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Interfacial dynamics in a water-oil system during electrical breakdown

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In this work, the formation of a conical water–transformer oil interface under high-voltage application to electrodes is studied experimentally and through numerical simulation in an axisymmetric three-dimensional formulation. The use of cylindrical electrodes with rounded ends enabled more detailed numerical modeling, with results that agree well with experimental data. It is shown that the phase-variable profiles and the normalized axial velocity profiles should be used to track the interface. The proposed simulation method can serve as a tool for the preliminary assessment of the resistance of high-voltage oil-filled equipment to local electrical breakdowns caused by potential moisture presence.

Keywords: conductive water, transformer oil, pulsed electric field, water cone, EHD flows.

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Introduction

Humidity in the oil insulation of high voltage equipment is a critical risk factor contributing to the initiation of dielectric breakdown, which can result in catastrophic consequences. A particular danger is the presence of elongated (compared to inter-electrode gaps in high voltage equipment) “water-oil” phase boundary, the behavior of which in a pulsed electric field has not been fully studied, and the mechanism of electrical breakdown requires a detailed study in this case.

The presence of even a trace amount of water in transformer oil reduces its dielectric strength. This is due to the fact that water, having a high dielectric permittivity ($\epsilon \sim 80$) compared to that of oil ($\epsilon \sim 2.2$) and low electrical conductivity, is polarized in an inhomogeneous field, forming ohmic bridges and locally increasing the electric field strength [1, 2]. The condensation of moisture on the inner surfaces of the tank or the formation of free water

droplets can lead to local charge accumulation that initiates internal breakdown and emergency depressurization of the transformer’s active part.

Two classical breakdown mechanisms prevail in homogeneous dielectric liquids [3]. The streamer-leader (avalanche) breakdown is due to impact ionization and the development of fast tree-like channels (streamers). It is characteristic of pulsed voltage application (nanosecond to microsecond ranges) in strong fields (>100 kV/cm) and has been well studied [3, 4]. Its dynamic is similar to breakdown in dense gases, where electron emission of electrodes from the cathode and the formation of gas bubbles due to Joule heating play a crucial role [3–12]. Thermal breakdown occurs in weaker but long-lasting fields, where the heating of the liquid from leakage currents and conduction exceeds the heat removal resulting in thermal instability and the formation of a conductive channel.

A factor significantly complicating the situation is a presence of an interphase boundary (gas-liquid or liquid-liquid). Its presence leads to

a contrast in dielectric properties and the accumulation of polarization charges, which significantly reduces the overall gap electrical strength of the gap. In particular, for the oil-water boundary at an average field strength below 5 kV/cm, the development of classical streamers in the volume of any of the liquids is impossible [3], and the thermal mechanism in water is also not realized due to the capacitive nature of the initial current. Thus, electrohydrodynamic instability starts to play a dominant role.

When applying a pulsed electric field to the boundary of two immiscible liquids with different conductivities and permittivities, free charges are induced at this boundary. The interaction of the external field with these charges creates tangential electrostatic forces (pressure), which cause boundary instability according to the Tonks-Frenkel instability type [13]. This results in non-linear deformation of the boundary – the occurrence of pointed edges or a cellular structure; electrohydrodynamics currents – the formation of convective currents in both liquids; and the explosive growth of disturbances – when the critical voltage is exceeded, the edge from the side of the more conductive liquid (water) can stretch into a thin jet capable of quickly reaching the opposite electrode and causing gap closure. This process can occur orders of magnitude slower than streamer breakdown and lead to the gap closure.

The studies show that the pulse polarity, electrodes geometry, and the ratio of the conductivities of the liquids are key parameters determining the morphology of deformation and the threshold voltage [14–17].

In paper [18], an experimental and numerical study of the behavior of the “water-transformer oil” phase boundary was conducted, where a sphere acted as a high-voltage electrode. The simulation results showed a lag of about 1.4 times from the actual cone height, which was attributed to the two-dimensionality of the problem statement.

