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The development of electric breakdown in magnetic fluids in combined magnetic and electric fields

***Streszczenie:** (**Rozwój przebicia elektrycznego w cieczach magnetycznych w równocześnie działających polach magnetycznych i elektrycznych**). Badano rozwój przebicia elektrycznego w cieczach magnetycznych (MFs). MFs spreparowano z cząstek magnetycznych (Fe_3O_4) o wymiarach nanometrowych pokrytych kwasem oleinowym jako czynnikiem powierzchniowym, rozpuszczonych w oleju transformatorowym. Działano równocześnie stałym polem elektrycznym i magnetycznym na ciecze i obserwowano procesy elektrofizyczne, które wpływały na przebicie. Szczególną uwagę poświęcono stanom przedprzebiciowym, przebicia i poprzebiciowym w cieczach magnetycznych.*

***Abstract:** The development of electric breakdown in magnetic fluids (MFs) has been analyzed. MFs have been consisted of magnetit particles (Fe_3O_4) of nanometric size that were coated with oleic acid as a surfactant and dispersed in transformer oil. The DC electric and constant magnetic fields have affected on MFs simultaneously and electro-physical processes, which influence electric breakdown, were obserwed. The especial attention was devoted to pre-breakdown, breakdown and post- breakdown state in MFs.*

Słowa kluczowe: przebicie elektryczne, stany przedprzebiciowe, przebicia i poprzebiciowe, ciecz magnetyczna, pola elektryczne i magnetyczne, strukturalizacja cząstek magnetycznych
Keywords: electric breakdown, pre-breakdown, breakdown and post-breakdown state, magnetic fluid, combined electric and magnetic fields, structuralization of magnetic particles.

Introduction

It is well known that as a consequence of dipol-dipol 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 behaviour 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] 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 polarizable 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 [3].

The motivation of this work was to study the influence of combined electric and magnetic fields on electric stability of MFs. The first period of our work was oriented on investigation of both pre-breakdown state and electric stability of MFs during co-operation both homogeneous electric field created by high DC 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 effects.

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 log-normal particles size parameters were D_v = 8.6nm and standard deviation σ = 0.15 obtained by means of Chantrell et al [4] technique from VSM magnetization measurements.

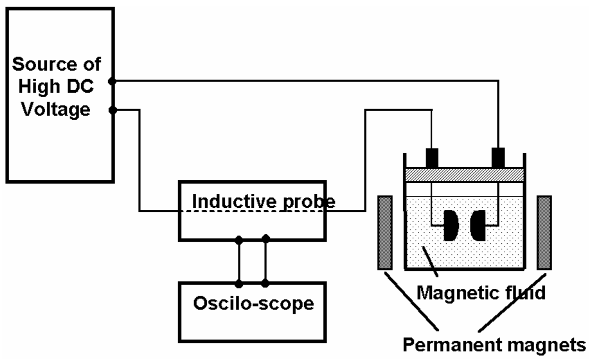

Fig.1. The experimental set up

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 [3]. 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 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%.

The channel of dielectric breakdown

The attention was devoted to research of the formation of electric discharge channel in both electric and combined electric and magnetic fields.The time of the formation of electric discharge up to breakdown was studied. The course of current – time dependence was recorded.

MFs are complex materials, that´s why during their stress by electric and magnetic fields dominate mainly these forces: gradient´s, Stokes, diffusional and force that is caused by magnetic field.

The total force acting on the particles during action of electric and magnetic fields on MF equals on the ground of the principle of superposition:

(1) $$\overline{F} = q\overline{E} + q\overline{v}x\overline{B}$$

This force changes velocity $\overline{v}$ of particles, what we can express by differential equation:

(2) $$\overline{F} = m\frac{d\overline{v}}{dt} \text{ or } m\frac{d\overline{v}}{dt} = q\overline{E} + q\overline{v}x\,\overline{B}$$

Let us divide vectors of a particle velocity $\overline{v}$ and intensity of electric field $\overline{E}$ into components paralel (//) and perpendicular (⊥) relative to vector $\overline{B}$:

$\overline{v} = \overline{v}_{//} + \overline{v}_{\perp}$ a $\overline{E} = \overline{E}_{//} + \overline{E}_{\perp}$.

Then equation (2) will be in form:

(3) $$m\frac{d\overline{v}_{//}}{dt} + m\frac{d\overline{v}_{\perp}}{dt} = q\overline{E}_{//} + q\overline{E}_{\perp} + q\overline{v}_{//}x\overline{B} \;\; a \;\; q\overline{v}_{\perp}x\overline{B}$$

The terms of equation (3) that contain parallel components relative to $\overline{B}$ ($\overline{v}_{//}$ a $\overline{E}_{//}$) are of value zero. As a result of equation (3) particles will move by cykloid and their track lengthen considerably. This effect influences electric stability of investigated medium (MF).

