DC and AC dielectric properties transformer oil based magnetic fluid

M. Timko*, P. Kopčanský*, L. Tomčo**, K. Marton**, M. Koneracká*,
F. Herchl* and N. Tomašovičová*

* Institute of Experimental Physics SAS, Watsonova 47, 040 01 Kosice, Slovakia, timko@saske.sk
** Faculty of Aviation, Technical University, Letna 9, 040 01 Kosice, Slovakia, ladislav.tomco@tuke.sk

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 and AC electric field and constant magnetic field on MFs, were observed. These processes have effect on electric 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. The second and third period were devoted to observation of influence of DC and AC electric field (f = 50 Hz) on the same parameters.

2 EXPERIMENTAL METHOD

For the experiments we have used magnetic fluids with magnetite particles coated with oleic acid as a surfactant dispersed in transformer oil TECHNOL 400 4000 (ε_r = 2.15). The volume concentrations of magnetic particles were in the range Φ = 0.0025-0.02, with corresponding saturation magnetizations I_s= 1–8 mT. 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 Figure 1. Each point of dielectric breakdown strength of the magnetic fluid was measured seven times and the maximum and minimum

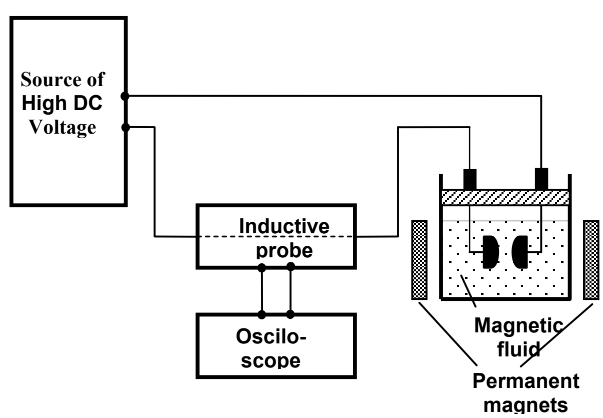

Figure 1: Experimental set up

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%.

3 INFLUENCE 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]

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

where r is radius of particle, ε_{r0} is relative permitivity of oil and ε_r is relative permittivity of particle oil cluster in surfactant .

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

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

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

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

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

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

Where D is diffusion coefficient and $N(x)$ *is* particle concentration. Modification of equation (3) and (4)

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

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

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

Then it is possible to write

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

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 V/m.

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 AND DISCUSSION

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 (Figure 2) was observed by optical and electron microscope.

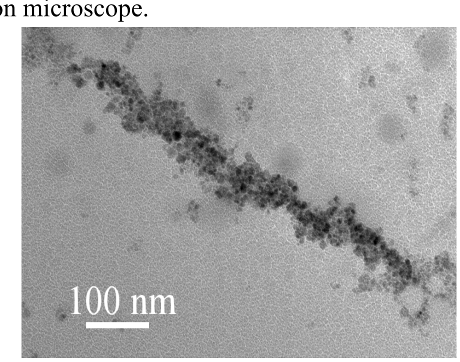

Figure 2: The magnetic particles aggregation in magnetic fluid with volume concentration of NPs f= 0.015.

The structure of magnetic particles in MF was solved in [6]. It was observed that clusters of magnetic particles in

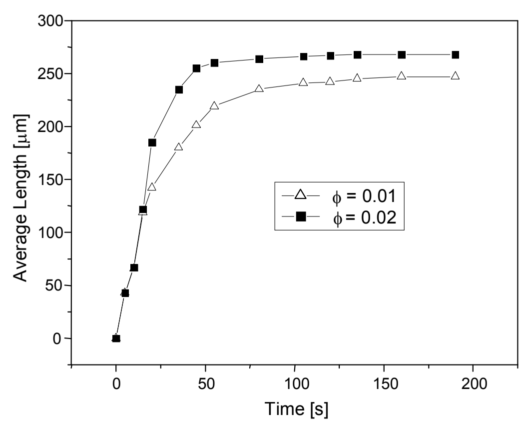

Figure 3: The average length of the needle like clusters vs. time after application of magnetic field 10 mT

NSTI-Nanotech 2009, www.nsti.org, ISBN 978-1-4398-1782-7 Vol. 1, 2009

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 wasreached after 3 minutes (Figure 3). Figures 4 and 5 illustrate the dependencies of the DC dielectric breakdown strength on the distance between the electrodes for two values of saturation magnetizations (low at Φ =0.0025 and high at Φ = 0.02) and various orientations of external magnetic field. In both fluids the DC-dielectric breakdown strength reaches its highest values at the $H \perp E$ orientation. The dielectric properties of magnetic fluid with Φ = 0.0025 and I_S=1mT are better than those of the pure transformer oil (Figure 4). In magnetic fluid with Φ = 0.02 and I_S=8 mT these properties are worse (Figure 5). The crossover from better to worse dielectric properties was found to appear in magnetic fluid with I_S=4 mT and Φ=0.01, approximately.

