Ročník 2008 electroscope Číslo IV

The Prebreakdown State of Magnetic Fluids at Influence of Electrical and Magnetic Field

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Abstract. The development of electric breakdown in magnetic fluids (MFs) has been analyzed. MFs have been consisted of magnetic particles (Fe_3O_4) of nanometric size, coated with oleic acid as a surfactant, dispersed in transformer oil. The electro-physical processes, which appear at action of the DC electric field and constant magnetic field on MFs, were observed. These processes have effect on electric breakdown. The especial attention was devoted to state in MFs before breakdown, during breakdown and post breakdown.

Keywords: Electric breakdown, pre-breakdown and post-breakdown state, magnetic fluid, conjunct electric and magnetic fields, structuralization of magnetic particles.

1. INTRODUCTION

It is well known that as a consequence of dipole - dipole interaction between magnetic particles in magnetic fluids, magnetic particles tend to attract the neighboring particles in the direction of the magnetic moment. It is expected, therefore, that the magnetic particles will form chains and chain like elongated clusters in which the particles are connected magnetically. Such structural configurations of particles result in many physical properties of magnetic fluids i.e. magnetomechanical effects, magnetooptical effects, magneto-dielectric behavior and so on. The long-chain and cluster models of the magneto-dielectric effect have been analyzed in papers [1, 2] for example. It has long been recognized [3,4] that the presence of foreign particles in liquid insulators has a profound effect on the dielectric breakdown strength of liquids. In magnetite based magnetic fluids (transformer insulation oil as carrier base for example) the suspended particles are polarized and are of higher permittivity than the liquid. As a result they experience an electrical force directed towards the place of maximum stress. With uniform field electrodes the movement of particles is presumed to be initiated by surface irregularities on the electrodes which give rise to local field gradients. The accumulation of particles continues and tends to form a bridge across the gap, which leads to the initiation of breakdown [4].

The motivation of this work was to study the influence of conjunct electric and magnetic fields on electric stability of MFs. The first period of our work was oriented on investigation of both before-breakdown state and electric stability of MFs during co-operation both homogeneous electric field created by high voltage source and homogeneous magnetic field (B = 5 mT, 10 mT, 20 mT, 30 mT, 40 mT). The second and third period were devoted to observation of influence of AC electric field (f = 50 Hz) on the same parameters.

2. EXPERIMENTAL METHODS

For the experiments we have used magnetic fluids with magnetite particles coated with oleic acid as a surfactant dispersed in transformer oil ITO 100. The volume concentrations of magnetic particles were defined precisely. The lognormal particles size parameters were D_v = 8.6nm and standard deviation σ = 0.15 obtained by means of Chantrell et al [5] technique from VSM magnetization measurements. For the observation of agglomeration processes a drop of magnetic fluid was sandwiched between two parallel glass cover slips with the thickness d = 20µm and placed normal to the optic axis of the microscope. The optical microscope was equipped with a video camera. Helmholtz coils parallel to the magnetic fluid film plane produced a magnetic field of up to 50 mT. Dielectric breakdown strength measurements were carried out using appropriate shaped electrodes of a uniform gap of electric field-Rogowski profile [4]. The size of the electrodes was approximately 1.5 cm in diameter with the possibility to change the distance between electrodes in range of 0.1-1mm. The generating circuits generated high voltages up to 10 kV. Two permanent NdFeB magnets with sizes 5x5x0.3 cm produced the external magnetic field up to 50mT and the magnetic field was approximately uniform in measured gap of electric field. Experimental set up is on Fig.1. Each point of dielectric breakdown strength of the magnetic fluid was measured seven times and the maximum and minimum values were omitted in the calculation of its mean value according to the rules of high voltage techniques [3]. The experimental error of determination of dielectric breakdown strength was ±4%.

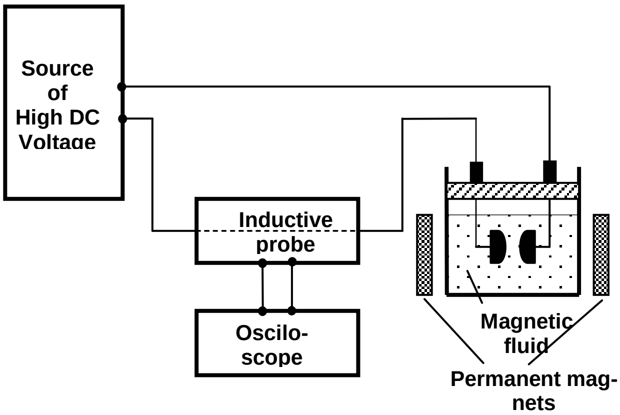

Fig.1: Experimental set up

3. THE DEPENDENCY OF PARTICLE CONCENTRATION ON ELECTRICAL FIELD INTENSITY

Emanate for the first time from conditions which are in electrical field in magnetic fluid under magnetic field with B=0. There is pollution of for example transformer oil with magnetic fluids with Fe_3O_4 in needle shape and polarization of theses elements of nanosize occurs. Gradient force affects on polarized particles will be [5], [6]

$$F_e = F_{grad} = r^3 \varepsilon_0 \varepsilon_{r0} \cdot \frac{\varepsilon_r - \varepsilon_{r0}}{\varepsilon_r + 2\varepsilon_{r0}} \cdot E \cdot gradE \qquad (1)$$

where

r- radius of particle

ε_{r0} – relative permitivity of oil

ε_r – relative permitivity of particle oil cluster in surfactant .

