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Novel method of charge mobility assignation in liquid dielectrics by streaming electrification

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The mobility of charge carriers is the parameter used for describing conductivity caused by the electrification activity. It is studied for substances of various states of aggregation, in the range including gases, liquids and solid bodies, for conductors, semi-conductors and dielectrics. The knowledge of this value is of great significance for the research work on insulation liquids. Transformer insulation oils, where due to the range of interest this issue is especially significant, serve as a good example. The paper presents a new method of the research on the mobility of charge carriers in insulation liquids, based on the application of the streaming electrification measurements of such liquids.

Key words: *mobility; streaming electrification; oil insulation*

1. Introduction

In insulation liquids, despite the fact that they are dielectrics, an infinite number of charge carriers exist. Their behaviour in the electric field is of significance in the description of the mechanisms of conductivity, loss, breakdown, charge injection from the electrodes, currents limited by a spatial charge and electroconvection phenomena. The parameter used for describing the behaviour of charge carriers is their mobility. In practice, a lot of methods are used for investigating the charge carrier mobility in conductors, semi-conductors and insulators. Their application results from the usefulness of the particular methods. In insulation liquids, the research work in this scope was developed by Adamczewski [1]. The research was based on examining the phenomenon of conductivity induced by an external ionizing factor. An observation of the phenomenon of the currents limited by the spatial charge was carried out as well. Also the research work on the charge injections from the electrodes was of great significance. The methods based on the measurements of the Hall phenomenon, so widely used in the research on carrier mobility in semi-conductors, did not find their application in

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the research on charge mobility in dielectric liquids. However, the mobility measurement method, based on the observation of the electrokinetic phenomena, the so-called electrophoresis phenomenon, was found useful. The method is based on the measurement of electrokinetic potential ζ. It may be determined through the observation of movement of solid particles in liquid affected by the electric field applied [2, 3].

The paper presents the suggestion of determining the charge carrier mobility in liquid using for measurements a different electrokinetic phenomenon – the so-called flow potential.

2. Streaming electrification

The flow potential occurs when, on the border of the solid and liquid phases, their mutual relocation takes place causing the disruption of the charge double layer on their border. The electrostatic charge that is generated may be of a high value and constitute hazard to the apparatus in which it occurs. Such hazard was observed in power transformers with a forced insulation oil flow. Due to a considerable hazard to the insulation caused by the static electricity generated, thus also economic aspects, these issues have been investigated in a wide range of the occurring phenomena [4, 5]. They can be presented on the example of the research tests carried out in a model laboratory system with a spinning disk [6, 7] (Fig. 1).

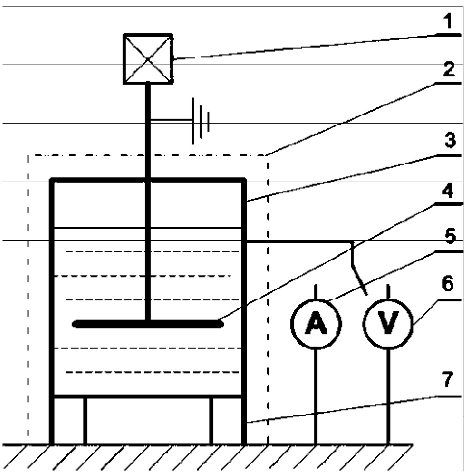

Fig. 1. Diagram of the measuring system with a spinning disk: 1 – motor, 2 – shield, 3 – measuring container, 4 – spinning disk, 5 – electrometer, 6 – electrostatic voltmeter, 7 – insulators

On the interfacial surface (the solid phase of the disk and the liquid under study), a double layer of charges is formed due to a selective adsorption of ions. The activity of centrifugal forces at the disk rotation causes its disruption. The charge generated can be the source of the current measured with an electrometer or charge the capacity of the disk–measuring container and be measured with an electrostatic voltmeter. Hydrodynamic conditions, at which the electrostatic charge generation takes place, depend on the disk size, its rotations and on the properties of the liquid under study. Figures 2–5 show selected characteristics that determine them. They were calculated for insulation oil the properties of which are shown in Table 1.

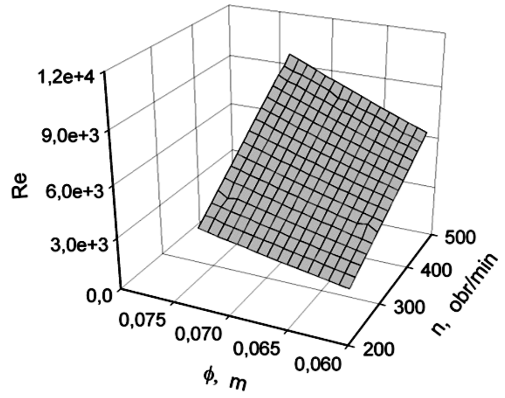

Fig. 2. Dependence of the Reynolds number on the rotational speed and the disk diameter