The preparation of dielectric breakdown (pre-breakdown state) and the formation of electric discharge channel is based on creating of an electric conductive bridge in space between electrodes. The change of particle concentration N in place, where value of electric intensity is maximum, is described by equation:

(4) $$\frac{\partial N}{\partial t} = -div(N.\vec{v})$$

The velocity of particles has considerable importance in this case. We proved by physical-matematical analyse [6] that this velocity is determined by transversal component of velocity, difusal component and component that depends on intensity of electric field and is reverse proportional to induction $\overline{B}$ of magnetic field. Equation (4) can be rewritten to form:

(5) $$\frac{\partial N}{\partial t} = -\frac{\partial (Nv)}{\partial x}$$

The increasing of concentration of dipoles in place where electric intensity is maximum can be obtained by integration in dependence on time t. Electro-physical processes during building of bridge are depended on time, because there is time needed for creating of channel i.e. delay period of electric breakdown. The concentration change of particles is depended on total energy both electric and magnetic fields. The dependence is exponential and if $\overline{B}$ is constant then particles velocity and their concentration N increase. As a result current between electrodes increases exponentially too.

Results

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

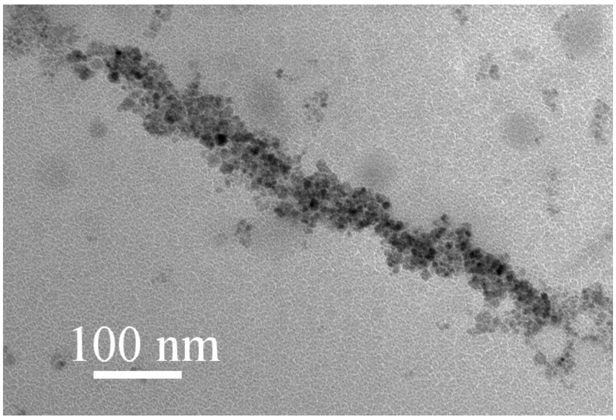

Fig.2. The example of the magnetic particles aggregation in magnetic fluid (observed in electron microscope) with concentration of magnetic particles f= 0.015

The structuralization of magnetic particles in MF was solved in [5]. 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 value of external magnetic field and concentration of magnetic particles. As a result agregation process is influenced by relative permittivity of MFs, concentration of magnetic particles in MFs and value of applied external magnetic field. The saturation of a cluster length of magnetic particles was reached after 3 minutes (Fig. 3).

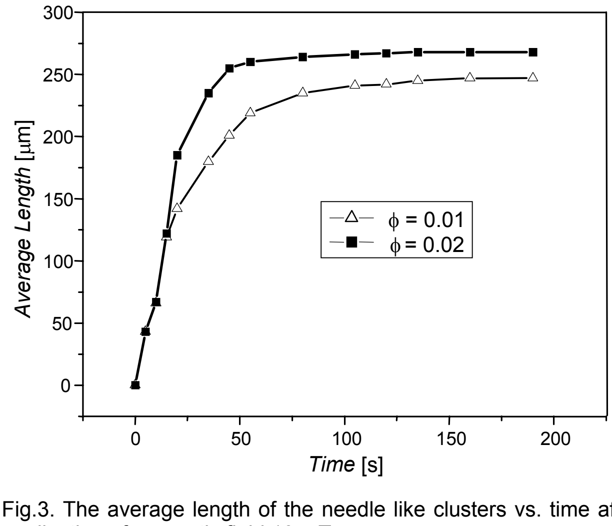

Fig.3. The average length of the needle like clusters vs. time after application of magnetic field 10 mT

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

The period of electric discharge formation during continual increasing of voltage in homogeneous DC electric field up to breakdown was observed in these materials: air, transformer oil ITO 100 and magnetic fluid with volume concentrations of magnetic 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 course of time dependence of current in air, transformer oil ITO 100 and in MF with magnetic particles concentration of value ϕ = 0.125% are illustrated in Figures 7, 8, 9, 10, and 11.

