МИНИСТЕРСТВО ОБРАЗОВАНИЯ РОССИЙСКОЙ ФЕДЕРАЦИИ

АДМИНИСТРАЦИЯ КРАСНОЯРСКОГО КРАЯ

НАУЧНО-ИССЛЕДОВАТЕЛЬСКИЙ ФИЗИКО-ТЕХНИЧЕСКИЙ ИНСТИТУТ КРАСНОЯРСКОГО ГОСУДАРСТВЕННОГО УНИВЕРСИТЕТА МИНИСТЕРСТВА ОБРАЗОВАНИЯ РОССИЙСКОЙ ФЕДЕРАЦИИ

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DYNAMIC ELECTRIC STRENGTH OF PERFLUORODIBUTYL ETHER*

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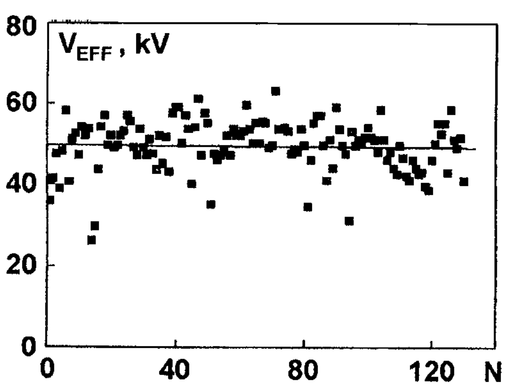
Perfluorocarbon liquids are well known as good dielectrics with high resistance and electric strength. Besides, they have very small viscosity and high density. The most important features are their chemical inactivity and incombustibility. Considered together, these properties make perfluorocarbon liquids very perspective for industrial application in the high-voltage equipment.

It is assumed that ability of a dielectric to maintain the dielectric properties in strong electric fields is characterized by its electric strength. However, it is well known, that average value of electric field, at which breakdown of a dielectric occurs, also depends on specific experimental conditions such as the form and the sizes of electrodes, distance between them, magnitude and the form of applied voltage, etc [1, 2]. Therefore, the classical concept about fixed "electric strength" loses sense. Instead of this, the concept of "dynamic electric strength" of dielectrics that depends on the specific conditions listed above was introduced. A particular case of concept of dynamic electric strength is well known time-voltage curves. Researches of late years showed that the probability of breakdown initiation in some local area of dielectric should depends only on magnitude of local electric field in this area and properties of the substance, provided that pressure and temperature are constant during experiment. These features of breakdown phenomenon allowed describing dynamic electric strength of specific dielectric quantitatively, taking into account essentially stochastic nature of breakdown.

Experiments. The experiments on breakdown in the perfluorodibutyl ether (PFDBE) CF_3-$(CF_2)_3$-O-$(CF_2)_3$-CF_3 were carried out. The liquid was previously boiled for degassing over a period of 1 to 2 hours at the temperature 101°C with a returning cooler to prevent boiling out of liquid. Then the liquid was filtered. High AC voltage of frequency 50 Hz of linearly increasing amplitude was supplied with the standard generator AIM-80 designed for



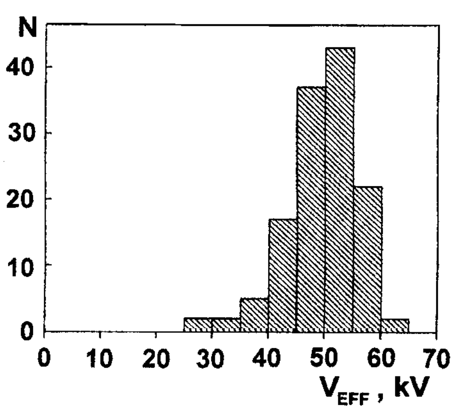


Fig. 1. Typical series of breakdowns in perfluorodibutyl ether under AC voltage of linearly increasing amplitude. Brass electrodes of radius R = 40 mm were used. Gap between them was d = 1.7 mm.

determination of the electrical breakdown strength of liquids in accordance with GOST 6581–66. The effective value of the voltage increased with a constant rate $k_e = 2$ kV/s. In experiments, the current effective value of voltage V_{EFF} at which breakdown of a dielectric occurred was registered (fig. 1). The surfaces of hemispherical electrodes were polished

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before each series of experiments (approximately 100 breakdowns in each series). The results of experiments are given in Table 1.

