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MEASUREMENTS OF PHYSICOCHEMICAL AND ELECTRICAL PROPERTIES OF INSULATING LIQUIDS

This paper provides a comparative analysis of key physicochemical and electrostatic parameters of Trafo En oil and Midel 7131® synthetic ester, changing in temperature and accelerated thermal ageing. The parameters tested included the density, kinematic viscosity, conductivity and relative electric permittivity. In addition to that, Electrostatic Charging Tendency (ECT) tests of those fluids were performed in a flow system using cellulose and aramid paper pipes. The effect of liquid flow velocity combined with temperature variations and accelerated ageing time on the streaming electrification current generated was determined. The relationship between the fluid electrification degree and measuring pipe material was also investigated.

KEYWORDS: Dielectric liquids, Transformer insulation, Electrical properties, Streaming electrification.

1. INTRODUCTION

The increase of demand for electric power imposed the necessity to increase the efficiency of power transformers. Engineering works in the scope of designing modern constructions of transformers aim at increasing the power of these facilities and at the same time minimizing their mass and size. This is possible owing to the application of modern solid and liquid insulating materials of increased electroinsulating parameters. They include natural and synthetic ester liquids [1] and aramid papers [2]. In order to intensify the cooling of transformer windings, the rate of the insulating liquid flow is increased. The side effect of this solution is the occurrence of the streamlining electrification phenomenon in a transformer [3]. The issue of electrification was dealt with by the working team 12/15-02 appointed by CIGRE [4], Massachusetts Institute of Technology (MIT) and Electric Power Research Institute (EPRI) [5]. The investigations of streaming electrification were carried out on real transformers [6] and large laboratory models [7]. The next step was the introduction of small flow and rotating laboratory systems [8]. The aim of the research is getting to know the nature of the generated phenomenon of streaming electrification and developing effec-

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tive methods of its elimination. Mineral and synthetic oils, pure hydrocarbons and their mixtures are investigated [9-11]. The influence of hydrodynamic conditions [12], temperature [13], aging processes [14], and also the properties of solid material are analyzed.

2. EXPERIMENTAL METHOD

In order to determine the ageing degree of an insulating fluid its resistance to oxidation was determined. This parameter depends on the acid value and amount of sludge formed. The ageing tests most commonly used in Europe include the methods IEC 74, IEC 474, as well as the new method IEC 813, which are currently compiled under IEC 1125 as A, B and C. The acid value of Trafo En mineral oil and Midel 7131® synthetic ester was determined in the ageing test using method C, consisting in blowing oxygen into the liquid at 120°C, using copper as catalyst. The density (ρ) of the insulating fluids tested was determined experimentally with an areometer, in compliance with ISO 3675. Conversion table of ISO 91-2 (at 20°C) was adhered to in converting the density to any temperature value. Kinematic viscosity (ν_k) vs. temperature of the insulating fluids tested was measured with a Brookfield Dv-Ii+Pro viscometer according to ISO 3104. Conductivity (σ) of the fluids was determined based on their resistance measurement according to IEC 60247, with a three-terminal capacitor and Megger BM25 meter. The relative electric permittivity (ε_r) was determined indirectly, as the ratio of electric capacitance of a capacitor with dielectric between plates to capacity of an air capacitor (IEC 60247 standard). A three-terminal capacitor and Hioki 3522-50 LCR Hitester device were used in the tests. Figure 1 shows a general diagram of the system for investigating streaming electrification of insulating liquids. The liquid under study (1), flowing from the upper container (2) through a pipe (3) becomes electrified and streams down to the separated lower container (4) placed in a Faraday cage (5). The flow of the gathered excessive electric charges to the ground is registered with a Keithley 6517A electrometer (6). The liquid flow rate through the pipe is regulated through the change of the pressure value of the gas pad (nitrogen) in the upper container. The liquid flow time through the measuring pipe is controlled by a solenoid valve (7). The liquid temperature is changed with a heater with a thermostat (8). Acquisition and initial processing of the measurement data from the electrometer takes place with the application of the measurement software installed on a portable computer (9). The pipes used for tests were made of cellulose paper made by Tervakoski, and Nomex® paper made by Dupont. Their length was 400 mm and diameter 4 mm. The measures were taken in temperature changing in the range from 20 to 80°C and liquid flow rate 0,34–1,75 m/s. Table 1 presents the most important physicochemical properties of the insulating fluids tested at 20°C.

