European Journal of Mechanics / B Fluids 75 (2019) 105–109

Contents lists available at ScienceDirect

European Journal of Mechanics / B Fluids

journal homepage: www.elsevier.com/locate/ejmflu

Deformation of bubbles in transformer oil at the action of alternating electric field

S.M. Korobeynikov [a,b,*], A.V. Ridel [a,b], D.A. Medvedev [a]

[a] Lavrentyev Institute of Hydrodynamics SB RAS, Russia
[b] Novosibirsk State Technical University, Russia

HIGHLIGHTS

- Bubble deformation in transformer oil at alternative electric field is recorded.
- The computational model based on the Lattice Boltzmann equation method for the electrohydrodynamic flows accompanying this process was developed.
- Simulations of the behavior of bubbles show the degree of deformation close to that observed in experiments.
- The bubble deformation profile is reasonably explained by a model with a constant surface tension.

ARTICLE INFO

Article history:
Received 10 April 2018
Received in revised form 6 September 2018
Accepted 12 October 2018
Available online 9 January 2019

Keywords:
Strong electric field
Floating bubbles
Transformer oil
Lattice Boltzmann method
Electrohydrodynamic flows
Bubble deformation

ABSTRACT

The experimental investigations of the deformation of bubbles floating in transformer oil under the action of uniform electric field were performed. The model based on the lattice Boltzmann equation method for the electrohydrodynamic flows accompanying this process was developed. The degree of deformation of bubbles observed in experiments is in agreement with the one obtained in simulations. Comparison with theoretical calculations show that the experimental data on the deformation of bubbles in transformer oil under the action of strong alternating electric field with a magnitude up to 4 kV/mm are reasonably explained by a model with a changeless surface tension.

1. Introduction

Bubbles in the high-voltage equipment with liquid electric insulation are usually considered as one of the most frequent sources of the inception of electric breakdown [1–4]. Besides of this, bubbles under the action of electric field play an important role in different technical processes: sterilization of food during preparation (non-thermal food preservation technology) [5], phase transitions [6], heat transfer [7], bubble column reactors [8], etc.

Surface tension plays an important role at the deformation of bubbles. It is assumed that the coefficient of surface tension can decrease under the action of electric field [9–11], and even to become a tensor, i.e., take different values depending on the orientation of the electric field relative to the interface [12]. Different behavior of surface tension should lead to different bubble deformations.

This work is devoted to the experimental investigation of the deformation of bubbles in alternating electric field and the numerical simulation of the bubble behavior.

* Corresponding author.
E-mail address: korobeynikov@corp.nstu.ru (S.M. Korobeynikov).

https://doi.org/10.1016/j.euromechflu.2018.10.027

2. Experimental setup

Deformations of a floating bubble in transformer oil under the action of alternating voltage with frequency 50 Hz were investigated using the experimental setup shown schematically in Fig. 1.

It consists of the high-voltage transformer (1), connected with the experimental cell (2), the light source (3) directed to the interelectrode gap coaxially with the high-speed camera (4). The gas was injected through the medical syringe into the electrode region. The distance between the electrodes was 6.8 mm. The optical video registration was made through optical glass windows mounted into the polymethylmethacrylate cell cage. The cell was filled with mineral transformer oil GK. The oil was taken from a transformer in service without additional purification. The real size of a bubble was obtained by the comparison of the images of a bubble and the cylinder of a diameter of D = 1 mm used as an etalon. The magnification coefficient was calculated by the comparison of the images of a bubble with the etalon. The semiaxes of the ellipsoid were calculated by the frames where the maximum deformation was registered. This moment was assumed to correspond to the

