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Thermal properties of nanoliquids in the aspects of their used in the insulation system of high voltage power transformer

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The article presents information concerning the electrical and thermal properties of nanoliquids in the context of their use in the insulating system of high voltage power transformers. It consists of six chapters. The first chapter is an introduction. The second chapter describes properties of the modern insulating nanoliquids created on the basis of mineral oil and nanoparticles. The third chapter is devoted to the measurement systems to the measure of the viscosity, thermal conductivity and density. The fourth chapter presents the methods of preparation of nanoliquids. In the fifth chapter the viscosity, thermal conductivity and density of mineral oil and nanoliquids were compared. Article ends with a summary.

KEYWORDS**:** nanoliquids, high voltage power transformers, thermal properties

1. Introduction

Power transformer is one of the most crucial and costly equipment incorporated in the power system. For over a hundred years, mainly mineral oils are used to its cooling. Low flash point and unsatisfactory thermal properties of mineral oils were often the cause of failure and transformer fire, in the past. The result was large material losses and creation of hazardous situation to people and environment. The trouble-free exploitation of the transformer depends on properties of electro-insulating liquid. With the increase in the load of the transformer rises the internal temperature, and thus, shortens its life. The length of life of the transformer depends primarily on the life of the transformer winding insulation, which in turn depends on the operating time and temperature [1]. Previously, used mineral oils have a pretty good electrical properties, but unfortunately they have a poor thermal properties, so their cooling properties are not sufficient in many cases.

Recently, several research centers around the world continue work on the modification of insulating liquids in order to improve their properties, both electrical and thermal [2, 3, 5-7].

Improving the thermal properties of insulating liquids can be obtained by adding the nanomaterials. The resulting nanoliquids are likely to be true solutions or colloidal. In true solutions, nanomaterials are dissolved in the liquid base, whereas in the colloids they are dispersed and suspended throughout their volume.

This paper presents the results of the presence impact of two selected nanomaterials in mineral oil for its thermal conductivity, viscosity and density. These values, in addition to the specific heat and thermal expansion determine the heat transfer, that decides on the effectiveness of cooling. Nanomaterials used in the study were C_{60} and TiO_2.

2. Properties of nanoliquids

In this chapter, on the basis of literature data, electrical properties of electro-insulating nanoliquids created based on nanomaterials, such as TiO_2 and C_{60} are presented. The idea of using electro-insulating nanoliquids, in place of the previously used mineral transformer oils, appeared relatively recently. As mentioned previously, in several research centers around the world research on modifications of insulating liquids are carried. Their aim is to improve their electrical properties and cooling efficiency. The paper [2] presents results of research on the impact of nanoparticles semiconductor TiO_2 on the electrical insulating properties of mineral oil. Particles of TiO_2 were added to the transformer oil to form the semiconductive nanofluids (SNF – Semiconductive NanoFluid) characterized by enhanced, as compared to a clear oil, electrical properties. Table 2.1 shows the comparison of obtained results for SNF with the data for pure mineral oil. By the result of the tests, it was found, that the SNF is characterized by increase in DC, AC and lightning breakdown voltage, as compared with the pure mineral oil [2]. This nanoliquid is also characterized by a higher inception voltage of partial discharges. SNF resistivity value, relative to the value of the resistivity of mineral oil (table 2.2), is smaller, but still meets the requirements for the resistivity of electro-insulating liquids of SNF imposed in operation. In contrast, the relative dielectric permittivity exceeds the mineral oil one, which is suitable for distribution of the electric field in the paper-oil insulation [4].

The results, presented in the papers [5, 8], relating to mineral properties of transformer oils doped fullerenes $C_{60,}$ indicate that they may have a positive impact on some electrical parameters, both fresh and of aged oils. The results of this work demonstrate, that the improvement in the electrical parameters of electro-insulating liquids is possible at the different concentrations of fullerene C_{60}. However, due to amelioration of both dielectric factor, resistivity, and permittivity, the use of concentrations of 8 mg/l and 16 mg/l is recommended [8]. Depending on the concentration of fullerene C_{60} can also change the electrification current. Due to this parameter the optimal concentration of C_{60} in mineral oil is 100 mg/l [5, 6].

