip can be hundreds of times higher than the average field in the interelectrode gap. Let us estimate the streamer radius r_d in terms of the avalanche radius (Table 1). Here the estimation of the shock ionization coefficient is taken from [10-, 12].

Table. 1

E_{CR}, kV/mm	α, 1/m	αd	r_d, μm	
1	8000	12	126	
2	40000	63	89	
3	100000	160	73	
4	200000	300	63	
5	350000	500	56	

The streamer's radius should be smaller, in our opinion; it should approximately remain the same as reached by the time of the avalanche-streamer transition. Then, in table 1, the dimensions will be adjusted according to the expression [13,14]

$$r_d=\sqrt{\frac{8U_T x}{3eE}} \quad (1)$$

If we take the distance x when the avalanche-streamer transition is reached, then at a field strength of 4 kV / mm, the radius will be 20-255 μm, and at E = 5 kV / mm it will be 15-20 μm.

Suppose we assume that the streamer's electrical conductivity is high so that its entire body has approximately the same potential. In that case, the field strength at the ends of the streamer will be high enough to transform the "gas" streamer into a "liquid" streamer when it touches the bubble wall.

Another mechanism for streamers' appearance in a liquid after PD in a bubble was proposed in [15]. It is believed that after the discharge in the bubble that touches the positive electrode, protrusions appear on its surface facing the cathode, near which the field is amplified. The field amplification factor k taken from the paper [16] is expressed as k= $(2+L/r_p)$. Here L is bubble length, r_p is protrusion radius.

4.2. ELECTRIC FIELD ≥1.3 KV/MM.

Analysis of the data presented in the table allows us to draw some conclusions. At low intensity, a multi-avalanche Pashen’s discharge is realized. In this case, a charge is uniformly deposited on the bubble walls; its field leads to the extinction of the partial discharge. The Coulomb force's action on this charge distributed on the bubble-liquid interface leads to the bubble's deformation. Let us underline that X-rays were used in these experiments since, in their absence PDs were absent. X-rays interacting with helium atoms released free electrons. To clarify the picture, Fig. 8, we emphasize that initiating electrons can appear in any part of the bubble. Therefore, primary electron avalanches, which began not on the cathode part of the bubble, do not have time and distance to develop and pass into the self-discharge mode. When the voltage polarity was changed (polarity reversal), the direction of the external field coincided with the direction of the intrinsic field of charges on the bubble walls; thus, the field strength inside the bubble increased. It led to a more effective repeated PD and a more significant deformation of the bubble. This pattern can be repeated several times, as a result of which the condition of the appearance of a streamer in the gas phase, which can escape into the liquid, can be realized. The exit mechanism, in our opinion, is associated with instability and the formation of the so-called Taylor cone. The bubble does not break, and streamers develop from its tips.

4.3. E>2.4 KV/MM.

At higher field strength, PD in the bubble immediately appears in the form of a streamer. However, the streamer's radius is large enough, and a rather large charge is deposited on the surface of the bubble, comparable to the radius of the bubble. The field amplification in the liquid is insignificant, allowing the streamer to move directly into the liquid. Under Coulomb forces' action, the bubble begins to elongate at high speed (~0.2-0.3 m/c). The elongation rate does not contradict the electrohydrodynamic mechanism [17]. Due to fast elongation, after reaching the limiting values $\Delta\sim 2$ of deformation, it breaks into two smaller but charged bubbles, which, under electrical forces, move to the electrodes having the opposite charge.

Let us estimate the charge of each of the bubbles. It can be roughly assumed that the charge Q is approximately equal to $Q\sim 2\pi r^2 E\varepsilon\varepsilon_0$, E is the external field or a little more than this one. Then, assuming the bubble is round, the field of this charge will be approximately E/2, i.e., less than or approximately equal to the external field.

When the polarity changes, bubble movement changes its direction, bubbles come closer, diverge again, and so on. When approaching one of the electrodes, the local electric field strength between the charged bubble and the electrode sharply increases. Two factors contribute to this. The first one is the appearance of the action of the forces of the image. In this case, the electric field between the charged bubble and the electrode approximately doubles.

