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Preliminary study of electrohydrodynamic motion (EHD) and electrostatic charging tendency (ECT) of transformer ester-based nanofluids

***Abstract**. This work experimentally studies the impact of three different nanoparticles (NPs), namely TiO_2, ZnO, and CuO on the electrostatic charging tendency (ECT) and electrohydrodynamic (EHD) motion of natural ester (NE, Envirotemp FR3). The nanofluids (NFs) are prepared using a combination of mixing and ultrasonication. The preliminary results indicate that the insertion of NPs in NE leads to various changes in ECT and EHD for implemented concentrations. The most significant change is observed for ZnO NPs, with an increase in the EHD initiation voltage by 9.8% and a change of the charge current of the tested sample.*

***Streszczenie.** W niniejszej pracy zbadano eksperymentalnie wpływ trzech różnych nanocząstek (NP), a mianowicie TiO_2, ZnO i CuO na tendencję do ładowania elektrostatycznego (ECT) i ruch elektrohydrodynamiczny (EHD) estru naturalnego (NE, Envirotemp FR3). Nanofluidy (NF) są przygotowywane przy użyciu kombinacji mieszania i ultradźwięków. Wstępne wyniki wskazują, że wprowadzenie NPs do NE prowadzi do różnych zmian w ECT i EHD dla zaimplementowanych stężeń. Najbardziej znaczącą zmianę obserwuje się dla ZnO NPs, ze wzrostem napięcia inicjacji EHD o 9.8% i zmianą prądu ładowania badanej próbki. (**Wstępne badania ruchu elektrohydrodynamicznego (EHD) i tendencji do ładowania elektrostatycznego (ECT) nanocieczy na bazie estrów transformatorowych**).*

Keywords: dielectric fluids; natural ester based nanofluids; electrohydrodynamics (EHD); electrostatic charging tendency (ECT).
Słowa kluczowe: ciecze dielektryczne; nanociecze na bazie estrów naturalnych; elektrohydrodynamika (EHD); tendencja do ładowania elektrostatycznego (ECT).

Introduction

The power transformer is an essential component in electro-energetic transmission systems, and the longevity of its insulation ensures that the energy supply operates reliably [1]. The service life and performance of forced oil-flow transformers are highly dependent on the condition and quality of the paper-oil insulation. The history and progress of dielectric fluids for transformer applications is long and has been [2], [3]. The dielectric strength of transformer fluids, as well as their cooling ability are two basic properties that should be considered when selecting insulation fluids. The demand for efficient and sustainable dielectric fluids in power transformers is driving research into the development of innovative materials.

Nowadays, we frequently encounter the term nanofluids (NFs); these are liquids with dispersed nanoparticles (NPs). Due to their unique properties, they have found applications in many scientific disciplines, including electrical engineering and power engineering [4]. Studies have shown that the addition of nanoparticles can have a very positive effect on the dielectric strength and thermal conductivity of base liquids. For that reason, in recent years, many researchers have undertaken the study of the impact of various types of nano-additives on the electrical properties of dielectric fluids. Many works have been comprehensively presented in reviews, e.g. [5], [6], [7]

In addition, there are also many other important properties that can determine the suitability and reliability of a fluid in transformer insulation. Among these properties the flow of fluid in transformer which can generate static charges at the interface between the solid insulation (pressboard) and the fluid highlighting the importance of two correlating properties such as electrostatic charging tendency (ECT) and electrohydrodynamic movement (EHD). EHD can be described as a flow generation or modification caused by an electrostatic field in a volume of insulators or poor electrolytes. Maxwell's equations are reduced to quasi-electrostatic ones only. While ECT of a fluid refers to the tendency of the fluid to accumulate and separate charges at the interface, affected by factors such as fluid motion and material properties at the interface.

The combined effects of these two phenomena can be catastrophic for the transformer as reported by numerous researchers, e.g. [8], [9]. In the case of transformer ester-based nanofluids, the leading part of researchers focused above all on ECT properties, without analyzing EHD properties. However, in recent years several interesting papers have been published on the EHD phenomena in various liquids.

Jaroszewski et al. [10] reported that the electro-hydrodynamic initiation voltage (EHDIV) value in natural esters (NE) is affected by various phenomena. According to these authors, the EHDIV of ester depends on the distribution of the electric field, the electrodes gap, the water content (less dependence than for mineral oil) and dissolved gases in the liquid, the temperature and the electrode material on which the ion injection mechanism from the electrode surface depends. Rouabeh et al. [11] focuses on the comparison of EHDIV in alternative mixtures to mineral oil, the effect of aging, and the density of static charges. According to Hwang et al. [12] the NE charge relaxation time constant has a great influence on the EHD processes occurring in the nanofluid: if the relaxation time constant is smaller relative to the streamer growth scale, then the nanoparticles will significantly affect the electro-hydrodynamics.

