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Streaming electrification of insulating liquid mixtures

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Abstract: Extensive efforts have been made for many years by the power generating industry to replace conventional solid and liquid insulation with synthetic materials. Those measures are aimed at increasing the load capacity, improved fire safety and extending transformer life during exploitation. Modern insulating materials include aramid fibre-based paper and insulating fluids made of synthetic and natural esters. The paper presents research results of the electrostatic charging tendency (ECT) of mixtures of fresh and aged mineral oil Trafo En with synthetic ester Midel 7131 and natural ester Midel 1204. The measurements were taken in a flow-through system using the pipes made of metal, cellulose and aramid paper. The influence of the liquid flow velocity, the type of material of the measuring pipe and the mixture content on the level of the streaming electrification current generation was determined.

Key words: dielectric liquids, streaming electrification, transformer insulation

1. Introduction

The increasing demand for electrical energy has led to an increase in the output of power transformers. Rapid growth of material engineering has enabled the development of advanced technologies for manufacturing synthetic liquids and solid materials with increased insulating performance, allowing an increase of power rating of that equipment while minimising changes in its size. Such materials include insulating fluids made from organic esters [1–5] and paper based on aramid fibres [6–11]. Increasing load capacity of transformers while attempting to minimise their weight and dimensions required, however, changes to be made in the design, involving, among others, bringing transformer active parts closer. Also the problem of effective waste heat dissipation has emerged. To intensify cooling of transformer windings, the flow velocity of cooling fluid was mainly increased. That, however, resulted in increased generation of static electricity [12]. The electrification problem was tackled by a work group appointed by CIGRE 12/15-02 [13–15], Massachusetts Institute of Technology (MIT) and Electric Power Research Institute (EPRI) under the project Static Electrification in Power Transformers [16]. Therefore, electrification tests were performed on actual transformers [17] and then, on large laboratory systems modelling their operation [18]. Then, small laboratory systems were introduced [19–27]. The objective of the extensive research was to gain a thorough knowledge of the nature of the streaming electrification phenomenon and to find efficient means of reducing it. Mineral oils [12–18, 20–32] and synthetic liquids [33–37], as well as pure hydrocarbons and their mixtures [38–40] were tested. Among others, the effect of hydrodynamic conditions [41], temperature [14, 33, 37, 42], ageing processes [29, 36, 37, 43, 44] and properties of solid materials [37, 45] were analysed. The investigation results presented in the paper of streaming electrification of insulating liquid mixtures are a continuation of the investigations presented in works [37, 47, 49] In this works streaming electrification of mineral oil Trafo En and ester Midel 7131 in the functions of speed and time of liquid flow through the pipes made of different materials (cellulose and aramid paper, copper, aluminum, brass, glass epoxy laminate and carbon fiber) was measured. Also the influence of temperature and accelerated thermal aging of liquids on electrification current value was analyzed. The issues studied are important from both, the scientific and practical point of view. Modern solid-state insulating materials, e.g. aramid paper are characterised by different physicochemical properties and, in combination with liquid insulating materials, e.g. mineral oils, esters and their mixtures, they may have substantially different features. Studies of electrostatic properties of paper and insulating liquid mixtures systems contribute to the materials science, providing a vast resource of information that can be used in further research and for the development of modified materials for use in power engineering.

2. Measuring system

Fig. 1 illustrates the general layout of the flow-through system with a pipe for testing the ECT of insulating fluids.

The electrification process in such system is as follows: fluid at a controlled temperature (from 20°C to 90°C), flowing at a specified velocity (from 0.34 to 1.75 m/s) from the top tank (1) through the pipe (7), is electrified and flows to the isolated bottom tank located in a Faraday cage (3). The leakage of the excess static charge to the ground is recorded with a Keithley 6517 electrometer (5). Measuring data is archived and then processed and imaged by a portable computer (4). Fluid flow velocity through the pipe is controlled by changing the pressure of a gas cushion (with nitrogen) in the top tank (1). The fluid from the bottom tank is forced up to the top tank by the pump (6). Fluid flow was cut off with the solenoid valve (8). Measuring parameters (velocity, temperature and fluid flow time) were controlled automatically by microprocessors in the control box (9). The pipes used for tests were made of metal, cellulose paper made by Tervakoski, and Nomex® paper made by Dupont. Their length was 400 mm and diameter 4 mm. ECT experiments (at 20°C) were carried out on the samples of insulating liquid mixtures which consisted of fresh and aged mineral oil combined with synthetic and natural esters in proportions changing every 10%. For testing purposes mineral oil Trafo En manufactured by Orlen Oil company and synthetic ester Midel 7131 and natural ester 1204 manufactured by M&I Materials were suggested. A single