The purpose of this work is an experimental and numerical study of the behavior of the “water-transformer oil” phase boundary, where a cylinder with a working end in the form of a hemisphere acts as a high-voltage electrode. Such a statement makes possible a three-dimensional axisymmetric simulation, which was impossible

with the previous electrode geometry due to numerical oscillations occurring at the sphere pole opposite to the liquid boundary. This problem does not occur in the case of a cylindrical electrode, and the simulation results match the experimental ones with good accuracy.

Experimental unit and mathematical modeling methods

The experimental unit used in this work is identical to the one in [18] except for the high-voltage electrode, which in this work was chosen to be cylindrical with a diameter of 7 mm, the working edge of which facing the water-oil phase boundary was made as a hemisphere of the same diameter. A brief description is presented below. To conduct the research, a layer of water (300 $\mu\text{S}/\text{cm}$) is poured into a transparent Plexiglas container and then a layer of transformer oil is poured on it. The thickness of the layers is selected in such a way that the phase boundary is between the upper and lower electrode and is equidistant from them. The grounded electrode, made of a 1.6 mm brass rod with a rounded edge at the working end, is placed in the water layer. A high-voltage electrode in the form of a brass rod with a diameter of 7 mm is immersed in the oil layer to a depth of 12 mm. The discharge gap is monitored using an MBS-10 microscope and a Phantom v2012 photocalera. The voltage pulse is formed using a semiconductor high-voltage commutator (“half-bridge” type) connected to storage capacitor. The commutator is capable of raising the potential of the high-voltage electrode to the required value (as well as lowering it to 0) in a time of about 100 ns.

The simulation is conducted in an axisymmetric setup in a cylindrical region into which two electrodes are inserted. The lower electrode has a radius of 0.8 mm, its height is 25 mm, and the rounded electrode tip radius is 0.4 mm. The lower electrode is immersed into the water to a depth of 3 mm. The external cylindrical surface is at a distance of 40 mm from the electrode axis. A 12 mm thick layer of oil is located above a 28 mm thick layer of water. A rounded electrode with a radius of 3.5 mm is completely immersed in it. Thus, its lower surface is at a distance of 3 mm from the media phase boundary. The lower electrode is grounded

(voltage $V = 0$ V), and a constant voltage equal to $V = 3360, 3900, 4440$ V is applied to the top one. The computational domain is additionally divided into several subareas which are covered by a grid with different characteristics. Namely, in areas where the phase composition does not change, a calculation mesh of triangles is used. In all other areas where the phase boundary moves, an orthogonal grid is set. Spatial discretization based on the finite element method is used to jointly solve the Poisson's equation, the Navier-Stokes equations and phase transport. The implicit Euler scheme with a variable time step is used for temporal discretization. The algorithm uses splitting by physical processes: at each time step, the electric field, the distribution of velocities and pressure in the resulting flow, as well as the movement of the phase boundary, are sequentially calculated. The phase boundary has a finite thickness and is modeled based on the Level-Set method [19]. The occurrence of the driving electrostatic force is due to the divergence of the Maxwell stress tensor in a medium with non-uniform dielectric permittivity.

Findings and Discussion

Fig. 1 shows records of the movement of water – transformer oil phase boundary under the influence of pulsed voltages with an amplitude of 3360, 3900, and 4440 V. In the first moment after the voltage is applied, the boundary deformation near the electrode axis occurs almost uniformly, as in the case of a spherical electrode [18]. Then the boundary acquires a noticeable curvature with a radius of a constant sign. At a height of about 1 mm, a sharp peak starts to form at the boundary (where the curvature radius changes its sign). Further water movement deep into the oil occurs due to the sharpening and stretching of the tip of the boundary. When the distance to the electrode is reduced to approximately 0.2 mm, small droplets begin to separate from the tip of the cone at: *a*) 42.5 ms, *b*) 34.286 ms, and *c*) 29 ms, respectively, and form a stream that reaches the electrode surface. Electrical breakdown (34.994 ms in Fig. 1*b*) is initiated as a result of the simultaneous separation and stretching of many droplets, which consequently form a thin water channel that completely closes the gap or

appears at distances from each other sufficient to break through the oil gap. The formation of a plasma channel is only observed at the thin top part of the cone, where the current density is sufficient for the thermal initiation mechanism. As the voltage increases, the total process time decreases, and the shape of the phase boundary goes through a similar evolution (see, for example, 34.826, 29, and 25 ms for *a*), *b*) and *c*), respectively).