Table 2.1. Comparison of AC, DC, lighting breakdown voltages and results of partial discharge inception voltage for pure mineral oil and SNF [2]

Liquid	**Mean breakdown voltage (AC)**	**(DC+) Breakdown voltage**	**(DC-) Breakdown voltage**	**Lightning breakdown voltage**	**Time to breakdown**	**Mean Partial Discharge Inception Voltage (PDIV)**
	kV	**kV**	**kV**	**kV**	**µs**	**kV**
Mineral oil	67,9	49,1	66,3	77,6	15,2	30,6
SNF	80,9	45,1	84,6	95,9	23,3	33,1

Table 2.2. Comparison of relative permittivity and resistivity of pure mineral oil and Semiconductive Nanofluid (SNF) [2]

Liquid	**Relative permittivity**	**Resistivity**
	-	**Ω·m**
Mineral oil	2,26	$1{,}82\cdot10^{12}$
SNF	3,92	$8{,}30\cdot10^{10}$

Analyzing the properties of nanoliquids presented in this chapter it can be concluded, that they are characterized by many positive characteristics, essential from the point of view of the requirements of electro-insulating liquids. Undoubtedly, it is necessary to carry out several studies of their properties, including the thermal ones, allowing complete determination, whether the use of them is preferably in power transformers.

3. Measurement systems

The chapter presents the measurement systems used to measure the thermal properties of electro-insulating nanoliquids created on the basis of mineral oil and nanoparticles C_{60} and TiO_2.

Figure 3.1 shows the system for measuring the viscosity of the insulating liquids. The system has been designed and built according to the standard [9]. For the measurement of kinematic viscosity Ubbelohde's viscometer were used. In order to determine the kinematic viscosity using the viscometer the time of the flow of liquid through the capillary at a known constant is needed to know. The measurement is performed at a fixed temperature. Depending on the expected value of the viscosity of the tested liquids and the duration of the measurement viscometer with the appropriate fixed capillary should be chosen.

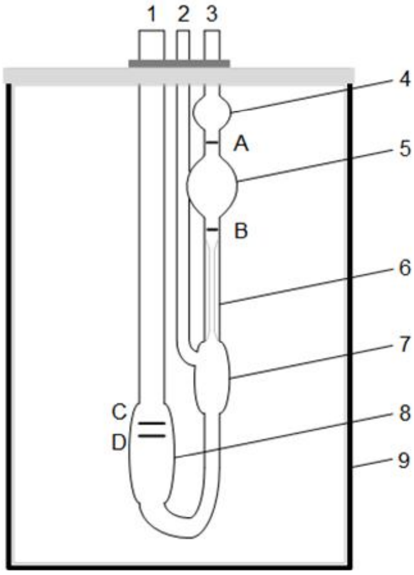

Fig. 3.1. System for measuring the viscosity υ of the insulating liquids.; 1, 2, 3 – tube, 4, 5, 7, 8 – container, 6 – capillary, 9 – viscosimetric bath

Viscometer reservoir (8) should be filled in the tested liquid, such that the meniscus of the liquid is between levels C and D (in Fig. 3.1). Before the measurement, wait for the right time in order to tested liquid has reached the temperature at which the measurement should be carried out. After the temperature has stabilized, the tube (2) is closed and the liquid pulls up to half the height of the tank (4). The tubes (2) and (3) are open. The measurement involves determining the time of flow of liquid from the level A to level B. Then, the value of the kinematic viscosity is calculated according to the formula:

$$\nu = K \cdot t \qquad (1)$$

where: K – constant of capillary [mm^2/s^2], t – flow times arithmetic average [s].

A system for measuring the thermal conductivity of the insulating liquids is described in detail in the work of the authors [10-13].

Figure 3.2 shows a system for measuring the density of insulating liquids. The system has been designed and built according to the standard [14]. For density measuring glass hydrometers with graduation were used [15], and the suitable size of the cylinder to measurements. In order to make measurements for different values of temperature and eliminate its fluctuation, cylinder filled with the investigated liquid was placed in a water bath. The hydrometer immersed in the investigated liquid was left for a period of time. After the temperature has stabilized indication of the hydrometer was read.