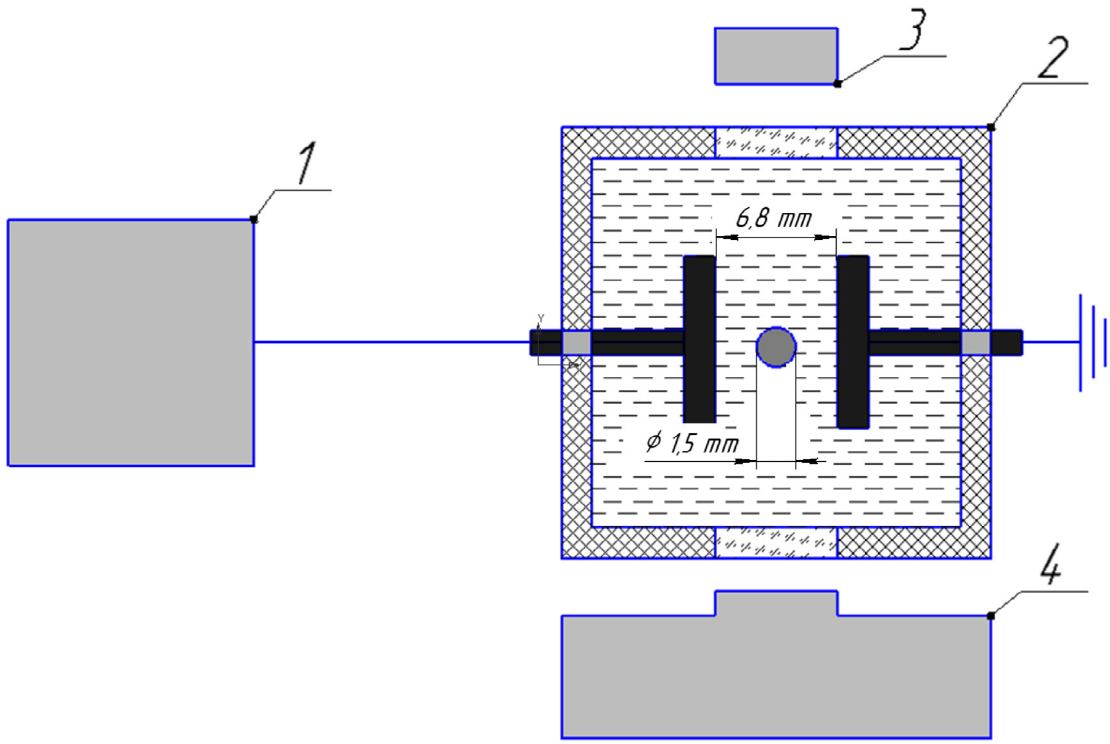

Fig. 1. Experimental setup. Below (behind the picture plane) is the system for the injection of gas bubbles (not shown).

amplitude voltage value with a voltage accuracy of less than 1%. The way to prove this assumption proof is the following. At high voltages, the partial discharge (PD) inside bubbles sometimes occurs. By using the optical and electrical registration of this event one could see simultaneously the voltage oscillogram with the mark of PD and bubbles at this moment. When the voltage is practically maximum [13], deformation of the bubbles is almost maximum too. The error in the time of maximum deviation using video system could be estimated as half of the time duration between frames, i.e. less than 0.01 s. The error in the voltage due to this factor is less than 1%.

3. Experimental results

The recording speed was 1200 frames per second. The video recording was decomposed into frames using graphic editor. The per frame analysis revealed the deformation frequency which was equal to 100 Hz, it is doubled frequency of acting voltage. Fig. 2(a) and (b) shows the image of floating bubbles of different diameters placed in the center of the experimental cell: (a) at the time moment when the voltage goes through zero, (b) at the moment of the amplitude voltage value.

The electrodes are placed vertically at the left and at the right of the floating bubbles. Arrow shows the direction of the buoyancy force.

4. Simulation of the bubble behavior

The lattice Boltzmann method (LBM) was used for the simulation of electrohydrodynamic flows with possible phase transition liquid–vapor and the calculation of the internal energy transfer, the pressure work and latent the heat of evaporation in dielectric liquid. The transfer of the internal energy in LBM was simulated using the method of passive scalar [14].

The advection of heat is described by the introduction of a second set of distribution functions representing the internal energy density

$$W = C_V \rho T = \sum g_k \tag{1}$$

The evolution equation for these distribution functions is

$$g_k(\mathbf{x}, t + \Delta t) = g_k(\mathbf{x} - \mathbf{c}_k \Delta t, t) + \frac{g_k^{eq} - g_k}{\tau_E} + \Delta g_k \tag{2}$$

The change of distribution functions Δg_k consists of two parts. The first one includes all the sources: the pressure work, the release or absorption of the latent heat of phase transitions, the joule heating of conductive medium by the electric current. When the change of the internal energy density due to the sources is equal to ΔW, the corresponding changes of the distribution functions are calculated by

$$\Delta g_k^{(1)} = g_k \Delta W / W \tag{3}$$

The special "pseudoforces" are introduced in order to prevent the non-physical energy spreading at phase boundaries (large gradients of the fluid density). They lead to the change of the distribution functions expressed as

$$\Delta g_k^{(2)} = g_k^{eq}(\mathbf{u} + \Delta \mathbf{u}) - g_k^{eq}(\mathbf{u}) \tag{4}$$

Here, $\Delta \mathbf{u} = \mathbf{F}\Delta t/\rho$ is the change of the fluid mass velocity at a node under the action of forces (interaction forces providing the phase transition, electric forces, gravity forces etc.).