Fig. 2 shows the curves of the cone vertex position. “E” and “m” indices refer, respectively, to the results of the experiment and modeling. The three-dimensional problem formulation provides a much better match with the experiment compared to the two-dimensional one [18].

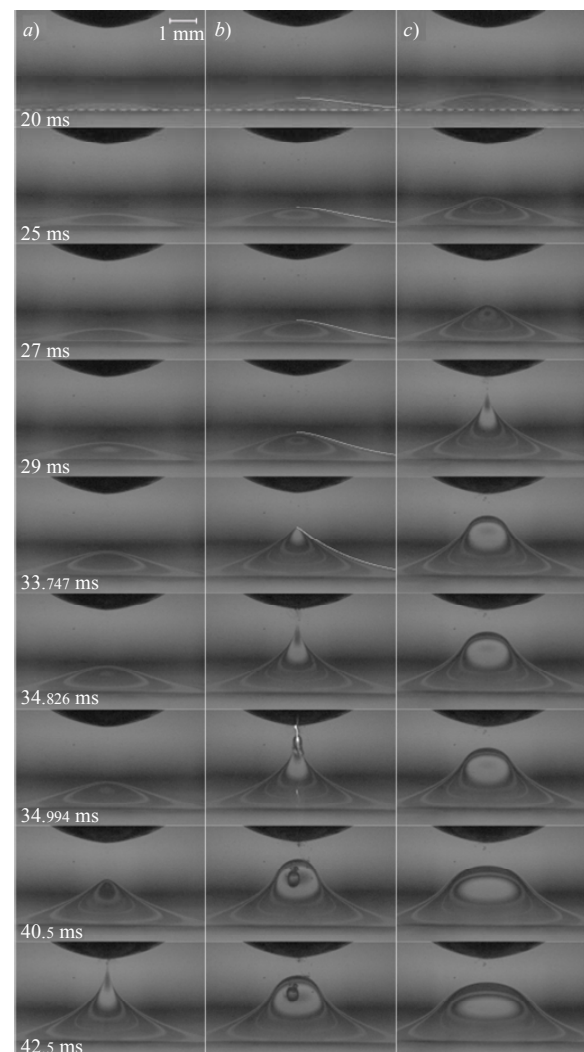


Fig. 1. Motion record of the water-transformer oil boundary in a vertical electric field at a voltage of *a*) 3360, *b*) 3900, and *c*) 4440 V. Results of the boundary position modeling are indicated with a white line for the case of 3900 V at the 20–33.747 ms frames. The dotted line indicates the location of the unperturbed boundary

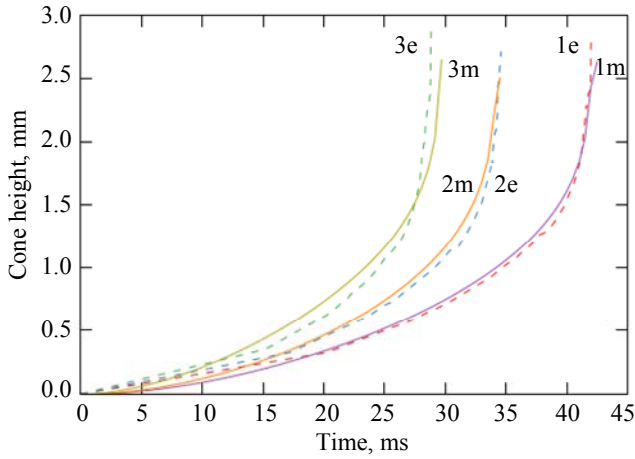


Fig. 2. Graphs of the dependencies of the cone vertex position on the time of voltage supply in the experiments (with the “e” mark) and numerical modeling (with the “m” mark) at a voltage of 1) 3360, 2) 3900 and 3) 4440 V

The vertex movement occurs with a constant increase in speed (curve 2 in Fig. 3) due to a constant increase in forces from the electric field side, which increase with a decrease in the distance between the vertex and the surface of the high-voltage electrode.