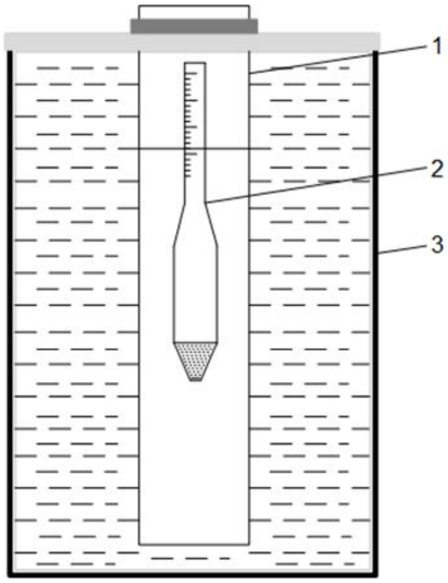

Fig. 3.2. System for measuring the density ρ of insulating liquids; 1 – cylinder, 2 – hydrometer, 3 – water bath

4. Preparation of nanoliquids

The chapter discusses the methods for preparing insulating nanoliquids constructed based on mineral oil and nanoparticles.

Nanoparticles are compounds sparingly soluble or insoluble in electro-insulating liquids. An example of the nanomaterial, which is dissolved in a insulating liquids is fullerene C_{60}. Depending on the concentration of fullerene in base liquid, its dissolution time is from two to several weeks. In the case of other nanomaterials, such as Al_2O_3, SiO_2, SiC, Fe_2O_3, and TiO_2, added to the insulating liquid, it is impossible to obtain the proper solution. In order to uniformly disperse these materials in a base liquid, it is necessary to add surfactant to it. Depending on the concentration of nanoparticles in the base liquid, adding to it only nanoparticles may result in occurrence of sedimentation (falling of solid slurry under the force of gravity). As a result, a large part of them can be deposited on the components of the insulation system impairing its properties. As previously mentioned, one of the solutions allowing for counteracting sedimentation process is the use of surfactants called dispersants. Dispersants are surface-active substances allowing the formation of stable suspensions and reduction of particles size. Depending on the used nanoparticles and the base liquid for the preparation of stable colloidal suspensions, it is necessary to use various surfactants. The selection of an appropriate concentration of dispersant in the base liquid is also important. Surfactants can be added directly into the base liquid, wherein in order to obtain a uniformly dispersed in a liquid, they are often subjected to the process of sonication (with ultrasound). To the prepared base liquid, the nanoparticles are added, which are also treated with ultrasound. Depending on the type of used nanoparticles and the base liquid, in order to uniformly disperse the nanoparticles, and a stable suspension in the base liquid, different times of the sonication process should be used. Furthermore, sonication should be conducted in a bath providing a constant temperature in the nanoliquids. Before performing studies, samples of nanoliquids should be discontinued for a few hours, in order to eliminate micro bubbles generated during the sonication process.

5. Thermal properties of nanoliquids – test results

This chapter presents the results of viscosity and thermal conductivity measurements of the insulating liquids.

For testing there were used the following insulating liquids:

- mineral oil,
- mineral oil + C_{60} – concentration of fullerene in mineral oil with 100 mg/l,
- mineral oil + SPAN – concentration of SPAN in mineral oil with 5 g/l (SPAN – surface-active substance, $C_{18}H_{34}O_6$),
- mineral oil + SPAN + TiO_2 – concentration of TiO_2 and SPAN in mineral oil respectively with 5 g/l and 0.816 g/l.

All doped liquids were subjected to sonication process in order to dissolve or suspended added modifier in a base liquid. In the case of the fullerene, appropriate solution was obtained. It was impossible to dissolve TiO_2 in mineral oil. For this reason, an attempt was made to obtain the colloid by applying a surfactant.

Measurements of viscosity, thermal conductivity and density were performed using the measurement systems described in chapter 3.

Table 5.1 and Figures 5.1 - 5.3 present the studies' results of viscosity, thermal conductivity and density of the mineral oil, mineral oil with surfactant and nanoliquids resulting from the added fullerene C_{60} and nanoparticles TiO_2 to mineral oil.