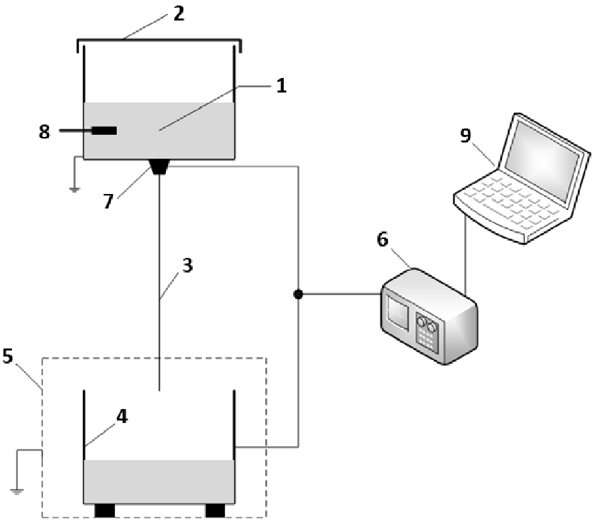

Fig. 1. Flow system with a pipe for testing streaming electrification of insulating fluids: 1 – insulating liquid, 2 – top tank, 3 – measuring pipe, 4 – bottom tank, 5 – Faraday cage with measuring tank located inside, 6 - Keithley 6517 electrometer, 7 – solenoid valve, 8 – heater, 9 – notebook

Table 1. Properties of the insulating liquids under study (20°C).

Property, parameter		Value	
		Trafo En	Midel 7131®
Density (ρ)	[kg/m^3]	885	970
Viscosity (ν)	[m^2/s]	$2{,}04 \cdot 10^{-5}$	$7 \cdot 10^{-5}$
Molecular diffusion coefficient (D_m)	[m^2/s]	$4{,}35 \cdot 10^{-5}$	$1{,}16 \cdot 10^{-7}$
Relative permittivity (ε_r)	–	2,23	3,19
Conductivity (γ)	[S/m]	$7{,}94 \cdot 10^{-13}$	$8{,}77 \cdot 10^{-12}$

3. RESULTS OF EXPERIMENTS

3.1. Testing of physicochemical parameters

Figure 2 presents the results achieved for the acid value vs. the accelerated ageing time. The resulting data demonstrates that MIDEL 7131® fluid exhibits a higher ageing resistance than Trafo En oil. For mineral oil, considerable change of that parameter is observed, which for the ageing time 100 h reaches almost a tenfold value. Midel 7131® synthetic ester is characterised by higher stability of acid value in the entire time interval analysed.

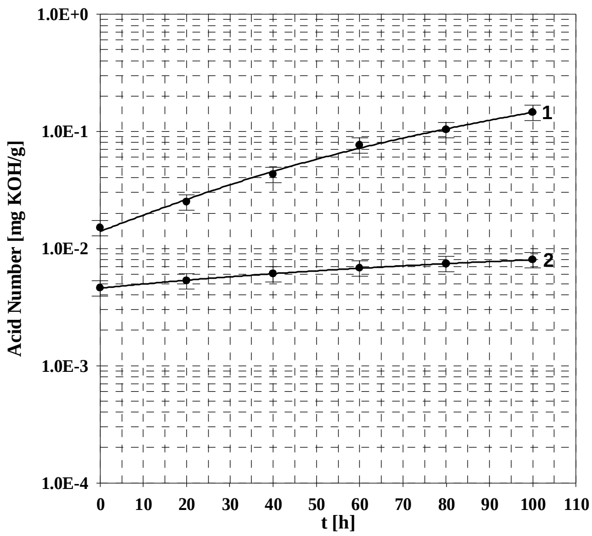

Fig. 2. Acid number vs. accelerated ageing time: 1 – Trafo EN oil, 2 – Midel 7131® synthetic ester