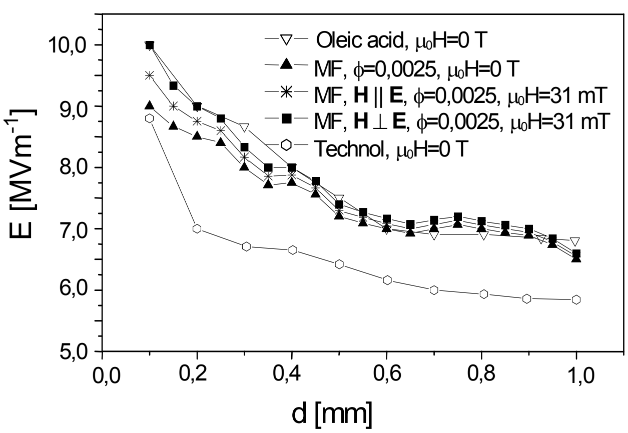

Figure 4: Dielectric breakdown strength vs. distance between the electrodes for concentration Φ=0,0025.

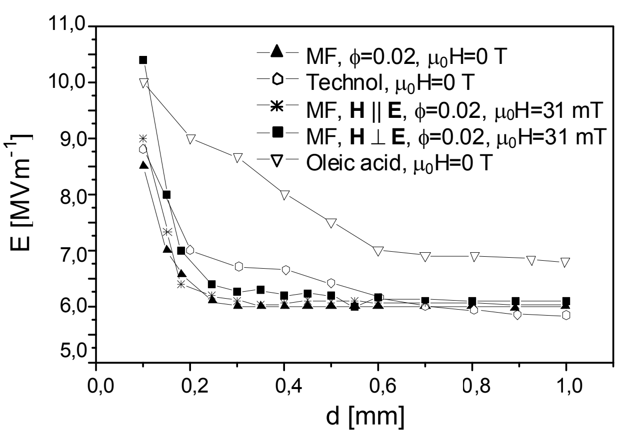

Figure 5: Dielectric breakdown strength vs. distance between the electrodes for magnetic fluids Φ =0,02 and I_s=8mT

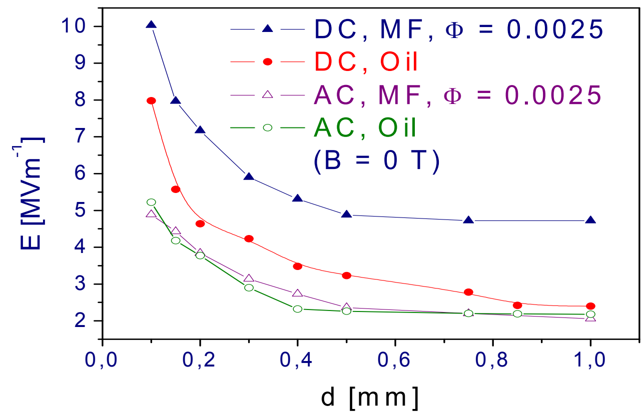

Figure 6: The AC dielectric breakdown strength vs. distance between the electrodes in magnetic fluid with concentration Φ= 0.0025) in B = 0, B||E and B ⊥ E.

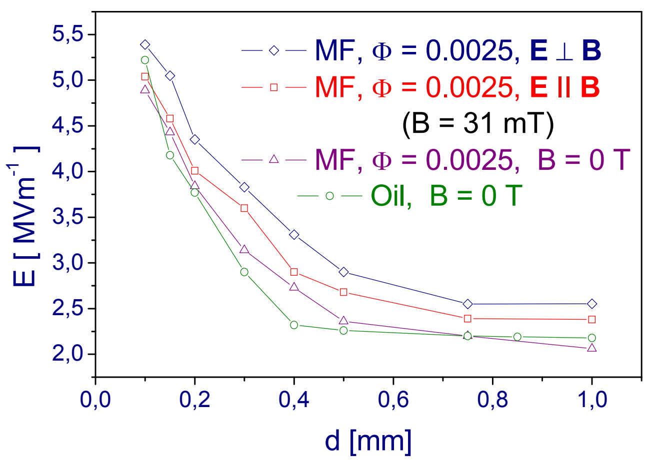

Figure 7: The DC and AC dielectric breakdown strengths of magnetic fluid (Φ= 0.0025) and pure transformer oil.

This is in agreement with the observations of Segal et al. [7] found for the DC impulse voltage. The development of the AC dielectric breakdown in magnetic fluid was compared with the development of the DC dielectric breakdown.