In the case of $\varepsilon_r >> \varepsilon_{r0}$ then it is possible

$$F_e = \varepsilon_0 \varepsilon_{r0} r^3 \cdot E \frac{dE}{dx}. \qquad (2)$$

Stokes force $F_s=-6.\gamma.\pi.r.v(x)$ influences on polarized particles. As $F_e+F_s=0$, then the transversal element of velocity is

$$v_e(x) = \frac{r^2}{6\pi\eta} \varepsilon_0 \varepsilon_{r_0} E \cdot \frac{dE}{dx} \qquad (3)$$

Spike clusters create micro non-homogeneous field. It activates diffusion at the place with they high concentration. Diffusion velocity is

$$v_{dif}(x) = -\frac{D}{N(x)} \cdot \frac{dN(x)}{dx}, \qquad (4)$$

where

D - diffusion coefficient

$N(x)$ – particle concentration.

Modification of equation (3) and (4)

$$v_{dif}(x) = -\left(\frac{kT}{6\pi r\eta}\right) \frac{1}{N(x)} \cdot \frac{dN}{dx} \qquad (5)$$

Critical value of transversal field $E(x)$ can be obtained by comparison of $v_e(x)$ and $v_{dif}(x)$. If the stability is disturbed, electric breakdown appears. Mathematical stability can be described as

$$\frac{r^2}{6\pi\eta} \varepsilon_0 \varepsilon_{r_0} E \cdot \frac{dE}{dx} = -\left(\frac{kT}{6\pi r\eta}\right) \frac{1}{N(x)} \cdot \frac{dN(x)}{dx}. \qquad (6)$$

Then it is possible to write

$$N(x) = N(\infty) \exp\left[\frac{\varepsilon_0 \varepsilon_{r_0} r^3 \left(E^2(x) - E^2(\infty)\right)}{2kT}\right]. \qquad (7)$$

Equation (7) shows to exponential increasing of particle concentration in DC electrical field and by that current increasing at pre-breakdown area in strong and week electrical field boundary at 10^6-10^7 Vm^{-1}.
During exponential increasing of current it formed breakdown canal from one electrode to other in magnetic fluids.
The same results as in equation (7) can be obtained in research force impact during combined electrical and magnetic field [6]

4. RESULTS

Measurements showed that concentration of nanoparticles (Fe_3O_4) in MFs influences not only relative permitivity of MFs but their electric conductivity too. The aggregation of magnetic particle (Fig.2) was observed by optical and electron microscope.

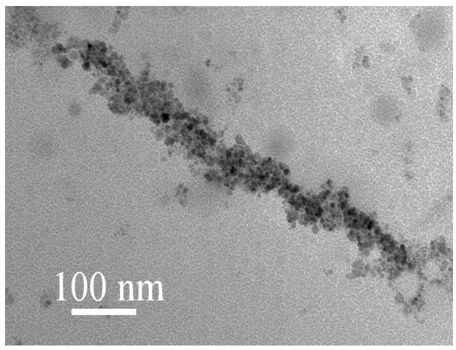

Fig.2: The example of the magnetic particles aggregation in magnetic fluid with concentration of magnetic particles f= 0.015.

The structure of magnetic particles in MF was solved in [6]. It was observed that clusters of magnetic particles in external magnetic field have shape of needles with average length in interval 100-300 μm in dependence on both values of external magnetic field and concentration of magnetic particles. As result aggregation process influences relative permittivity of MFs, concentration of magnetic particles in MFs and value of applied magnetic field. The saturation of a cluster length of magnetic particles was reached after 3 minutes (Fig.3).

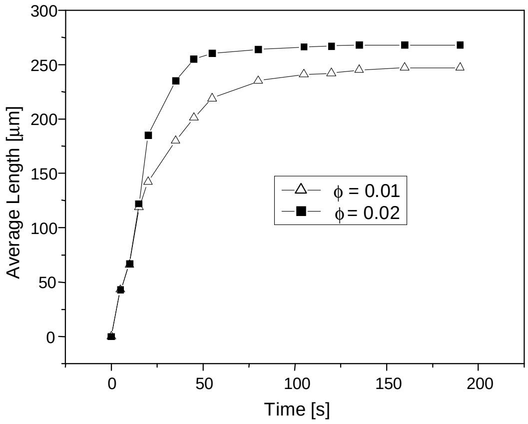

Fig.3: The average length of the needle like clusters vs. time after application of magnetic field 10 mT

The dependence of relative permittivity of MF on concentration of magnetic particles (Fig.4) and dependence of breakdown electric intensity on distance between electrodes (Fig.5, 6) were observed too.