Figure 3 shows the plots of density changes vs. temperature for Trafo En oil and Midel 7131® synthetic ester. The functions ρ = f(T) recorded are linear and decrease along with temperature increase, whereby the density decreases a little faster in the ester than in the oil. Analysing the data of the plot, it can be noted that the density of organic ester at 20°C is higher by 85 kg/m^3 than that of the mineral oil. The difference decreases as the temperature of both fluids increases.

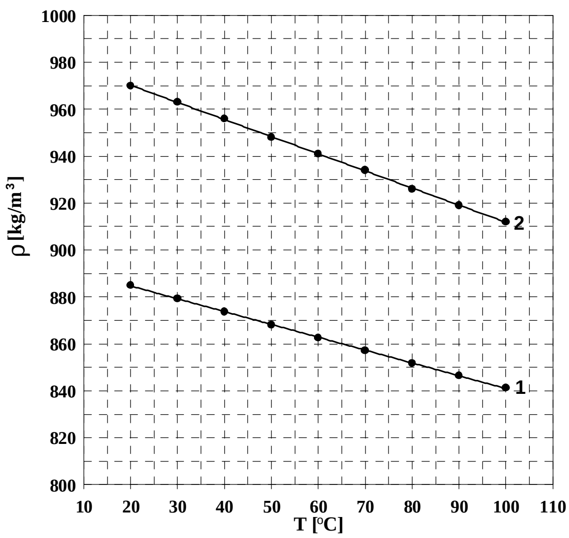

Fig. 3. Density vs. temperature: 1 – Trafo EN oil, 2 – Midel 7131® synthetic ester

The data presented in Figure 4 indicates that viscosity of both fluids decreases in a non-linear manner over the entire temperature range analysed. Midel 7131® insulating fluid, both at low and high temperatures, is characterised by almost three times as high viscosity value as that of TRAF EN mineral oil. Therefore, it has to be concluded that the mineral oil is more suitable for cooling the active part of the transformer than Midel 7131® synthetic ester.

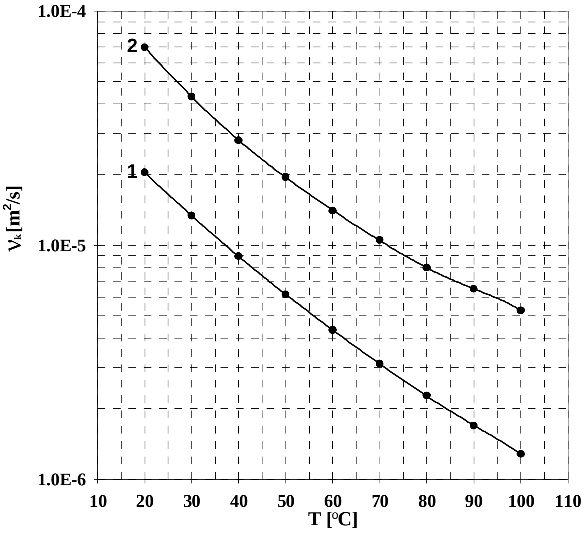

Fig. 4. Kinematic viscosity vs. temperature: 1 – Trafo EN oil, 2 – Midel 7131® synthetic ester