Moreover, the second factor is that the bubble significantly changed its shape. Under the enhanced nonuniform field's action, a sharp cone-like tip appeared on the side directed to the electrode. As a result, the electric field reaches values that form the conditions for the breakdown of the gap between the bubble and the electrode, followed by the total breakdown of the insulating gap (Figure 8). Let us note that the formation of cone-like type poles of the bubble in an external electric field is confirmed with the numerical simulations of electrohydrodynamic processes in the system of conducting bubble between plane electrodes [18].

4.4. STREAMER FIELD ESTIMATIONS.

Let us look at the development of streamers. As can be seen from Fig. 4 (bottom image, second frame), there are always two streamers from different ends of the bubble. Why isn't a single streamer from the bubble registered? The fact is that when the streamer moves, a charge accumulates on its "tail," which reduces the field strength in the streamer and reduces the intensity of ionization processes, which stops the formation of the streamer. However, if both streamers arise and develop, then one streamer's growth contributes to the second streamer's growth because the current in both streamers is the same. Considering the images of streamers, one can make some more conclusions. Usually, a streamer generated at the cathode and propagating to the anode grows at a subsonic speed and has an opaque bush's shape [11]. The streamer generated at the anode and directed to the cathode has a filamentous structure and develops faster.

It can be assumed that the discharge from the cathode at such low fields develops in the form of electrohydrodynamic (EHD) instability [16]. Then the estimation of EHD mobility for transformer oil will give a value of about 0.5 10^{-7} m^2/sV, and the value of the flow velocity will be about 0.2 m/s for the average field of 4 MV/m. If we assume about ten times the field gain in streamer formation, the speed will be two m/s. During the voltage action for 2-5 ms, the distance covered will be 4-10 mm. It is approximately the length of the streamer.

The formation of a streamer in a liquid dielectric from the bubble surface after PD is an unusual and inexplicable fact. When considering the possibility of a streamer's appearance in a single bubble that does not touch the electrode, both a cathode-directed streamer and an anode-directed streamer should be considered simultaneously. Since they can only form simultaneously, the conditions for formation must also be considered simultaneously.

The situation with formation, in our opinion, is more straightforward with an anode-directed streamer (usual cathode streamer). Here, the negative charge of electrons that move in front of the streamer when touching the bubble's surface is inevitably captured by oil molecules, forming a surface charge. A charged surface is unstable in an electric field. It leads to the formation, movement of a plurality of protrusions of the charged surface. It is the slow subsonic cathode streamer.

As long as the developing streamer is fed with current, it will continue to move, even in a relatively weak field. However, for the formation of a cathode-directed (anode) streamer, more high fields are required. They can be created by the ions remaining in the streamer's ion track, spreading towards the cathode when it touches the bubble wall. The diffusion and mobility of ions determine the ion tail's lateral size; accordingly, the streamer's width at the cathode wall of the bubble should be much less than the width of the streamer defined above. It means that the anode streamer can create a field sufficient to initiate the streamer in the liquid when it touches the bubble surface. It is known that the initiation and development of anode filamentary streamers in a liquid requires local electric fields of the strength of several MV/cm. If the electric charge is distributed over the all bubble-oil interface, the field magnitude is significantly smaller than this value. That is why we suppose that partial discharge in the gaseous bubble can be in the streamer form. In this case, the electric charge will be transported to the interface in the streamer channels.

Moreover, it will be deposited on it within the diameters' spots comparable in size to the channel diameters. Let us consider the following model of the streamer channel in the bubble. As a first approximation, we neglect the above considerations about the streamer width in its cathode-directed part. The streamer channel is approximated with an ellipsoid of revolution, as shown in Fig. 9. Thus, we consider a well-conducting (plasma) ellipsoidal region inside the elongated gas bubble.