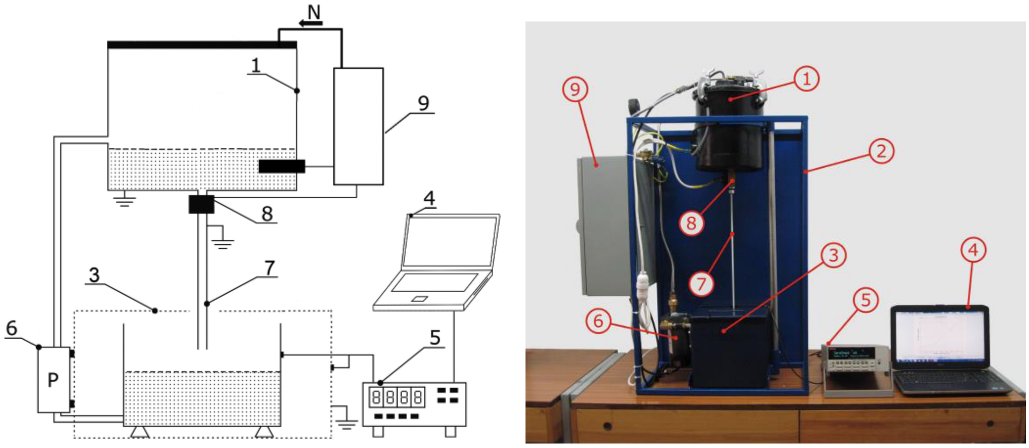

Fig. 1. Layout of the test stand with a flow pipe for testing streaming electrification of insulating fluids: 1 – top tank, 2 – supporting structure, 3 – Faraday cage with measuring tank located inside, 4 – measuring computer, 5 – electrometer, 6 – pump, 7 – measuring pipe, 8 – solenoid valve, 9 – control box

point on the diagram of the streaming electrification current is an average from 50 measurements. Accelerated thermal aging of mineral oil Trafo En was performed based on IEC 1125C (120°C, 164 h, with an addition of cooper catalyst – 2 g/litre) method. Table 1 presents the most important physicochemical properties of the insulating fluids tested at 20°C.

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

	Value			
Property	Trafo En fresh oil	Trafo En aged oil	Midel 7131	Midel 1204
Density [kg/m^3]	885	891	970	918
Viscosity [m^2/s]	$2.04 \cdot 10^{-5}$	$2.43 \cdot 10^{-5}$	$7 \cdot 10^{-5}$	$8.4 \cdot 10^{-5}$
Relative permittivity [–]	2.23	2.14	3.19	3.21
Conductivity [S/m]	$7.94 \cdot 10^{-13}$	$1.33 \cdot 10^{-11}$	$8.77 \cdot 10^{-12}$	$8.26 \cdot 10^{-12}$
Acid number [mg KOH/g]	0.015	0.145	< 0.01	< 0.01

3. Results of experiments

In power transformers it is necessary to use an induced circulation of insulating liquid to increase the effectiveness of carrying away heat losses from their interior. The insulating liquid flowing in a transformer becomes electrified due to its contact with materials of various physicochemical properties and of various surface structures. Both solid dielectrics (paper, pressboard) used for transformer winding insulation and the metal of which a transformer tank is built as well as the cooling system elements (pumps, cooler radiators) are used in this type of facilities. Flow velocity, physicochemical properties of insulating liquid and also the properties of solid material have a significant influence on the occurrence and development of the streaming electrification phenomenon. Fig. 2 shows exemplary plots of the streaming electrification current of the insulating liquids under study flowing through a metallic pipe with the velocity in the range from 0.34 to 1.75 m/s. Analyzing the diagrams it can be observed that increasing the liquid flow velocity causes a linear increase of the streaming electrification current value. The investigations carried out showed that fresh mineral oil has the lowest ECT and aged oil shows almost twice higher susceptibility to streaming electrification. Comparing the electrification of natural and synthetic esters it can be concluded that Midel 1204 becomes ca. 30% more electrified than Midel 7131. In order to confirm the influence of properties of solid phase materials on ECT values, the measurements of streaming electrification current of liquid Midel 1204 in the function of flow velocity using metallic, aramid and cellulose pipes were taken (Fig. 3). The experiments confirmed that ECT of insulating liquid strongly depends upon the type of material of which a measuring pipe is made. The generation of electrostatic charges in liquid Midel 1204 takes place to the highest degree in a metallic pipe. These liquids were the least electrified during their flow through a pipe made of cellulose paper. The significant differences in ECT values should be explained by the properties of a double electric layer of a charge on the border of the solid and liquid phase contact as well as the surface roughness of the pipe material.