The period of construction of electric discharge up to total breakdown was observed. This quantity was studied at continual increasing of voltage in homogeneous DC electric field [7] in different materials (air, transformer oil ITO 100 and magnetic fluids with volume concentrations of magnetic particles in range 0.125% – 4%). The experiments were carried out in different orientation of **E** and **H** (**E**||**H**, **E**⊥**H** a H =0). The courses of time dependence of current in MF with magnetic particles concentration of value 0.125% are illustrated on (Fig.7-11).

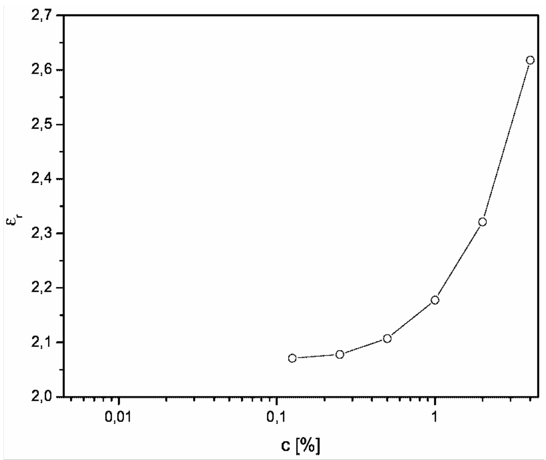

Fig. 4: The effect of volume concentration of magnetic particles on relative permittivity of MFs

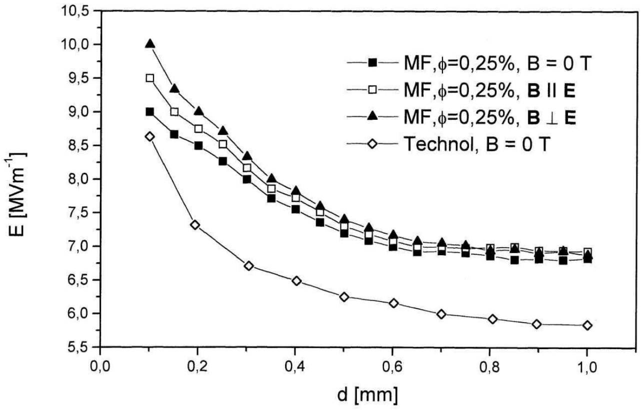

Fig. 5: Dielectric breakdown strength vs. distance between the electrodes for magnetic fluids Φ=0,0025 and I_s=1mT

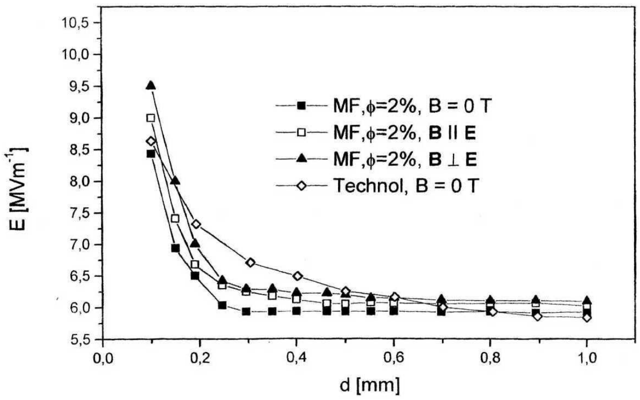

Fig. 6: Dielectric breakdown strength vs. distance between the electrodes for magnetic fluids Φ=0,02 and I_s=8mT

The periods of pre-breakdown state in investigated MF were in interval 150-220 ns what correspond to time needed for creating of an electric breakdown channel. The typical mark of quasi-exponential course is rise of an avalanche discharge (Townsed). This effect was observable in transformer oil ITO 100 for all concentrations of magnetic particles in MF and during observation pre-breakdown state in air too. While period needed on neutralization of avalanche in air is approximately 0.8-0.1 ns the same period for MF is approximately 1-3 ns. The clusters of magnetic particles arising as a result of magnetic field create in their surrounding micromagnetic fields that interact with existing electric field what influences shape of curve of exponential increasing of current. (Fig.9)