The Helmholtz force acting on a dielectric fluid in an electric field $\mathbf{E}$ is expressed by

$$\mathbf{F} = -\frac{\varepsilon_0 E^2}{2}\nabla\varepsilon + \frac{\varepsilon_0}{2}\nabla\left(E^2\rho\left(\frac{\partial\varepsilon}{\partial\rho}\right)_T\right) \tag{5}$$

The last term is the electrostriction force.

The electric field is determined from the solution of the Laplace equation for the electric potential φ

$$\mathrm{div}(\varepsilon\nabla\varphi) = 0 \tag{6}$$

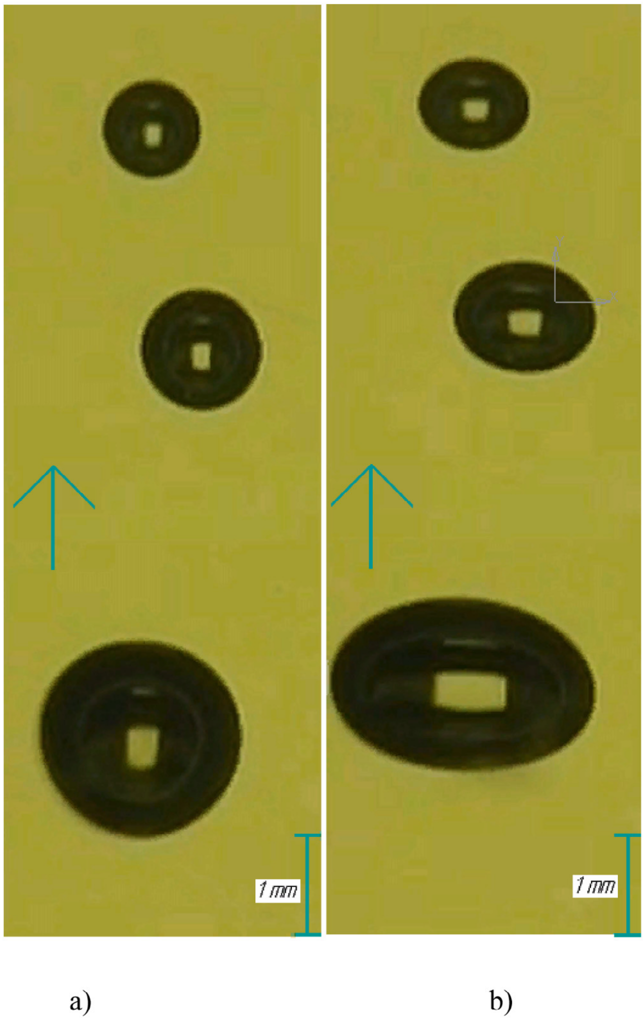

Fig. 2. (a) Bubbles of different diameter at the time when the electric field magnitude is zero. (b) The same bubbles at the moment of the amplitude voltage value.

This equation was solved using the time-implicit finite-difference scheme. The iterations are repeated until the relative change of the electric potential becomes smaller that a certain value $|\Delta\varphi/\phi| < 10^{-8}$.

The size of the calculation region was 161×161×320 nodes. Boundary conditions were periodic in horizontal directions both for the flow and electric potential, and no-slip rigid walls with fixed electric potential at the top and bottom. The system was equilibrated during 5000 time steps before the electric field was applied. The initial radius of the bubble was $r = 30$ lattice units, the non-dimensional surface tension was $\tilde{\sigma} = 0.0691$, the non-dimensional average electric field was $\langle E\rangle = 0.376$. This corresponds to the electric capillary number

$$\mathrm{Ca} = \frac{(\varepsilon - 1)\,\langle E\rangle^2\, r}{\sigma} = 80 \tag{7}$$

equal to one used in the experiments. The relaxation time was $\tau = 1$ for the fluid, and $\tau_E = 0.51$ for the internal energy.