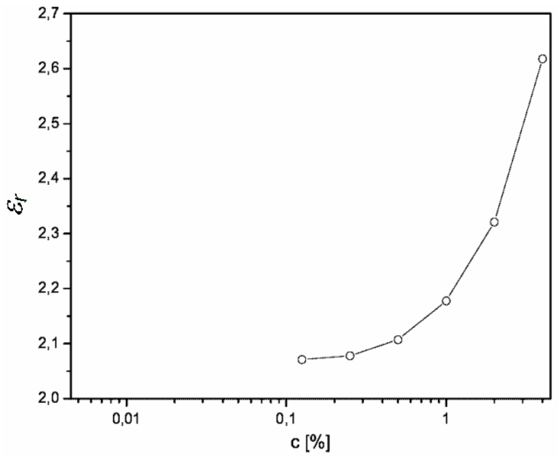

Fig. 4. The effect of volume concentrations of magnetic particles on the relative permittivity of MFs

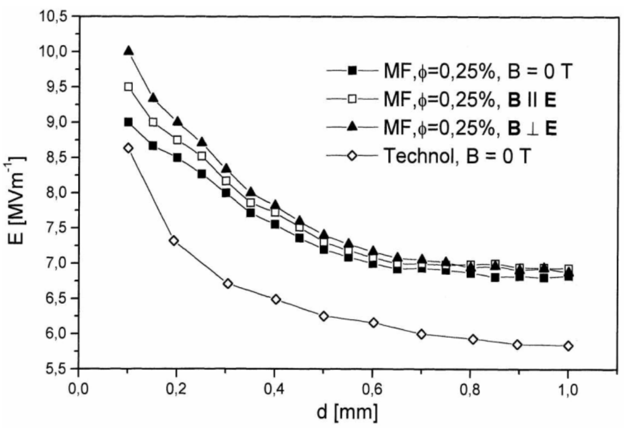

Fig. 5. Dielectric breakdown strength vs. distance between the electrodes for magnetic fluid (Φ =0.0025, I_s =1 mT) and transformer oil

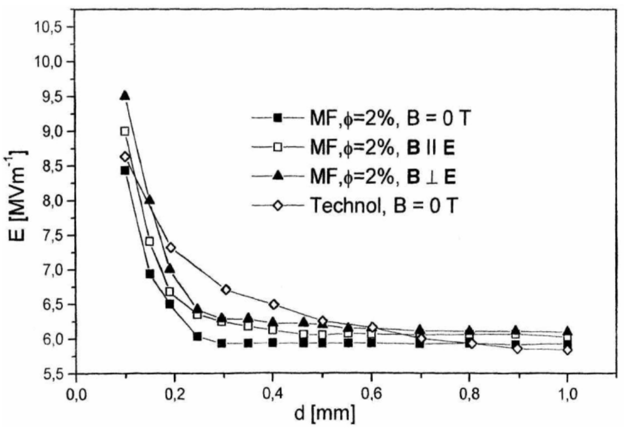

Fig. 6. The same as in Figure 5 but for Φ = 0.02, I_s = 8mT

The period of pre-breakdown state in investigated MF were in interval 150-220 ns what coresponds 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, MFs for all concentrations of magnetic particles 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, that magnify their size as a result of effect of electric 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).