The obtained results confirmed the effect of temperature on the examined characteristics of mineral oil. The increase in temperature caused a decrease in viscosity, thermal conductivity and density of oil. The results are consistent with literature data. The conducted studies have also shown effects of nanomaterials and a surfactant on the properties of insulating liquids. The smallest effect on the viscosity exerted fullerene C_{60}. In the case of TiO_2, to obtain the colloid, it was necessary to add surfactant to the oil. The addition of the surfactant resulted also in increase of the viscosity relative to the base liquid.

The largest increase in viscosity was observed in the case of mineral oil modified by surfactant and nanoparticles TiO_2.

The thermal conductivity of mineral oil doped with nanomaterial C_{60}, and oil modified by surfactant did not change compared to the conductivity of the mineral oil. The increase in thermal conductivity was only detectable in the case of a colloid formed by the addition of TiO_2.

There was no effect of doping mineral oil by nanoparticles C_{60} and TiO_2 on density resulting nanoliquids.

Table 5.1. Study results of thermal conductivity, viscosity and density of mineral oil, mineral oil with surface-active substance (SPAN) and nanoliquids for various values of temperature; λ – thermal conductivity, υ – viscosity, ρ – density

Temperature	Properties	25°C	40°C	60°C	80°C
Mineral oil	**λ [W/(m·K)]**	0.133	0.130	0.128	0.126
	υ [mm²/s]	17.11	9.79	5.43	3.44
	ρ [g/ml]	0.867	0.857	0.845	0.832
Mineral oil + C_{60}	**λ [W/(m·K)]**	0.133	0.131	0.128	0.126
	υ [mm²/s]	17.38	9.86	5.46	3.56
	ρ [g/ml]	0.867	0.856	0.845	0.832
Mineral oil + SPAN	**λ [W/(m·K)]**	0.133	0.131	0.129	0.126
	υ [mm²/s]	17.61	9.87	5.81	3.61
	ρ [g/ml]	0.867	0.856	0.846	0.832
Mineral oil + SPAN + TiO_2	**λ [W/(m·K)]**	0.143	0.135	0.132	0.129
	υ [mm²/s]	17.99	10.18	6.10	3.69
	ρ [g/ml]	0.868	0.858	0.846	0.832

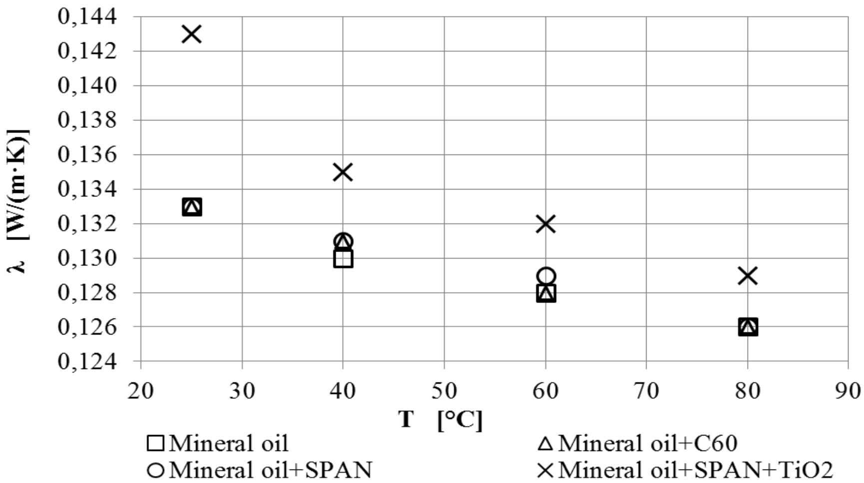

Fig. 5.1. Thermal conductivity coefficient of mineral oil and nanoliquids formed of its basis, as a function of temperature