The AC dielectric breakdown strength of magnetic fluid as a function of the distance between the electrodes in uniform electric gap was investigated for H = 0 and in magnetic field H = 31mT, oriented parallel and perpendicular to the electric field. As Figure 6 shows, in all three cases the decrease of the dielectric breakdown strength E with increasing d was observed. This is in agreement with theoretical predictions of Gupta and Sen [8], who studied the dielectric breakdown in a semi-classical bond percolation model for a non-linear composite material. The measured DC and AC dielectric breakdown strengths of magnetic fluid, compared with the DC and AC dielectric breakdown strengths of pure transformer oil, are shown in Figure 7. As the DC dielectric breakdown strength of studied magnetic fluid was found to be higher than that of pure transformer oil, the AC breakdown strength remains comparable with that of transformer oil, but not worse.

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 [9] in transformer oil based magnetic fluid with volume concentration of magnetite nanoparticles 0.0025. The experiments were carried out in parallel orientation of **E** and **H** (**E**||**H** at B=40 mT). The development of dielectric breakdown in AC electric field is shown in Figure 9. The course of time dependence of electric channel in observed interval (500 ns) can be divided into 3 regions. In the 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 bound electric charged particles to direction of electric intensity without irrespective of existence external magnetic field,. When electric intensity is greater than 10^7Vm^{-1}, the current in breakdown channel increases exponentially 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 of oscillation effect has

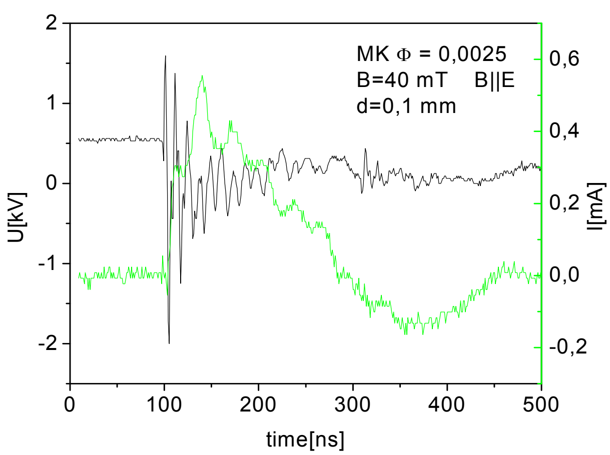

Figure 9: The time dependence of voltage and current in AC electric field and magnetic field B=40 mT.

also exponential attribute with lasting time equal to period of increasing density up to electric breakdown.

5 CONCLUSION

To conclude it can be said that the field induced aggregation of magnetic particles can significantly change the dielectric breakdown strength of magnetic fluids if the sizes of the aggregates are comparable with the distance between the electrodes of the measured gap. The comparison of the AC-dielectric breakdown strengths of pure transformer oil and transformer-oil based magnetic fluid showed better insulating properties of magnetic fluid in external magnetic field and comparable, but not worse, in B = 0. Regarding to the better heat transfer, provided by magnetic fluids, their application in power transformers may lead to the improvement of the operation of these devices. 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 work was supported by VEGA No. 0077, APVV-0509-07, NFP26220120051 and MNT ERA-Net project.

REFERENCES

[1] Xu. Pei-ying, Shi. Dong-Ning, Lu Xuai-xian, Acta Phys. Sinica **39**, 1192 (1988).

[2] P. Kopcansky, J.Cernak, P. Macko, D. Spisak, K. Marton, J.Phys. D: Appl. Phys. **22**, 1410 (1989).

[3] I. Kolcunova, R.Cimbala, The Transport Phenomena in Natural Liquid Esters, Scientific Proceedings of Riga Technical University , Riga seria 4 Volume 22 , pp 55-62, 2008, ISSN 1407-7345.

[4] E. Kuffel, W.S. Zaeungl, High Voltage Engineering Fundamentals, Pergamon Press Oxford, 1984.

[5] R.W.Chantrell, J.Popplewell, S.W. Charles, IEEE Trans. Mag. 14, 1978, 975.

[6] K.Marton, L. Tomco, M. Koneracka, P. Kopcansky, M. Timko, 5th International Conference VŠB TU Ostrava, 2003.

[7] V. Segal, A. Hjortsberg, A. Rabinovich, D. Natrass, and K. Raj, in: Conference Record of 1998 IEEE International Symposium on Electrical Insulation (Arlington, VA, USA, 1998), pp. 619–622.

[8] A. K. Gupta and A. K. Sen, Physica A 247, 30–40 (1997).

[9] R.Cimbala, I. Krsnak, I. Kolcunova, The Computation of Influence of Steady Element on Polarization Spectrum, Journal Acta Polytechnica Prague Vol. 43, No. 2/2003, str.3-9, ISSN 1210-2709.