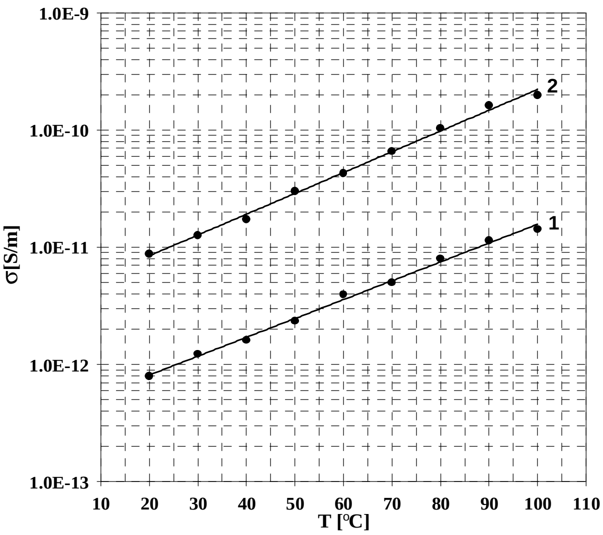

Fig. 5. Conductivity vs. temperature: 1 – Trafo EN oil, 2 – Midel 7131® synthetic ester

Figure 5 presents the relationships σ = f(T) between Midel 7131® fluid and Trafo En mineral oil. Analysing the plots, it can be stated that the synthetic ester shows greater conductivity than the mineral oil. Figure 6 shows conductivity plots recorded while changing the fluid ageing time. Increasing the ageing time results in a non-linear increase of conductivity, and more intense changes of that parameter are noted for the mineral oil. It reaches a comparable value for both fluids at the ageing time of 100 hours.

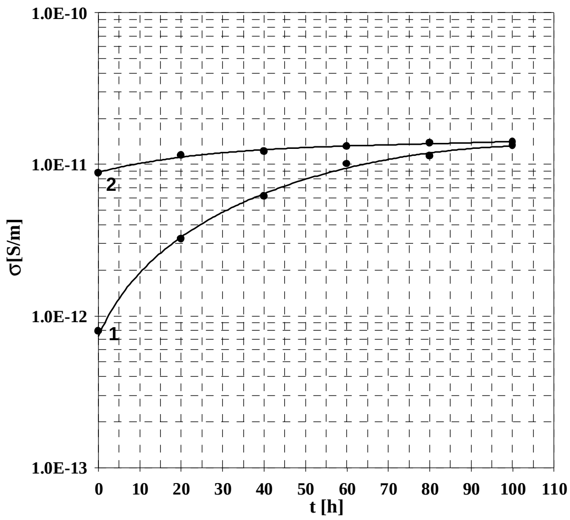

Fig. 6. Conductivity vs. accelerated ageing time: 1 – Trafo EN oil, 2 – Midel 7131® synthetic ester

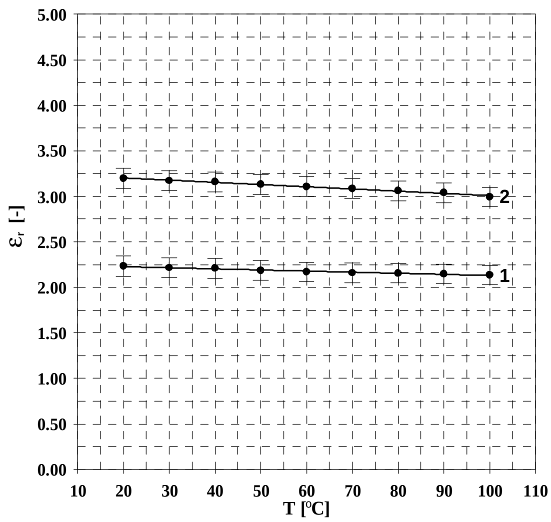

Fig. 7. Relative permittivity vs. temperature: 1 – Trafo EN oil, 2 – Midel 7131® synthetic ester

Figure 7 illustrates the effect of temperature on the change of the relative electric permittivity of the fluids tested. For Trafo En oil, that parameter reaches the value $\varepsilon_r = 2.23$ at 20°C. Permittivity of Midel 7131® is higher almost by one than the value determined for the mineral oil and is $\varepsilon_r = 3.19$. That temperature causes a slight, of several percent, decrease of dielectric permittivity in both liquids. Figure 8 depicts the relationship ε_r of mineral oil and ester fluid vs. the accelerated ageing time. It is apparent that ageing processes occurring in the insulating fluids tested have virtually no effect on the deterioration of electric permittivity.