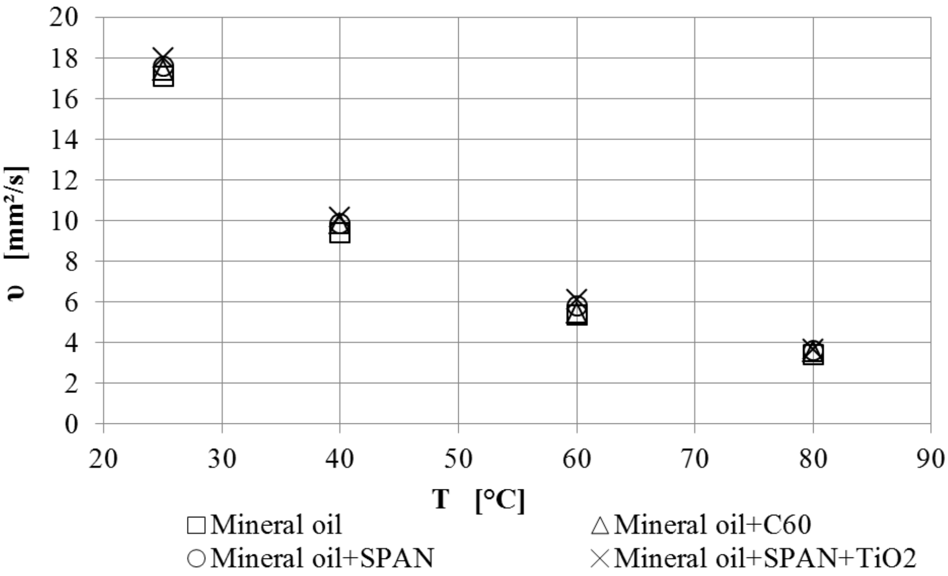

Fig. 5.2. Viscosity of mineral oil and nanoliquids formed of its basis, as a function of temperature

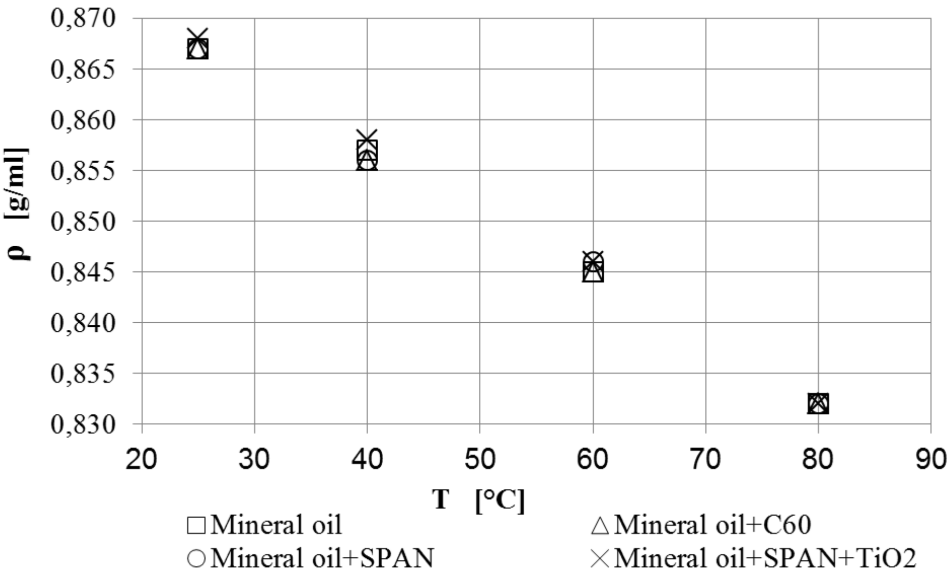

Fig. 5.3. Density of mineral oil and nanoliquids formed of its basis, as a function of temperature

6. Summary

The aim of the studies conducted in several research centers was to improve properties of the insulating liquids. Improvement of the properties is possible by doping the base liquids using nanomaterials. The resulting nanoliquids should be examined in terms of the key characteristics due to the operation of the transformer. Undoubtedly, from the point of view of the effectiveness of the cooling power, it is necessary to investigate the thermal properties of insulating nanoliquids.

The results of the studies presented in the article show the effects of nanoparticles of TiO_2 on thermal properties of nanoliquids. The studies showed an increase in viscosity and thermal conductivity of nanoliquids relative to the pure mineral oil. The increase in thermal conductivity is desirable because of the cooling effect, whereas the increase in viscosity impedes heat transfer. In addition to the results of the studies presented in the article concerning the viscosity, thermal conductivity and density of nanoliquids, the efficiency of cooling determine also specific heat and thermal expansion coefficient. Definitive statement, whether the tested nanoliquid improves heat transfer requires the examination of all these properties.

Tests on mineral oil doped with fullerene did not show improvement of the thermal conductivity of nanoliquids.

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