Table 1.

d, mm	R, mm	N_0	$<V_{EFF}>$, kV	$<E_0>$, kV/cm	V^*_{EFF}, kV	E^*_0, kV/cm
Stainless steel electrodes						
0.44	30	71	26.9	865	28.0	900
0.9	30	101	41.2	650	43.5	687
1.7	30	115	50.5	420	54.5	456
2.5	30	120	70.8	400	75.0	424
Brass electrodes						
0.44	40	161	20.3	652	23.0	740
0.9	40	135	37.7	592	42.0	660
1.7	40	130	49.4	413	52.0	435
2.5	40	80	73.4	415	77.0	436

Table 2.

d, mm	R, mm	k_e, kV/s	N_0	$<V_{EFF}>$, kV	$<E_0>$, kV/cm	V^*_{EFF}, kV	E^*_0, kV/cm
2.5	19	0.5	60	50.6	286	53	300
2.5	19	1	60	55.5	314	58	328
2.5	19	3	60	64.0	362	71	402
0.5	19	0.5	48	20.5	580	21.5	608
0.5	19	1	50	22.4	634	24	680
0.5	19	3	50	23.8	673	25	707

Here R is the radius of a surface of electrodes, d is the distance between them, N_0 is the number of breakdowns, V^*_{EFF} is the effective value of a voltage at which in a series of experiments breakdown occurred with the probability $P_+(t) = 0.63$, E^*_0 is the corresponding amplitude value of an average electric field along an axis between electrodes.

For comparison, the experiments on breakdown in synthetic transformer oil "TECHNOL 2002 (ISO 9001)" were carried out. A new pair of polished spherical stainless steel electrodes was used in each series of experiments. High voltage tests were carried out using "Baur A-6832". Value k_e was switched over after each breakdown. Thus, three data sets were obtained in one series of experiments under identical conditions (Table 2).

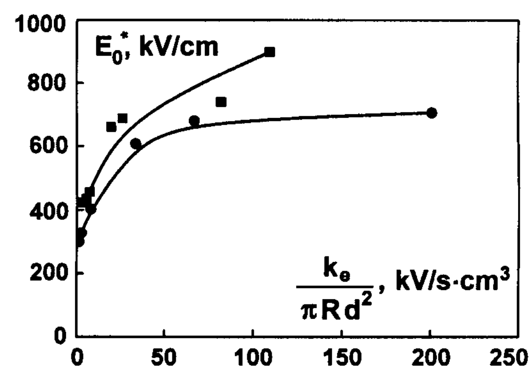

Fig. 2. Dependence E^*_0 on parameter b. (■) perfluorodibutyl ether, (●) transformer oil.

Reconstruction of probability density μ(*E*) from experimental data. In stochastic approach offered earlier in [3-6], macroscopic function $\mu(E)$ was introduced which depends on local electric field. The function $\mu(E)$ has physical sense of probability density of breakdown initiation on a small element of electrode surface in a short interval of time. The probability of breakdown inception in time t is equal to $P_+(t) = 1 - \exp(-H)$, where value of integral of electric field action changes in time is $H(t) = \int_0^t \left(\int_S \mu(E)\, ds \right) dt$. For example,

$$H(t) = S \int_0^t \mu(E)\, dt$$ for flat electrodes.

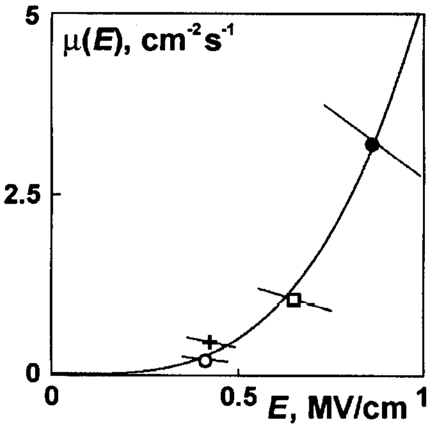

Fig. 3. Reconstructed values of function μ(E) for perfluorodibutyl ether. Gaps between hemispherical stainless steel electrodes were d = 0.044, 0.09, 0.17 and 0.25 cm. Radius of surface was R = 30 mm.

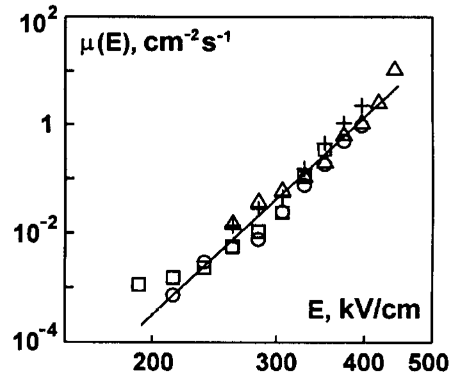

Fig. 4. Reconstructed values of function μ(E) for transformer oil. Pairs of flat brass electrodes of area S = 1.54 (Δ), 4.9 (+), 15 (o), 29 (□) cm^2 were used at d = 0.19 cm. Effective value of the applied AC voltage of frequency 60 Hz increased with constant rate k_e = 3 kV/s. N_0 = 400 for each pair of electrodes.

In case of power-law approximation for μ(E), several explicit analytical expressions for determination of values of μ(E) were obtained. For example, for hemispherical electrodes at small gap length d:

$$\mu(<E_0>)\frac{F(n)}{n-1}=\frac{\sqrt{2}\,k_e}{\pi d^2 R<E_0>} \quad \text{where function } F(n)=\frac{\int_0^{\pi}\sin^n(z)\,dz}{\pi(n+1)\,\Gamma\left(\frac{n+2}{n+1}\right)^{n+1}}$$

depends only on an exponent n in the approximation of μ(E). Here $<E_0>$ is the average value of electric field of breakdown. It is interesting, that the electric strength depends only on parameter $b=k_e/(\pi R d^2)$ in this case. The experimental data obtained for PFDBE and transformer oil are given in the figure 2.