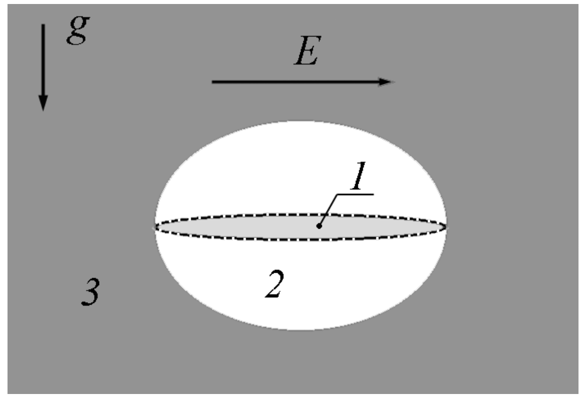


Fig. 9. Model for calculation of the field on the bubble-oil interface. *1* – conducting channel of a gas streamer, *2* – bubble, *3* – transformer oil.

We can evaluate the field at the top of the streamer in different ways. The field at the top of the streamer is mainly determined by the curvature of the top's surface. In [6,7], the field at the pole of an elliptical conducting bubble was calculated depending on the degree of its deformation. This field can be estimated as

$$E_{max} = \frac{E_0 (1-\lambda^2)^{3/2}}{\lambda^2 \left(\ln(1+\sqrt{1-\lambda^2}) - \ln \lambda - \sqrt{1-\lambda^2} \right)} \quad . \quad (2)$$

Here $\lambda = a/b$ is the ratio of the minor a and major b semiaxes of the ellipsoid, E_0 the average electric field in the gap. Fig. 10 shows the field's calculation at the pole of the ellipsoid depending on the radius of curvature of the surface near the pole (blue curve) according to (1). The radius of curvature is related to the streamer length as $R = b\lambda^2$. In fig. 10, we can see that with a streamer head radius of fewer than ten μm, the field at the apex exceeds several MV/cm, which may be sufficient to develop a streamer in transformer oil. A streamer released from the gas to the bubble-liquid interface supplies a noticeable amount of free electrons, which contributes to the development of liquid heating and ionization of liquid molecules.

It can be seen that, at low curvature, expression (2) gives values of the field strength close to the estimates of the field at the top of a sharp electrode during a breakdown in liquid hydrocarbons [3,16].

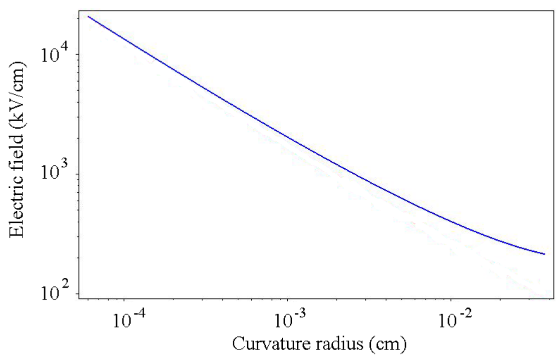


Fig. 10. The field at the top of the streamer in a gas bubble, depending on the top's radius of curvature, is calculated by (2).

Thus, we see that if a streamer in a gas bubble has a head curvature radius of ~ 1-10 µm, this is sufficient to initiate an anode streamer in a liquid medium.

Returning to the power transformer's emergency failure, described at the beginning of the paper, we add the following explanation. Although the composition of gases in bubbles was undoubtedly different in a real case, the point of comparison with helium bubbles was to demonstrate the role of PDs in bubbles as initiators of streamer formation and oil breakdown. Any bubbles, provided that PDs appear in them, are a trigger for the breakdown of small gaps of the insulating liquid, and for large gaps in the presence of a large number of bubbles, a chain mechanism of electric breakdown development may well be realized [1].

5 CONCLUSION

Bubbles are triggers of a breakdown in liquids at AC action too. Experiments show that at low electric field values of the order of 1 kV/mm, bubbles can promote the formation of streamers in a liquid. In this case, the streamer consists of two semi-streamers: cathode-directed streamer and anode-directed streamer, which develop simultaneously. The anodic streamer mechanism appears to be similar to the conventional subsonic cathode streamer mechanism. A cathode-directed streamer, in our opinion, is similar to the mechanism of a conventional anode streamer.