5. Discussion

It is clear from Fig. 2 that larger bubbles undergo larger deformations. The deformation of a bubble is characterized by the expression $\Delta = \frac{a-b}{2R_0}$ where a is the extension of the bubble parallel to the direction of the electric field, b is the bubble size perpendicular to this direction, and R_0 is the bubble size at the zero electric field. In the electric field, there is the well-known expression for Δ in the linear approximation (see, e.g., [15]).

$$\Delta = \frac{(\varepsilon_l - \varepsilon_g)^2 \varepsilon_0 R_0 \mathrm{E}_1{}^2}{8\,\sigma\,\varepsilon_l} \tag{8}$$

Here,
$\varepsilon_l = 2.3$ is the dielectric permittivity of the transformer oil,
$\varepsilon_g = 1$ is the dielectric permittivity of the gas inclusion,
$\varepsilon_0 = 8.85 \cdot 10^{-12}$ F/m is the electrostatic constant,
$\mathrm{E}_1 = \frac{3\varepsilon_l E_0}{2\varepsilon_l + \varepsilon_g}$ - electric field inside the spherical bubble
$E_0 = 3.3$ kV/mm is the average magnitude of electric field inside the gap,
$\sigma = 0.0464$ N/m is the surface tension of the pure transformer oil.

Calculation results Δ_c and experimental data Δ_e are listed in Table 1.

They are also plotted in Fig. 3.

Table 1
Theoretical and experimental levels of bubbles deformation.

Initial radius (mm)	0.5	0.6	1
Δ_c	0.136	0.168	0.279
Δ_e	0.2	0.25	0.46

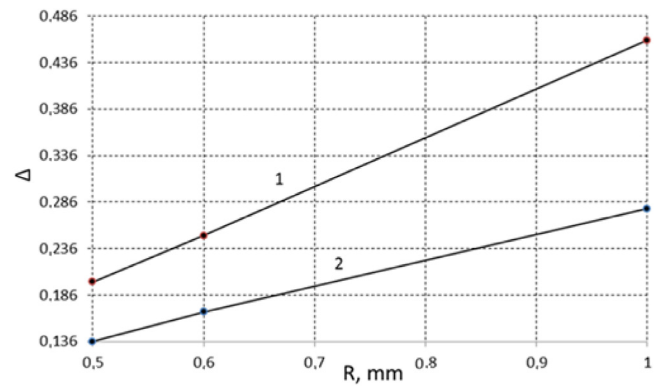

Fig. 3. Experimental (1) and theoretical (2) values of deformation for bubbles of different diameters.

The curves in Fig. 3 are distinctly different. We think that this is related to the uncertainty in the value of σ. It is known that the surface tension of transformer oil changes during the maintenance [16]. Thus, the aged oil can have the value of σ almost twice lower than that of the fresh oil. In particular, according to [16], the surface tension of the fresh oil should be not lower than 0.04 N/m, where as the lowest accepted σ of aged oil should be not lower than 0.022 N/m. Therefore, one can fit the value of σ which agrees best with the experimental data. In Fig. 4, the values of deformation are shown using the fitted coefficient $\sigma = 0.031$ N/m. In this case, experimental and calculated points almost coincide. In our opinion, the decreased by 30% value of σ may be caused by the aging of the oil.

Generally, experimental and calculated data allows one to conclude that the value of σ does not change in an electric field with magnitude up to 4 kV/mm. This conclusion is important since it is assumed in several models that the value of σ depends on the direction of electric field, the parallel to the surface field increases the value of σ, and the normal field decreases it. Such behavior should lead to the size-independent deformation of a bubble. In experiments, the degree of deformation is proportional to the bubble size which indicates to the constant value of σ.

The reduction in surface tension by the applied electric field is described by a simple model, in which the macroscopic liquid

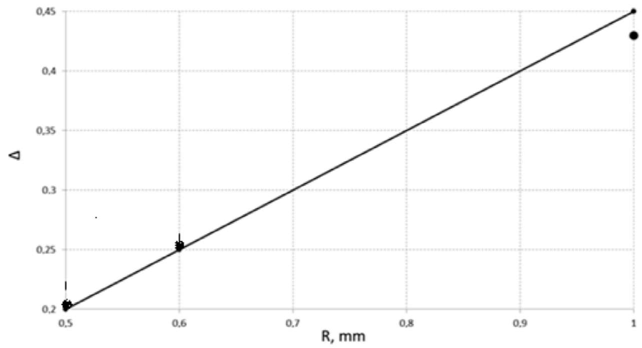

Fig. 4. Experimental (curve) and theoretical (points) values of bubble deformation for $\sigma = 0.031$ N/m.