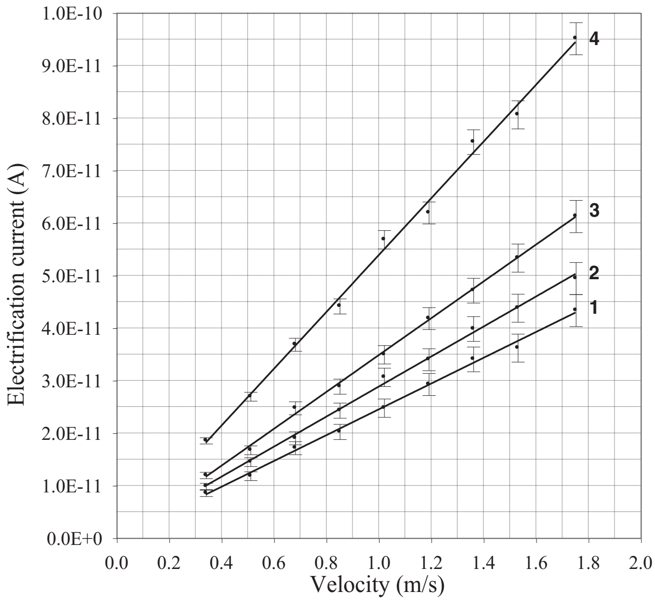

Fig. 2. Electrification current of insulating liquids vs. flow velocity through a metallic pipe:
1 – fresh mineral oil, 2 – synthetic Midel 7131, 3 – natural Midel 1204, 4 – aged mineral oil

Figs. 4 and 5 show dependencies of streaming electrification current on percent content of synthetic ester and natural ester Midel 1204 in mixtures with fresh mineral oil.

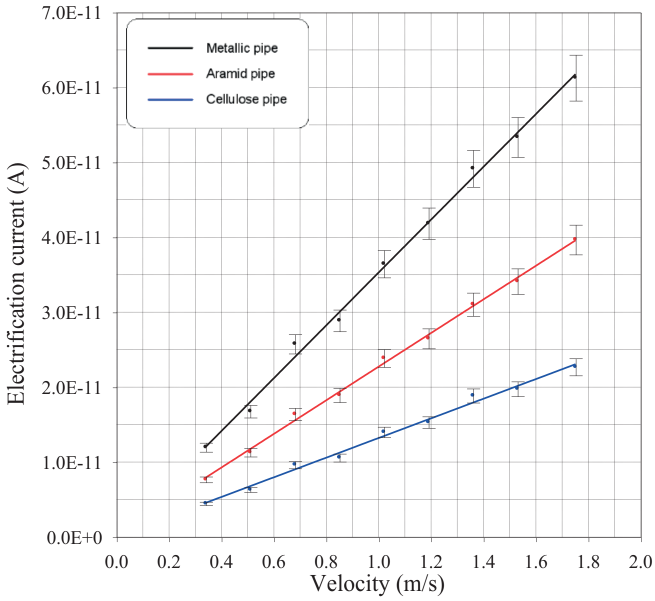

Fig. 3. Electrification current vs. flow velocity of natural ester Midel 1204 through the pipes made of various materials