ACKNOWLEDGMENT

RFBR, project number 19-38-90054 funded the experimental part of the reported study

REFERENCES

[1] A. L Kupershtokh. et al, “Stochastic model of breakdown initiation in dielectric liquids”, J. Phys. D: Appl. Phys. 2002. Vol. 35, No. 23. P. 3106–3121.

[2] A. Denat “High field conduction and prebreakdown phenomena in dielectric liquids” IEEE Transactions on Dielectrics and Electrical Insulation (Volume: 13 , Issue: 3 , June 2006 Page(s): 518 – 525

[3] Kattan, A. Denat and K. Bonifaci “Formation of vapor bubbles in non polar liquids initiated by current pulses”, CNRS. Laboratoire d'Electrostatique et de Materiaux Dielectrique BP 166X-38042 GRENOBLE Cedex (France) ICDL 1990, Conference Record, P.340-345.

[4] A.L. Bychkov et al, “Partial Discharges Registration in Transformer Oil at the ‘Point-Plane’ Electrode System” Applied Mechanics and Materials Vol. 698 (2015) pp 615-620.

[5] O. Yu. Shiller et al, “Overvoltage during switching of a block transformer 500 kV with an SF6 circuit // Electro,№6, pp.24-27, 2010 (in Russian) .

[6] Korobeynikov S.M.et al, “Mechanism of partial discharges in free helium bubbles in transformer oil IEEE Transactions on Dielectrics and Electrical Insulation 2019. - Vol. 26, iss. 5. - P. 1605-1611

[7] S.M. Korobeyikov et al, "Study of partial discharges in liquids", J. Electrostat., vol. 103, pp. 103412, 2020.

[8] S.M. Korobeynikov et al, "Intensification of electrohydrodynamic flows using carbon nanotubes", Journal of Physics: Conference Series (in press), 2020.

[9] Montijn, U. Ebert, “Diffusion correction to the Raether–Meek criterion for the avalanche-to-streamer transition”, Journ. of Phys. D: Applied Physics, 2006, vol. 39, no. 14, p.2979.

[10]. D. K. Davies, F. L. Jones, C. G. Morgan “Primary ionization coefficient of helium“// Proc. Phys. Soc. – 1962. – V. 80. – P. 898–908.

[11] J. Ran, H. Luo, Y. Yue, X. Wang “Measurement of the first Townsend’s ionization coefficients in helium, air, and nitrogen at atmospheric pressure “// J. Phys. Soc. of Japan. – 2014. – V.83. – P. 074503.

[12] S. M. Korobeynikov etr al, “Partial discharges in free helium bubbles in transformer oil“ IEEE international conference on high voltage engineering and application : sum. book of ICHVE 2018, Greece, Athens, 10–13 Sept. 2018. – New York : IEEE, 2018. – 3

[13] Gas discharge physics YP Raizer : Berlin, Springer: 1991 pp.: 449.

[14] S.M. Korobeinikov, A.V. Melekhov, A.S. Besov, “Breakdown initiation in water with the aid of bubbles “ High Temperature, 2002. T. 40. № 5. C. 652-659.

[15] Yongze Zhang et al “Role of Air Bubbles in the Breakdown of Flowing Transformer Oil“ IEEE Transactions on Dielectrics and Electrical Insulation V 27, N 5, Oct. 2020, pp. 1752 - 1760

[16] T. V. Top and A. Lesaint, “Streamer initiation in mineral oil. Part II: influence of a metallic protrusion on a flat electrode,” IEEE Trans. Dielectr. Electr. Insul., vol. 9, no. 1, pp. 92-96, Feb. 2002

[17] S. M. Korobeynikov et al “Optical Study of Prebreakdown Cathode Processes in Deionized Water“ IEEE Transactions on Dielectrics and Electrical Insulation, vol.16, Issue 2, pp. 504-508, April 2009

[18] D.A. Medvedev, A.L. Kupershtokh, A.A. Bukovets, “Dynamics of bubble in dielectric liquid in electric field: mesoscopic simulation”, 19th IEEE International Conference on Dielectric Liquids (ICDL), Manchester, United Kingdom, 25 – 29 June, 2017, P. 1305(1-4).