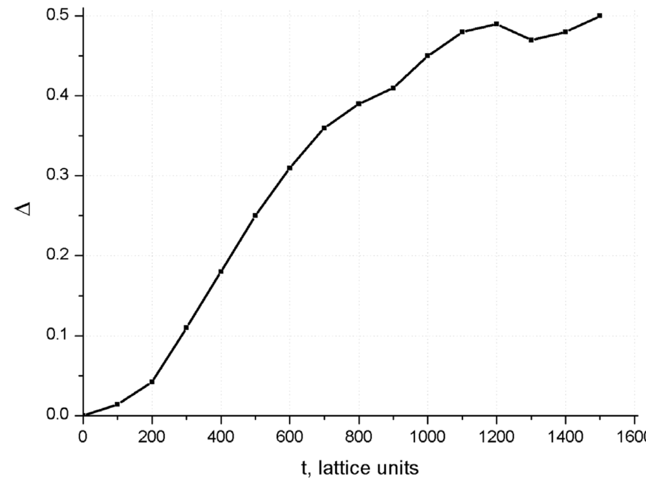

Fig. 6. Deformation of bubble in electric field.

particles (with electric charge on the liquid surface) repel each other, and, consequently, their tension force decreases [9]. The effect in [9] is great enough (more than (10–20)% for liquids with high electrical conductivity at the action of voltage level more than 1 kV. In our opinion the surface charge will be at the liquid–gas interface in case of Maxwell time of dielectric relaxation $\tau_{\mathrm{m}} = \varepsilon_0\varepsilon_l/\sigma$ lower than characteristic time of voltage action. In our case $\tau_{\mathrm{m}} \approx$ 0.2 s that is much more than the half of the voltage cycle 10 ms. In the modified mean-field density-functional theory [10] electric field actually reduces the thermodynamic surface tension at the field amplitude higher than 100 kV/mm.

In the papers [11,12] by consideration of surface waves in case of low temperature it was shown that parallel electric field should increase surface tension, but perpendicular electric field should decrease surface tension. The numerical evaluation of the characteristic electric field is hardly possible. Implicit data [11] points out the values of several kV/mm. Our experimental data shows that surface tension of transformer oil does not change up to 4 kV/mm.

Simulation results of the dynamics of deformation of a bubble in a liquid placed in electric field without the discharge inside the bubble agree with experimental data. For the fluid, the Van der Waals equation of state was used. Written in reduced variables (non-dimensionalized by the critical values of the density, pressure and temperature), this equation takes the form

$$P = \frac{8\rho T}{3-\rho} - 3\rho^2 \tag{9}$$

The Clausius–Mossotti expression for the density dependence of the dielectric permittivity was used

$$\varepsilon = 1 + 3\alpha\rho/(1-\alpha\rho) \tag{10}$$

Following parameters were used in the simulations: the initial temperature $T = 0.7$, the average electric field magnitude $E_0 =$ 3 kV/mm, the initial bubble radius $r = 1$ mm, the dielectric permittivity of the liquid phase $\varepsilon_l = 2.3$, the surface tension $\sigma = 0.05$ N/m.

The bubble deformation observed in the simulations was $\Delta \approx$ 0.50, which reasonably agrees with the experimental results. The difference between the calculations and the experiments can be caused by the different character of liquid flow since the lateral size of the region in calculations is essentially smaller. The process of the bubble deformation is shown in Fig. 5 (the fluid density in a central plane is shown), and the time dependence of Δ is shown in Fig. 6. The fully-3D simulations are rather memory and time consuming, and the lateral dimensions of the calculation region is smaller than the size of the experimental cell. Therefore, the flow pattern is different, and the agreement obtained is surprisingly good. Having all this in mind, only one series of calculations was performed.