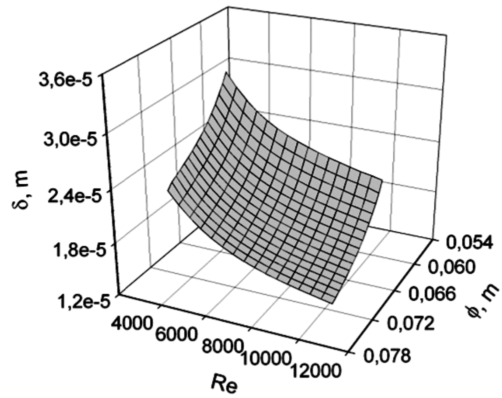

Fig. 3. Dependence of the laminar layer thickness on the Reynolds number and the spinning disk diameter

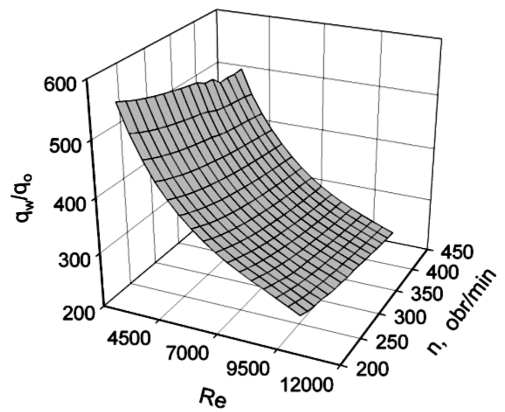

Fig. 4. Dependence of q_w/q_0 on the Reynolds number and rotational speed of the disk

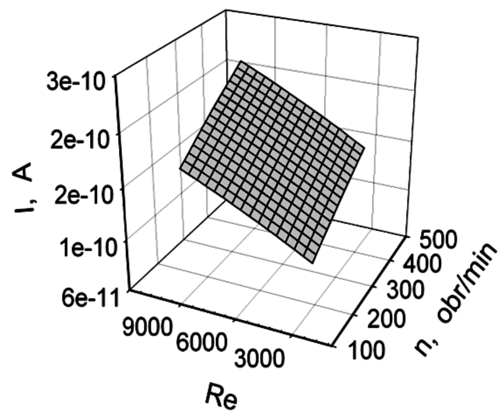

Fig. 5. Dependence of the electrification current on the Reynolds number and rotational speed of the disk

The dependence of the Reynolds number on rotational speed and the disk diameter is shown in Fig. 2. The range of the presented values *Re* refers to turbulent flows. Then, on the border of the solid and liquid phases, it is possible to distinguish a laminar sublayer, which, further on, moves into the turbulent area. Its thickness, depending on the hydrodynamic conditions, is shown in Fig. 3. It decides, among others, on the change of volume charge density, which in the laminar sublayer is of value q_w and lowers to value q_0 in the turbulent flow area. The dependence of these changes is shown in Fig. 4, and the electrification current value measured in the external circuit is shown in Fig. 5.

3. Liquid electrification in the disk system

A lot of models have been published which try to present quantitatively the electrification process of the liquid under study [8]. One of the most common models is the Abedian–Sonin model, which for the disk system can be presented in the form [9]:

$$I = \frac{\sigma q_0 V}{\varepsilon_0 \varepsilon_w} + \frac{D_m q_0 S_t}{\delta} - \frac{D_m q_w S_t}{\delta} \tag{1}$$

where: σ is the liquid conductivity, V – liquid volume in the measuring container, ε_w – relative permittivity of the liquid under study, ε_0 – vacuum permittivity, D_m – *the* molecular diffusion coefficient in liquid, S_t – disk surface, δ – average thickness of the laminar sublayer on the disk surface.

The calculation of the electrification current from the Abedian–Sonin model requires the knowledge of the definite parameters characterizing the liquid under study, such as density (ρ), conductivity (σ), viscosity (ν), permittivity (ε_w), molecular diffusion coefficient (D_m), volume charge density (q_w and q_0). Also the knowledge of the parameters characterizing hydrodynamic conditions such as the Reynolds number, laminar sublayer thickness (δ), shearing stresses (τ_w) is necessary. The measurement of such values as ρ, σ, ν, ε_w does not cause a metrological problem. However, the molecular diffusion coefficient (D_m) is usually calculated from Adamczewski's dependence [1], and the knowledge of charge density q_w requires, first of all, the measurement of the charge q_0 volume density. It can be determined from the measurement of voltage generated on the patulous outlet of the disk system:

$$U = \frac{V q_0}{C} \tag{2}$$

where: V – volume of the liquid under study, q_0 – volume charge density in the liquid under study, C – electric capacity of the disk system.

A mutual relationship between charges q_w and q_0 is described by the dependence:

$$\frac{q_w}{q_0} = 1 + \frac{\delta V}{S \lambda^2} \tag{3}$$

where: λ – Debye's length ($\lambda = (D_m \varepsilon_0 \varepsilon_w)/\sigma)^{1/2}$), S – contact surface of the disk and the container with the liquid under study, δ – thickness of the laminar sublayer on the disk surface.