Fig. 3 shows the dynamics of the normalized (to the maximum) cone vertex height H values, the velocity of the vertex movement v and the volume V of the cone’s visible part for the slowest case of 3360 V at the stages of growth and decline of the cone. It is noteworthy that the maximum values are not reached at the same time. The first to reach its peak is the maximum velocity, which is about 1 m/s. This is due to the beginning of liquid spraying from the tip which slows down the progress of the clearly visible part of the vertex. The maximum value of $H_{\max}$ height is 2.86 mm, which is less than the initial distance of 3 mm, also due to the spraying and de-energizing of the electrode before the breakdown. Much later, the maximum volume $V_{\max} = 41 \text{ mm}^3$ of the visible part of the cone is reached, which is explained by the inertia of the liquid moving inside the cone. This value is estimated from the bottom because over time, an increasing amount of liquid appears outside the visible area. The presented picture is qualitatively repeated for all voltage cases.

Fig. 4 shows an extended comparison of experimental and numerical results for 3360 V case.

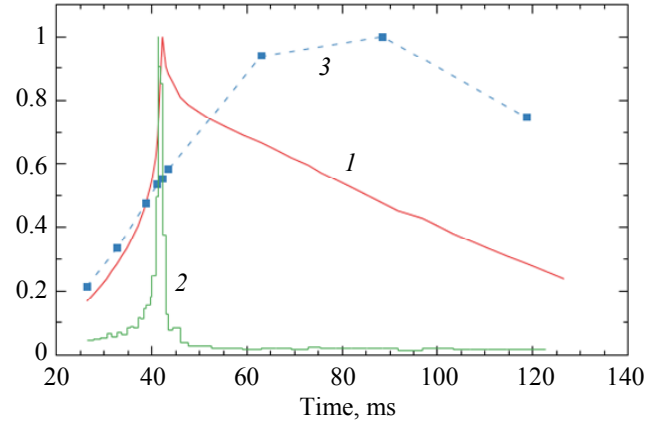


Fig. 3. Graphs of the dependencies of the cone vertex position $H/H_{\max}$ (1), its velocity $v/v_{\max}$ (2) and the volume $V/V_{\max}$ of the cone (3) normalized to their maximum values at the stages of growth and decline. The voltage is 3360 V; the voltage pulse decreases at $t = 42.2 \text{ ms}$. $(H_{\max}, v_{\max}, V_{\max}) = (2.86 \text{ mm}, 1 \text{ m/s}, 41 \text{ mm}^3)$

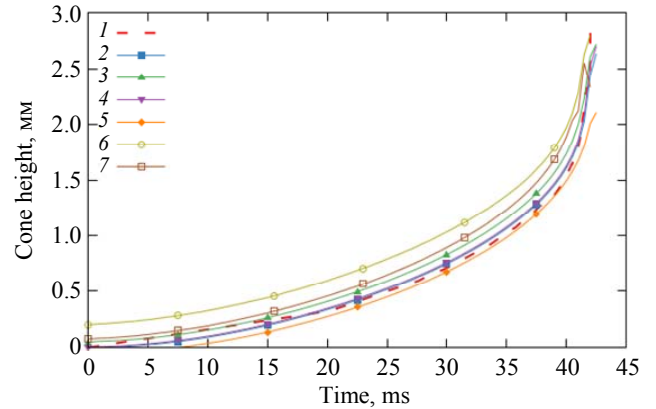


Fig. 4. Graphs of dependence of the cone vortex position H (1) in the experiment (3360 V) and the modeled values $\varphi = 0.5$ (2), $v_z/\max\{v_z\} = 0.1$ (3), $v_z/\max\{v_z\} = 0.5$ (4), $v_z/\max\{v_z\} = 0.9$ (5), $\min\{F_z\}$ (6), and $\max\{F_z\}$ (7)