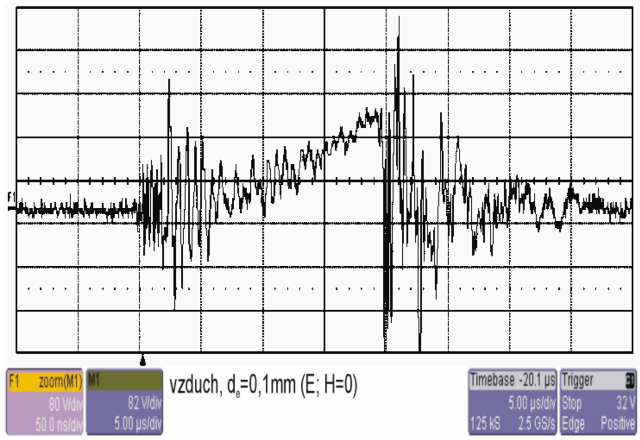

Fig 7. The time dependence of current in air

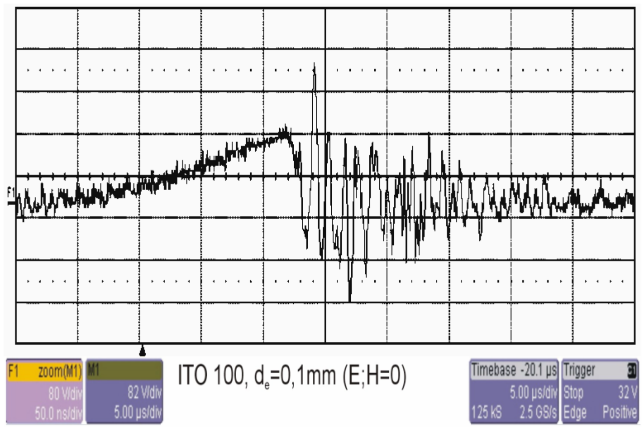

Fig 8. The time dependence of current in transfermer oil ITO 100

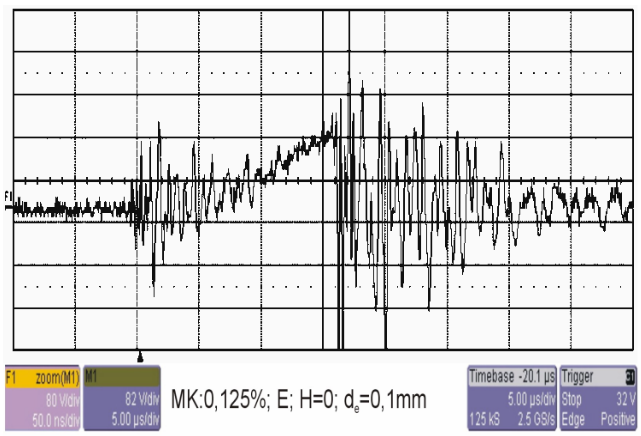

Fig 9. The time dependence of current in MF

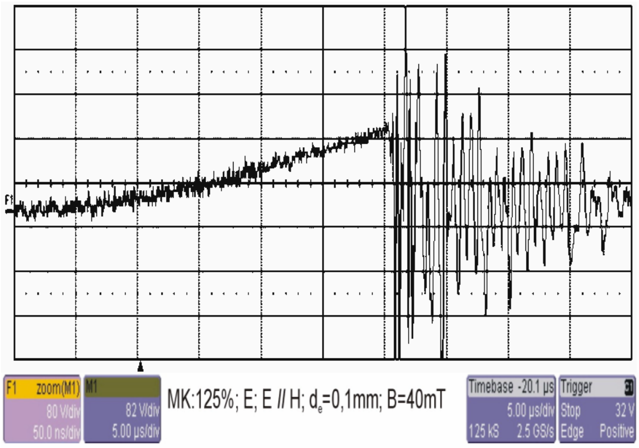

Fig. 10. The same as in Figure 9 but in external magnetic field when **E**||**H**

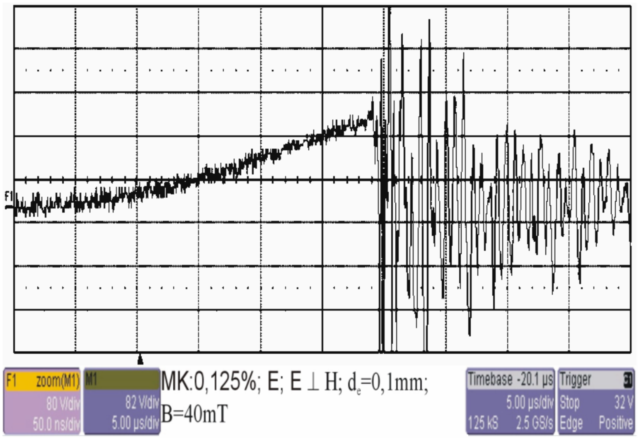

Fig. 11. The same as in Figure 9 but in external magnetic field when **E**⊥**H**

This effect is suppressed by external macroscopic magnetic field what can by observed (Fig. 8).

The time course of the formation of electric channel in observed time interval (500 ns) can be divided into three regions:

- in region of weak electric field (less then 10^7V/m) is carried out orientation of dipols of weak polar resp. polar material and also weak-binded electric charged particles to direction of electric intensity regardless of existence of external magnetic field,
- when electric intensity is greater than 10^7V/m current increases exponentialy in breakdown channel with transition from avalanche to streamer and leader character of discharge,
- in last stage, after creating of conductive channel, multiply oscillating current impulses of both polarities rise with time of existence 2-3 ns. The amplitudes of this current impulses exceed three times current amplitudes in pre-breakdown region. The attenuation of oscillation effect has also exponential course. The period of the attenuation equals to period of increasing of current density up to electric breakdown.

Conclusion

This contribution is theoretical introduction supported by experiments to study of creating, resp. formation of electric channel that creates track for electrical breakdown. The electro-physical accounting for formation of conductive channel is done on the base of a time change of concentration of electric charge carriers in dependence on their positions. This effects have been studied in coexistence of electric and magnetic field.

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The Slovak Academy of Sciences and Ministry of Education of SR, within the framework of Project VEGA No. 3199 and No.0383, supported this work.

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