Therefore, determining the density of the volume charge q_w on the border of solid and liquid phases requires only the calculation of the thickness of the laminar sublayer δ:

$$\delta = \frac{11.7\nu}{\left(\frac{\nu}{D_m}\right)^{0.33}\left(\frac{\tau_w}{\rho}\right)^{0.50}} \tag{4}$$

where: ν – kinematic viscosity of the liquid, D_m – molecular diffusion coefficient, ρ – liquid density, τ_w – shearing stresses

$$\tau_w \approx 0.1 Re^{-0,5} \rho(\varpi R)^2$$

Using these data and dependences in the Abedian–Sonin model makes it possible to calculate the current generated in the disk system.

4. Measurement of the charge carrier mobility

Electrostatic charge generation in the disk system can be also verified by the measurement of the current on the system outlet. Combining the results obtained in the voltage and current systems makes it possible to calculate one of the parameters from the Abedian–Sonin model. When this parameter is the molecular diffusion coefficient (D_m), then by using Einsten's dependence:

$$\frac{D_m}{\mu} = \frac{kT}{e} \tag{5}$$

we obtain the possibility of determining the charge carrier mobility in the liquid under study. The measurements of the electrification current and the voltage generated were taken for fresh transformer oil. Table 1 shows the properties of the oil under study and the parameters of the measuring system.

Table 1. Properties of the oil under study
and the parameters of the measuring system

Property, parameter	Unit	Value
Density (ρ)	kg/m^3	874
Viscosity (ν)	m^2/s	$2.38 \cdot 10^{-5}$
Permittivity (ε_w)	–	2.239
Conductivity (σ)	$\Omega^{-1} \cdot m^{-1}$	4.2×10^{-13}
Disk radius (R_1)	m	0.0675
Container radius (R_2)	m	0.075

The dependences of the electrification voltage on the disk rotational speed is shown in Fig. 6, and the dependence of the electrification current on the disk rotational speed is shown in Fig. 7.

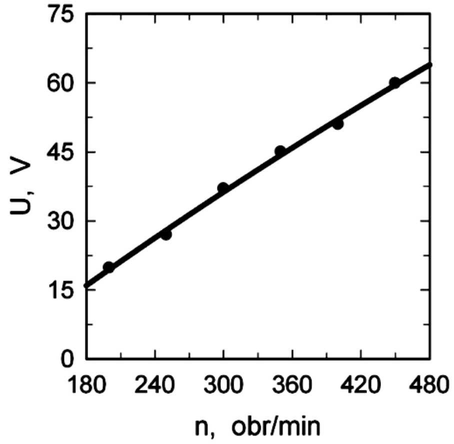

Fig. 6. The dependence of the electrification voltage on the disk rotational speed

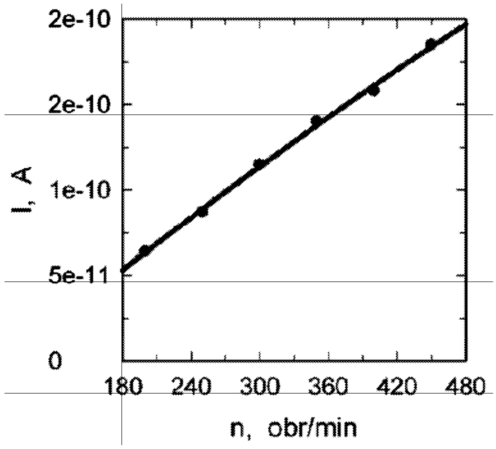

Fig. 7. The dependence of the electrification current on the disk rotational speed

Combining the dependence for the electrification current (1) with the dependence for the electrification voltage (2), through Einstein's dependence (5), the charge carrier mobility in insulation oil was calculated. The results are shown in Fig. 8.

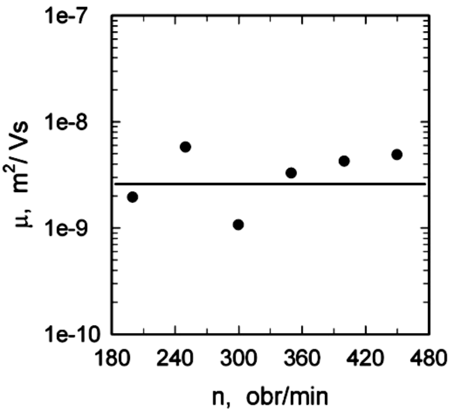

Fig. 8. Charge carrier mobility at various rotational speeds of the disk

The average value of the carrier mobility, obtained at various rotational speeds of the disk, is marked with a horizontal line. A considerable correspondence, of the value occurring in literature, of about (1×10^{-9} m^2/Vs) was obtained.

5. Summing-up

The obtained results of the charge carrier mobility in insulation oil prove that the research on the streaming electrification can be found useful for the evaluation of the conductivity phenomenon in such liquids. However, the method suggested still requires verification, first of all with the application of pure hydrocarbons. Insulation oils are liquids of a very complex chemical constitution, which makes it difficult to compare the research results obtained.

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