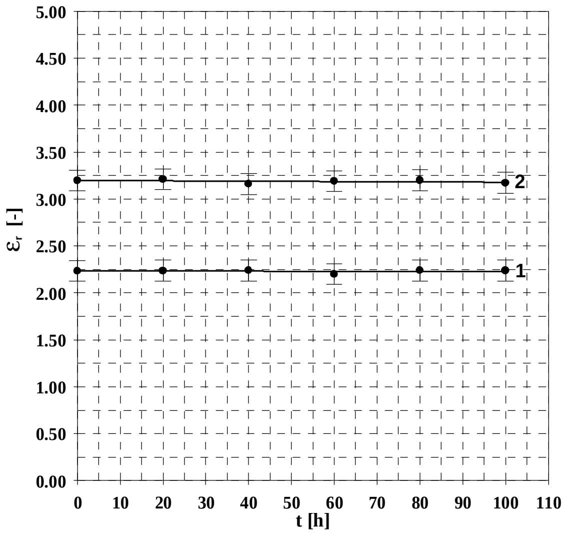

Fig. 8. Relative electric permittivity vs. accelerated ageing time: 1 – Trafo EN oil, 2 – Midel 7131® synthetic ester

3.2. ECT tests of insulating liquids

Temperature has a significant effect on the physicochemical properties of insulating fluids and, consequently contributes to the change of hydrodynamic conditions in the transformer. The type of solid insulation material used is also important here. Temperature-dependent processes occurring in transformer insulation may determine the streaming electrification phenomenon. Figures 9 and 10 provide 3D charts of electrification current changes vs. temperature and Trafo En oil flow velocity, using a measuring pipe made of cellulose and aramid paper. Analysing the plots, the temperature may be found to cause significant changes in ECT of the insulating oil. In the range between 20 and 50°C, the electrification current rises in a non-linear manner. Once that point is exceeded, the current curves begin to drop as far as to 80°C. In the temperature range considered, Midel 7131® synthetic ester shows no statistically significant changes of ECT (see Figure 11 and 12).

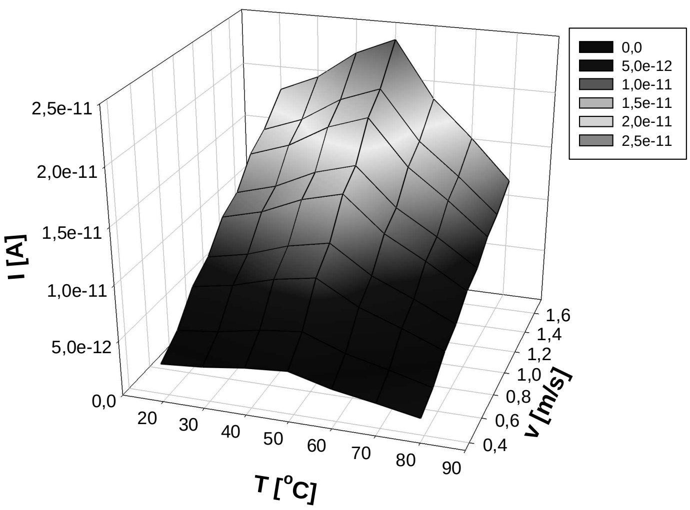

Fig. 9. Electrification current vs. temperature and flow velocity of Trafo En oil flowing through a cellulose pipe: l = 0.4 m; R = 2 mm