For each calculation, the axial distribution of three quantities (along the z -axis) is considered: the profile of the phase variable φ , the profile of the z -component of the electric field intensity, the profile of the z -component of velocity (V_z), and the profile of the z -component of the ponderomotive volumetric force (F_z). For the phase variable in the range of values $\varphi = [0, 1]$, a number of N level lines is selected, according to which a discrete set is determined φ_i , excluding the extreme values 0 and 1. At each time interval t_i (for which the results were obtained) the position of the nearest points on the profile $\varphi = \varphi(z)$ for a set of levels φ_i , $i = 0, N-1$ is

determined. The change in the positions of points over time $z_i = z_i(t)$ allows for the construction of a set of corresponding curves and the identification of numerical results for a certain curve to compare with the experiment. The main reason why several quantities are considered is that the final thickness of the phase boundary significantly exceeds its physical analog. Moreover, it is subject to “blurring” during the calculation due to model diffusion. In the case of the velocity V_z , the profile is normalized to the maximum at each time interval, and the V_z level lines are changed in the same way. The behavior of the E_z levels turns out to be similar ϕ , and therefore, is not considered. The force profile undergoes very strong changes in the process of calculation both in amplitude (its maximum values change by several orders of magnitude) and in shape. Setting a set of levels for this value turns out to be unreasonable. However, one can track the movement of its front. The first obvious “marker” is the F_z maximum position at each time point. Considering the force profiles immediately after the voltage is applied, it can be noticed that spatial discretization by the finite element method leads to the occurrence of nonmonotonicity and with further water displacement towards the high-voltage electrode, the F_z distribution is characterized by strong inhomogeneities that can propagate at a different rate than the “material” variable ϕ . As an additional criterion for the displacement of the phase boundary, the location of the last local minimum on the $F_z = F_z(t)$ profile can be considered. The best approximation is provided by the profile along the midline $\phi = 0.5$, the level line $\phi = 0.1$ gives an overestimated value of the cone vertex and $\phi = 0.9$ – an underestimated one during the entire calculation. Similarly to the phase variable, the level line $V_z/\max\{V_z\} = 0.9$ for velocity gives an underestimated value of the cone vertex for each time interval. In the initial stage ($t < 20$ ms) the best approximation is given by the level line $z_{V_z} = 0.0909$, and then the best approximation is given by the midline throughout the calculation. The use of the F_z maximum and the local minimum closest to the high-voltage electrode as the phase boundary motion markers gives underestimated values of the cone vertex and is unsatisfactory.

Conclusions

The motion of the phase boundary between water and transformer oil in a vertical electric field was studied experimentally and using numerical modeling. Data were obtained on the velocity of the phase boundary, the volume of the involved liquid, and the dynamics of the vortex of the water cone at the stage of its growth when the voltage was applied, as well as at the stage of its decline. It was shown that at a ratio 2:1 of the diameter D of the high-voltage electrode to the distance l to the phase boundary, the geometry of the electrode’s working end defines the nature of the boundary deformation, while its height does not significantly affect the motion and charge development.

The transition from the two-dimensional to the three-dimensional axisymmetric simulation allowed to significantly bring the experimental and numerical results for the dependence of cone vertex position on time into close agreement. Changing the shape of the high-voltage electrode from spherical to cylindrical with similar hemisphere on the working end allowed for the optimization of computational time (despite the three-dimensional formulation) by completely eliminating spurious currents appearing at the sphere pole opposite to the discharge gap; these currents have little effect on the movement of the liquid phase boundary, yet, they require computing resources comparable to the problem under consideration.

Despite a large number of model hypotheses and limitations related to the finite thickness of the phase boundary, empirical coefficients in the phase variable transfer model, and an approximate form of recording the volumetric force, the model can generally correctly describe the motion of the “water-oil” boundary towards the high-voltage electrode. The best ways to represent this motion are the level lines of the phase variable ϕ and the normalized axial velocity $V_z/\max\{V_z\}$. The description in terms of the local extreme points of the ponderomotive volumetric force $F_{es,z}$ is unsatisfactory; however, it shows the degree of field disturbance of the volumetric force due to the finite thickness of the phase boundary.

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