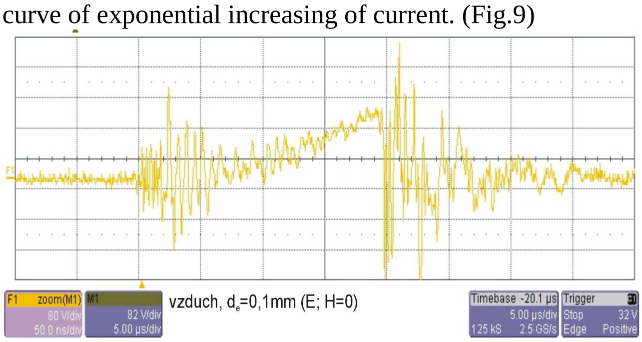

Fig. 7: The time dependence of current in air

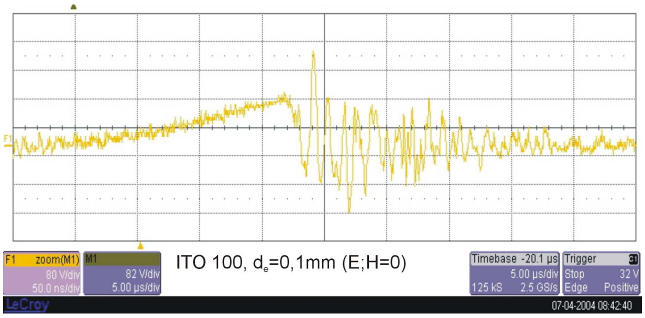

Fig. 8: The time dependence of current in transformer oil ITO 100

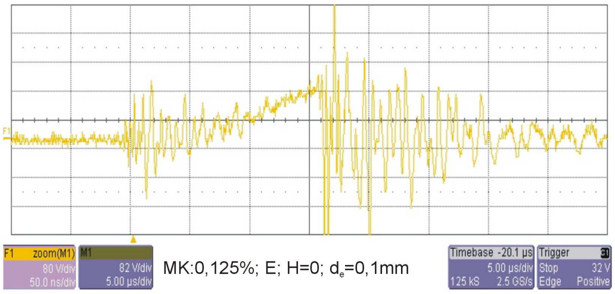

Fig. 9: Time dependence of current in MF

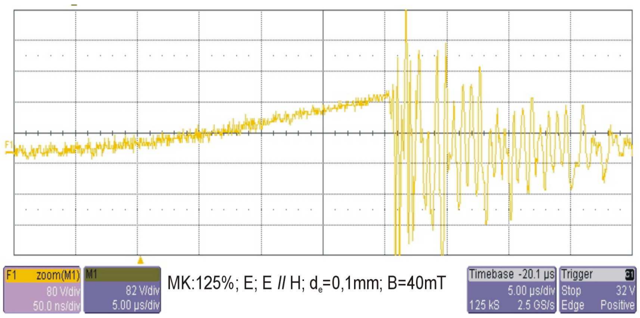

Fig. 10: Time dependence of current in MF in external magnetic field $E \parallel H$

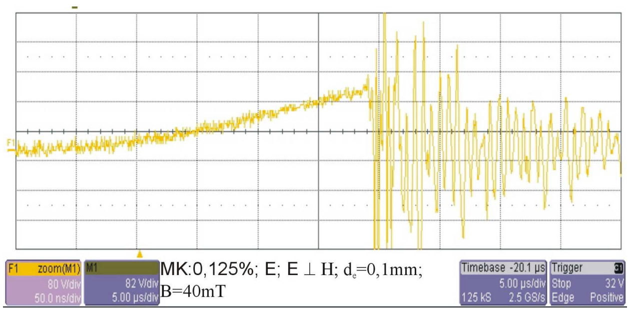

Fig. 11: Time dependence of current in MF in external magnetic field $E \perp H$

This effect is depressed by macroscopic imposed magnetic field what can by observed of (Fig.8). The course of time dependence of electric channel in observed interval (500 ns) can be divided into 3 regions:

- in region of weak electric field (less then 10^7Vm^{-1}) is carried out orientation of dipoles of weak polar, resp. polar material and also weak binded electric charged particles to direction of electric intensity without irrespective of existence external magnetic field,
- when electric intensity is greater than 10^7Vm^{-1} current increases exponentially in breakdown channel with transition from avalanche to streamer and leader kind of discharge,
- the multiply oscillations of current impulses rise in last phase (after creating of conductive channel); these oscillations last 2-3 ns and their amplitude exceed three times current amplitude in pre-breakdown region; the fade wade of oscillation effect has also exponential attribute with lasting time equal to period of increasing density up to electric breakdown.

5. CONCLUSION

This contribution is a theoretical introduction supported by experiments. There is studied the creation of electric channel that represents the track of electrical breakdown. The electro-physical accounting for building of conductive channel is done on base a time change of concentration of electric charge carriers in dependence on their positions. Theses effects have been studied in coexistence of electric and magnetic field.

Acknowledgements

This research was supported by the VEGA 1/3142/06 and 2/6166/06, APVV-20-006005.

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