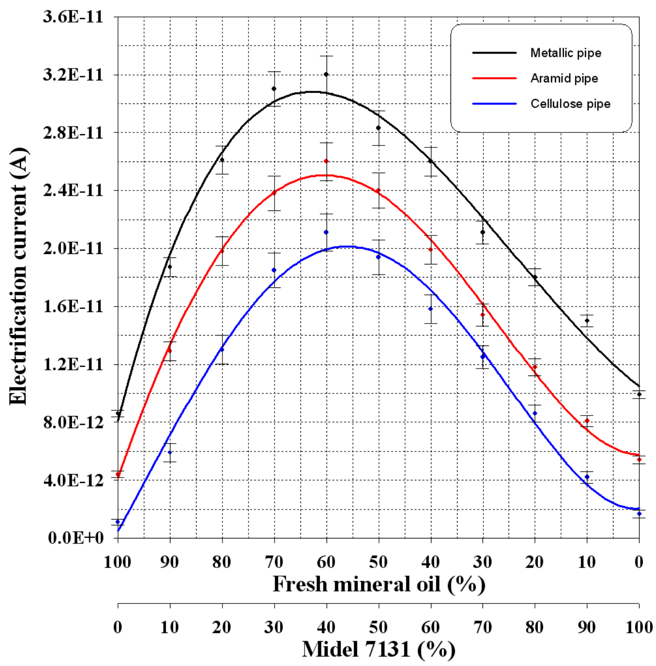

Fig. 4. Electrification current vs. percent content of synthetic ester Midel 7131 and fresh mineral oil in the mixtures

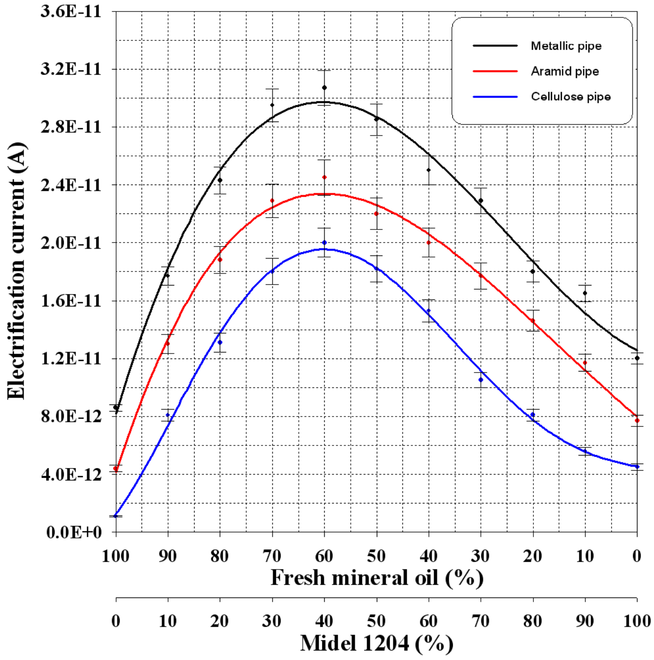

Fig. 5. Electrification current vs. percent content of natural ester Midel 1204 and fresh mineral oil in the mixtures

The tests were carried out using measuring pipes made of metal and aramid and cellulose paper. The liquid flow velocity was 0.34 m/s (gravity flow). In both types of mixtures a high dependence of ECT on the percent content of their particular components could be observed. An increase of concentration of synthetic and natural esters in mixtures with fresh mineral oil leads to a sharp increase of the electrification current value. In the case of the mixture the content of which constitutes 60% of fresh mineral oil and 40% of ester, a characteristic maximum of streaming electrification current is observed. With further increase of percent participation of esters in mixtures, electrification current decreases significantly.

Figs. 6 and 7 show dependencies of electrification current of mixtures in the function of percent content of aged mineral oil and synthetic and natural esters. The liquid flow velocity was 0.34 m/s (gravity flow). An increase of the percent concentration of liquid Midel 7131 and liquid Midel 1204 in the mixtures with aged mineral oil leads to a decrease of their electrostatic properties. The minimum of electrification current is obtained at 80% content of esters in mixtures regardless of the measuring pipe used. Further increase of percent content of esters causes a slight increase of electrostatic properties of the mixtures. Summing up, it should be concluded that the flow velocity of insulating liquid, the type of the pipe material and the mixture content significantly influence the value of the streaming electrification current measured. The highest level of ECT is registered for the mixtures, the content of which constitutes 60% of fresh mineral oil and 40% of esters. The lowest electrification shows the mixtures, the content of which constitute 80% of aged mineral oil and 20% of esters. The insulating liquids under study and their mixtures become electrified to the