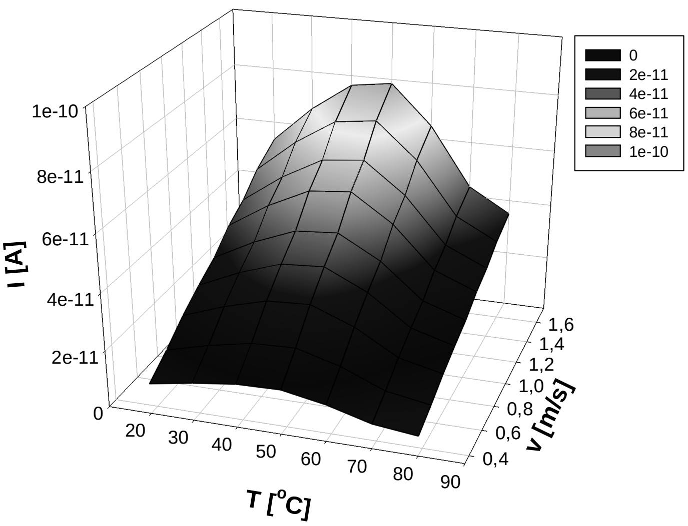

Fig. 10. Electrification current vs. temperature and flow velocity of Trafo En oil flowing through an aramid pipe: l = 0.4 m; R = 2 mm

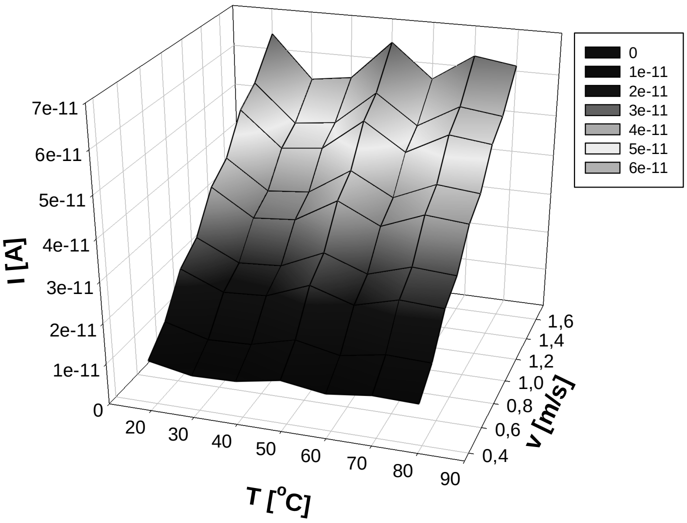

Fig. 11. Electrification current vs. temperature and flow velocity of Midel 7131® fluid flowing through a cellulose pipe: l = 0.4 m; R = 2 mm

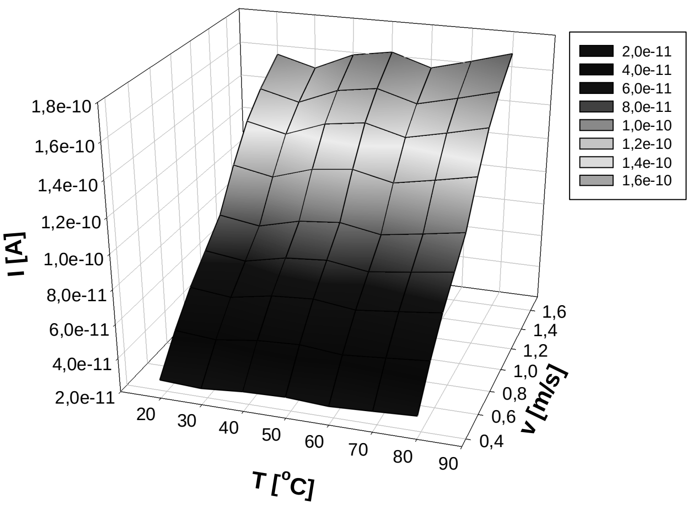

Fig. 12. Electrification current vs. temperature and flow velocity of Midel 7131® fluid flowing through an aramid pipe: l = 0.4 m; R = 2 mm

Ageing processes significantly affect also the electrification of mineral oil. Figures 13 and 14 show the relationships between electrification current of Trafo En oil, flow velocity and accelerated ageing time, for the cellulose and aramid pipes respectively. Rapid decrease of current value at the initial phase of ageing can be noted, which achieves its minimum (at t = 20 h), followed by its non-linear increase. For ageing time of 100 h, the current values equate with those recorded for fresh samples.