6. Conclusions

Experimental data on the deformation of bubbles in transformer oil under the action of strong alternating electric field with a magnitude up to 4 kV/mm are reasonably explained by a model with a constant surface tension. Simulations of the behavior of

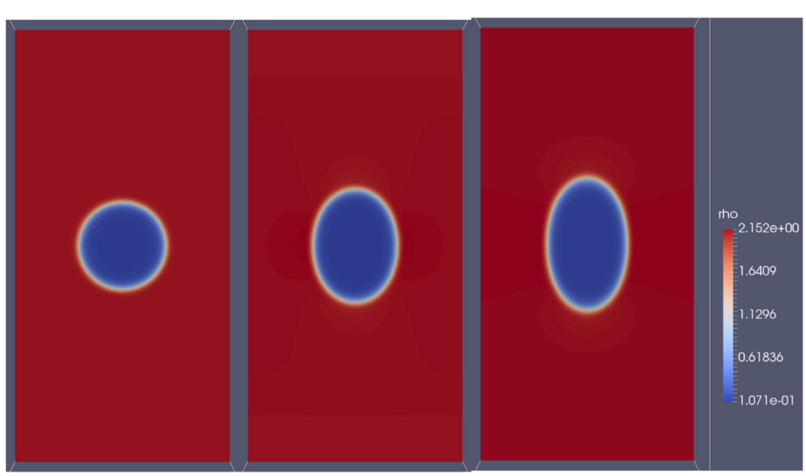

Fig. 5. Deformation of bubble in electric field. Time (left to right) t = 0, 2.5 ms, 5 ms, after 5 ms the bubble practically does not change its shape.

bubbles with the help of lattice Boltzmann method (LBM) show the degree of deformation close to that observed in experiments.

Acknowledgment

The paper was supported by Russian Science Foundation (grant No 16-19-10229).

Conflict of interests

We, authors of the paper ‘‘Deformation of bubbles in transformer oil at the action of alternating electric field’’, have no a conflict of interests.

References

[1] Y. Tsujikawa, M. Onoda, H. Nakayama, K. Amakawa, Japan. J. Appl. Phys. 27 (2) (1988) L451.
[2] M.Kh. Gadzhiev, S. TyuftyaevA, M.V. Il'ichev, Tech. Phys. 62 (2017) 1500.
[3] S.M. Korobeynikov, High Temperature 36 (1998) 340.
[4] M. Talaat, A. El-Zein, Electr. Inte. J. Electromagnet. Appl. 24 (2012) 4.
[5] M.M. Góngora-Nieto, P.D. Pedrow, B.G. Swanson, G.V. Barbosa-Cánovas, Innovat. Food Sci. Emerg. Technol 457 (2003) 1.
[6] Q. Yang, B. Li, Y. Qand Ding, 2013 Proceedings of the World Congress on Engineering, WCE 2013, Vol. 3 LNECS, pp. 1663-1668.
[7] Paolo Di Marco, Ryo Kurimoto, Giacomo Saccone, Kosuke Hayashi, Akio Tomiyama, Exp. Therm Fluid Sci. 49 (2013) 160–168.
[8] Shyam Sunder, Gaurav Tomar, Eur. J. Mech. - B/Fluids 56 (2016) 97.
[9] M. Sato, N. Kudo, M. Saito, IEEE Trans. Ind. Appl. 34 (1998) 294.
[10] V. Warshavsky, X.C. Band Zeng, Phys. Rev. Lett. 89 (2002) 246104.
[11] A. Mel'nikovskiL, S. Kriminski, AEffect of an electric field on the surface tension of a liquid at low temperatures, J. Exp. Theor. Phys. 84 (1997) 758.
[12] A.V. Zhukov, Vestn. Lobachevsky Univ. Nizhni Novgorod 47 (2011) 81.
[13] S.M. Korobeynikov, A.V. Ovsyannikov A. G. Ridel, D.A. Medvedev, Dynamics of bubbles in electric field : 2017 Journal of Physics: Conference Series 2017. - 899: 2 - Art. 082003.
[14] A.L. Kupershtokh, D.A. Medvedev, I.I. Gribanov, Numer. Methods Programm. 15 (2014) 317, in Russian.
[15] S.M. Korobeynikov, Journal of Engineering Physics and Thermophysics 36 588.
[16] Standard of the FSK EES organization Methodical guidance on the determining of the surface tension of transformer oils at the boundary with water using the method of the tearing-off of a ring from 02.03.2011 N 56947007-29.180.010.070 - 2011. http://www.fsk-ees.ru.-2011.