It is possible to obtain the values of parameters of the approximation of function μ(E) using several series of experiments at different values of parameters R, d and k_e. The values of μ(E) for PFDBE are given in the figures 3 and 5 (straight line 1).

When large set of data on breakdowns in each series of experiments (N_0 >> 100) is available, it is possible to reconstruct values of μ(E) using the histograms of breakdown voltages measured in experiments. The experimental data of Weber and Endicott [2] on breakdown in transformer oil were processed using this approach (fig. 4, curve 4).

However, power-law approximation of function μ(E) gives too weak dependence on an electric field. The approximation in the form

$$\mu = AE^2\exp(E/g) \qquad (1)$$

is sharper and describes the histograms of

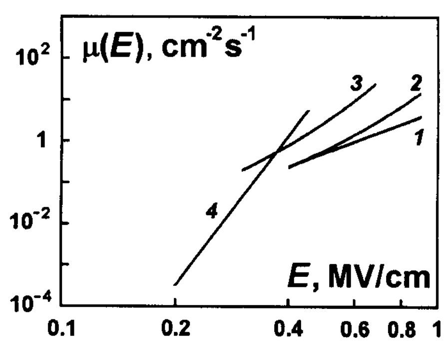

Fig. 5. Values of function μ(E) reconstructed from experiment. Curve *1* is the power-law dependence for perfluorodibutyl ether. Curves *2* and *3* are approximations in form (1) for perfluorodibutyl ether and transformer oil respectively. Straight line *4* is the function μ(E) reconstructed for transformer oil from the data of [2].

breakdown voltages and breakdown pitting on a surface of hemispherical electrodes better. Dynamic electric strength of PFDBE became higher than for transformer oil (fig. 2, fig. 5), provided that it was carefully cleared and degassed.

Modelling of stochastic properties of breakdown. The approach proposed describes stochastic nature of breakdown inception that is necessary to take into account at designing electrotechnical devices in which dielectric liquids are used. For example, a series of values of breakdown voltage V_{EFF} in PFDBE (fig. 6) was obtained in computer simulation. The distribution of places of breakdown inception on the electrode surface is shown in the figure 7.

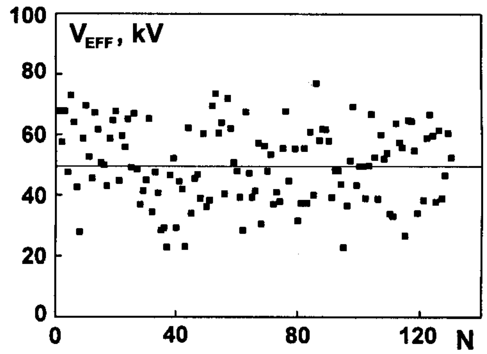

Fig. 6. Effective values of breakdown voltage V_{EFF} obtained in computer simulation of a series of breakdowns in perfluorodibutyl ether under AC voltage of linearly increasing amplitude. Brass electrodes of radius R = 40 mm. d = 1.7 mm. k_e = 2 kV/cm. N_0 = 130.

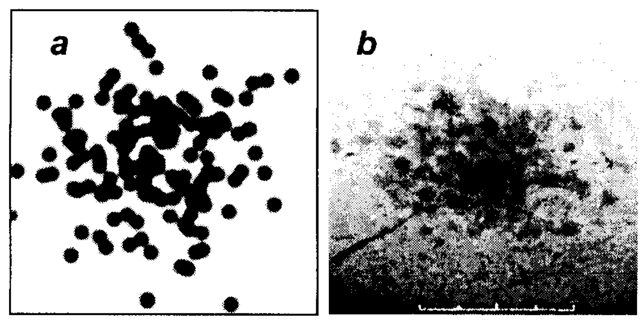

Fig. 7. Breakdown pitting on surfaces of an electrode. (a) Results of computer simulation of a series of breakdowns in perfluorodibutyl ether. (b) Photo of the electrode surface of stainless steel after a series of breakdowns in perfluorodibutyl ether. Areas of size 8×8 mm are shown. R = 30 mm, d = 0.44 mm, N_0 = 140.

Conclusions. It is shown that dynamic electric strength of PFDBE increased after careful clearing and degassing and became higher than dynamic electric strength of transformer oil. Within the framework of the stochastic approach a several new analytical dependences for distribution of probabilities of breakdown initiation was obtained at changes of geometry of an inter-electrode gap (S or R and d), and also of rate of increase of AC voltage. The opportunity of stochastic modelling of experiments on breakdown in dielectric liquids is demonstrated.

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