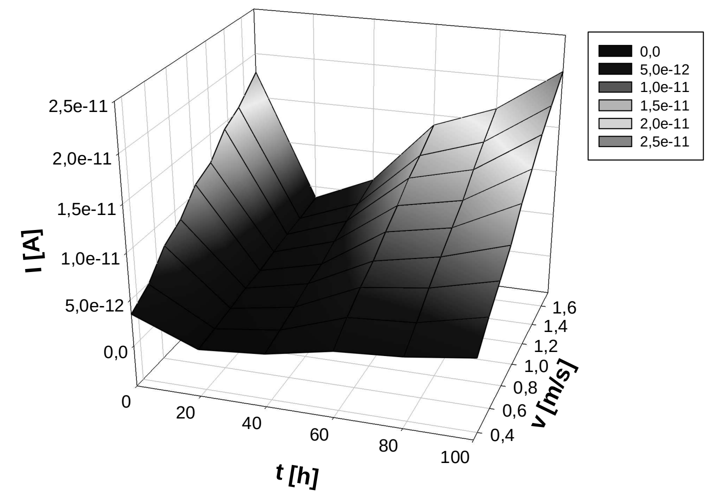

Fig. 13. Electrification current vs. accelerated ageing time and flow velocity of Trafo En oil flowing through a cellulose pipe: l = 0.4 m; R = 2 mm

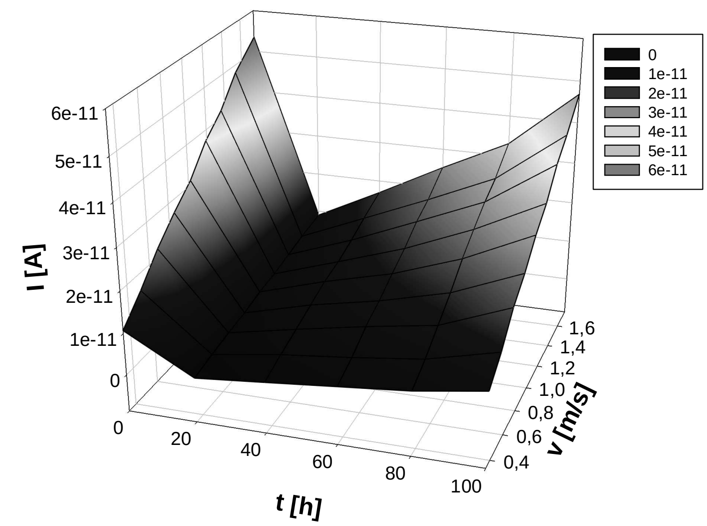

Fig.14. Electrification current vs. accelerated ageing time and flow velocity of Trafo En oil flowing through an aramid pipe: l = 0.4 m; R = 2 mm

Likewise the temperature, Midel 7131® ester fluid shows no significant dependency between ECT and sample ageing time (Figure 15 and 16). Changes of electrification currents in the mineral oil, as opposed to the ester fluid, are very rapid and show no clear regularity. Important factors in the electrification process for both fluids are the flow velocity and material of the measuring pipe. The tests demonstrated that the aramid paper increases electrification of insulating fluids almost three times, as compared to classic cellulose paper.