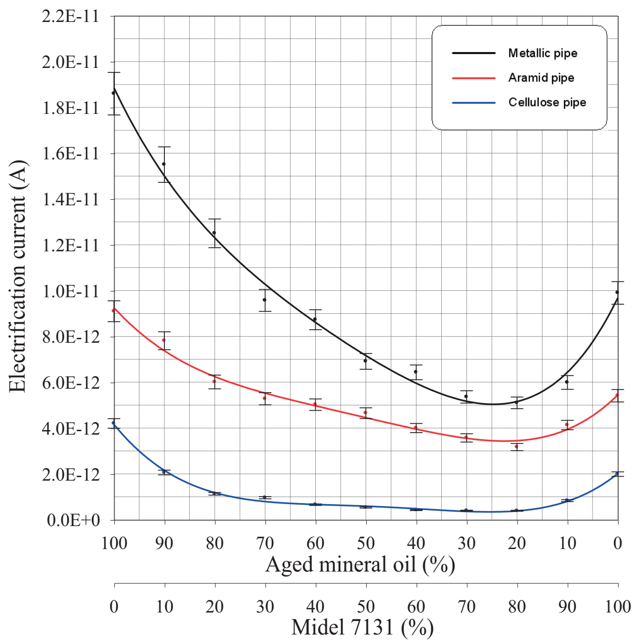

Fig. 6. Electrification current vs. percent content of synthetic ester Midel 7131 and aged mineral oil in the mixtures

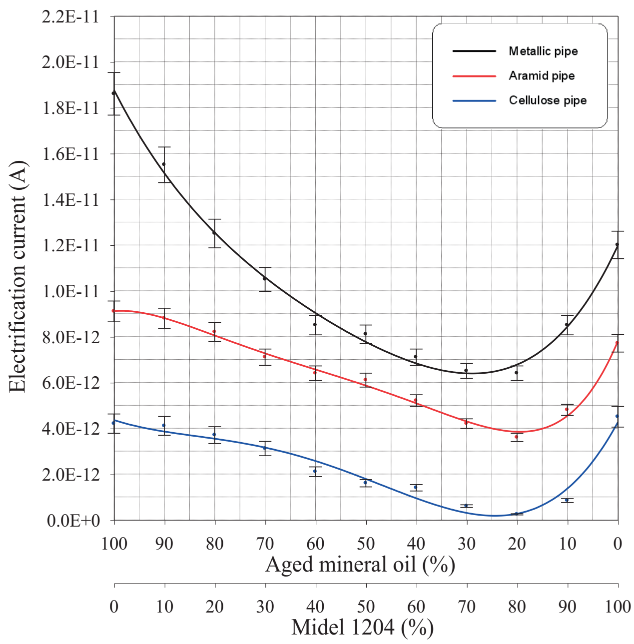

Fig. 7. Electrification current vs. percent content of natural ester Midel 1204 and aged mineral oil in the mixtures

highest degree during their flow through a metallic pipe. Lower values of streaming electrification are observed when using an aramid pipe, and the lowest values when using a cellulose pipe.

4. Conclusions

The paper presents experimental research results of ECT of insulating liquids used in power transformers and their mixtures. The mixtures were made based on fresh and aged mineral oil Trafo En, synthetic ester Midel 7131 and natural ester Midel 1204. The measurements of streaming electrification current were taken in a flow-through system with a pipe. The research work carried out showed a high dependence of generated streaming electrification currents on the type of insulating liquid (Fig. 2), flow velocity and the pipe material used (Fig. 3). Furthermore, the research work carried out showed that ECT of the mixtures made strongly depends on their content (Figs. 4–7). The mixtures of esters with fresh mineral oil show significantly different electrostatic properties than the mixtures with aged mineral oil. In the first case, streaming electrification current increases and decreases after achieving a 40% content of esters in the mixtures with fresh mineral oil. In the case of the mixtures of esters with aged mineral oil in the range from 10% to 80%, a significant decrease of electrification current takes place and after exceeding this level, its slight increase is observed. It is difficult to compare directly the investigation results of electrification of mineral oils as their susceptibility to electrification depends significantly on their chemical composition (the content of particular groups of hydrocarbons), which is shown in works [38–40]. Presently, there are no similar investigations published in specialist literature therefore there are no direct references in the paper. The research on physicochemical and electrostatic properties of insulating liquids and their mixtures can be useful in designing the insulating systems of power transformers and in the process of retrofilling, the aim of which is the improvement of transformer work reliability and reduce environmental hazards or increase fire safety. In the future, studies on physicochemical and electrostatic properties of mixtures as a function of temperature are planned.

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