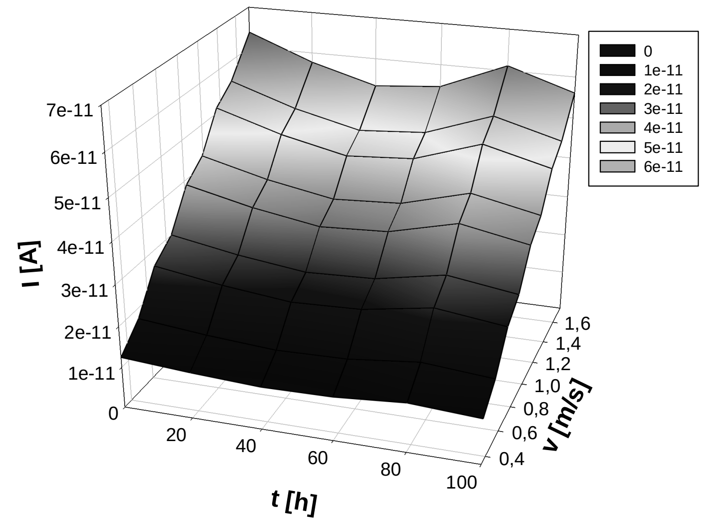

Fig. 15. Electrification current vs. accelerated ageing time and flow velocity of Midel 7131® fluid flowing through a cellulose pipe: l = 0.4 m; R = 2 mm

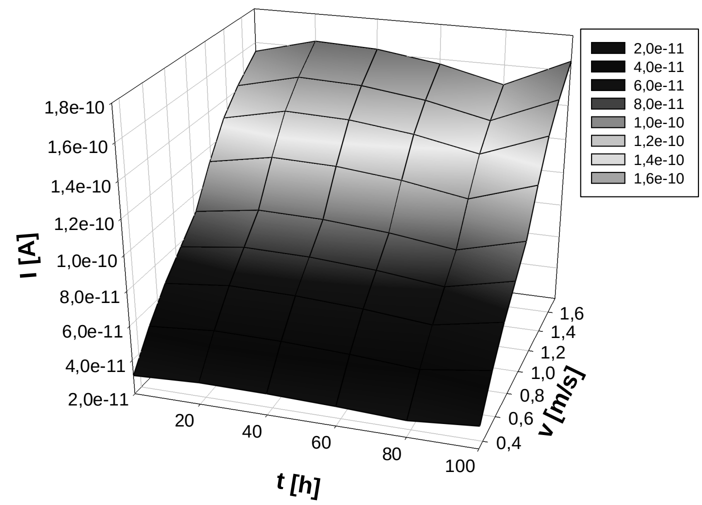

Fig. 16. Electrification current vs. accelerated ageing time of Midel 7131® fluid flowing through a cellulose pipe: l = 0.4 m; R = 2 mm

4. CONCLUSIONS

The work of the author aimed at providing a comparative analysis of physicochemical properties and ECT of Trafo En mineral oil and Midel 7131® synthetic ester, used as a cooling and insulating medium in power transformers. Tests of acid value proved higher resistance to oxidation of Midel 7131® fluid, comparing to Trafo En oil. Trafo En mineral oil is characterised by a lower density and viscosity than Midel 7131® synthetic ester which proves its better cooling properties. A conventional transformer oil is characterised by a lower conductivity, as compared to that of ester fluid, which proves its better insulating performance in this respect. Measurements of the relative electric permittivity proved that the synthetic fluid has the permittivity of approximately one relative unit higher than the mineral oil. This has a positive effect on stress distribution in the insulating system of a transformer, which may result in its increased strength. Analysing the effect of the measuring pipe material type on the streaming electrification, it was demonstrated that both insulating fluids had a lower ECT while flowing through a pipe made of standard insulating paper. Nomex®, advanced insulating material based on aramid fibres increases almost three times the susceptibility to electrification of the insulating fluids tested. The effect of temperature on the ECT of Trafo En mineral oil is revealed at the initial heating phase by an increase of the electrification current being recorded, followed by its decrease, when the temperature increases above 50 °C. The temperature does not significantly affect electrification of Midel 7131® ester. The electrification current measured remained relatively stable, regardless of the change of that parameter. Analysing the effects of the accelerated ageing time on electrification of the insulating fluids tested, it was proved that, in case of the mineral oil, the properties depend considerably on the sample ageing time. ECT of Midel 7131® synthetic ester remained relatively stable, regardless of the ageing degree of that fluid.

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