Interesting papers have been published on ECT in various nanofluids [13], [14], [15]

This paper aims to preliminarily investigate the effect of adding various types of nanoparticles (NPs) such a TiO_2, ZnO, CuO NPs on both EHD phenomena and ECT properties of natural ester (NE), namely Enirotemp FR3.

Procedures and Measurements

A. Preparation of Nanofluids

The nanofluid samples are prepared using the two-step method. This later is the most popular technique, applied on a very large scale. Its greatest advantage is its universality; it can be used to obtain most nanofluids [16].

The process starts by filtering an appropriate amount of fresh ester sample, specifically the natural ester Envirotemp FR3. After filtration, and before the ultrasonic process, the sample was additionally degassed under a vacuum of 10 kPa. For improving the stability of the created nanofluid, oleic acid ($C_{17}H_{33}COOH$) was used as a surfactant, and the sample was then mixed.

Three types of nanoparticles were selected (purchased from PlasmaChem): copper(II) oxide (CuO), zinc oxide (ZnO), and titanium dioxide (TiO_2). For comparison purposes, a single concentration of NPs of 0.2 g/l was chosen due to the feasibility of the tests, particularly the limitations of the shadow technique, and falls within the ranges of concentrations tested in the previously cited publications. To obtain the desired NPs concentration, the precise mass of the chosen NPs was dispersed in the NE using a mixer stirrer and ultrasonication with UP200Ht, and oleic acid as the surfactant. Ultrasonication was carried out on a 10/5 cycle for two hours, followed by a 5/5 cycle for 5 minutes to degas the samples. After this process, there was no sedimentation before the measurements began; the solution was homogeneous.

B. EHD Measurement

In fluid flow phenomena, there is an exchange of such physical quantities as energy, heat, mass and momentum. To analyse the transport phenomena of these quantities, both theoretical and experimental approaches can be used. A distinction can be made among experimental methods between those that focus on measuring individual flow-related parameters and those that visualize the phenomenon. A crucial problem in many kinds of fluid flow investigations is visualization. The development of visualization techniques has been influenced by the significant increase in camera recording parameters. Among the optical techniques used for studying electrohydrodynamic motion, shadowgraph technique, Mach-Zehnder interferometer, pulse light velocimetry (PTY and PIV) and polarized light.

The range of applicability of each technique is basically related to the speed of flow, the degree of transparency and the required purity of the considered medium.

In our research, we used the shadowgraph technique.

To preliminarily characterize the differences in EHD motion the optical experimental setup is that depicted in Fig. 1. It is based on Toepler-schlieren system with parallel light passing throughout the flow facility's test area [17].

This method is based on the phenomenon of a change in the light factor caused by a local change in the density of the fluid. Its advantage is that there is no need to introduce external elements into the medium. The principle of this method is to illuminate the test slit of an object with a parallel beam of light, which, after passing through an object with a specified permeability of light, returns an undisturbed image. However, if there is an inhomogeneous area in a certain area of the liquid under study then the light passing through it will be dispersed and will not fully reach the lens.

LED light source (white) is directed through the slit onto the lens system which captures the light and turns it into a collimated beam. Parallel light rays pass through the test sample and hit the focusing lens, next slit and go into the camera lens. The recording plane's illumination is cut by the adjustable slit's edge, which blocks off a particular portion of the light source picture.

According to [18] the key role of the occurrence of the EHD phenomenon in transformer oils is played by DC voltage, and the influence of the 50 Hz AC component field is negligible. For this reason, it was decided to perform the study only under the influence of DC voltage. All the test samples were subjected to a voltage step applied to plane-sphere electrode configurations with a 10-mm gap, under DC, negative polarity on plane electrode. To do this, we used a Glassmann High Voltage DC power supply. The volume of the samples tested was 220 ml. Each sample was measured 10 times. To enhance the observational capabilities of the method, a slight temperature gradient was produced by heating the sphere electrode. Thus, the initiation voltage of EHD was measured.

C. ECT Measurement

In order to measure the phenomenon of ECT of liquids, many techniques can be distinguished. A. Sierota and J. Rungis at [19] made a comprehensive review on this subject.

For our purpose, we used the spinning disk method similar to that used in [20] (fig. 2). This method is currently the widely used method for ECT testing. The disk is made of brass with 150 mm diameter and 2 mm thick; a pico-ammeter enables to measure the ECT current. The tests were conducted on one litre volume samples. Before the actual measurements were carried out, each sample was set aside in the measuring vessel for 30 minutes; each measurement lasted one hou

r.

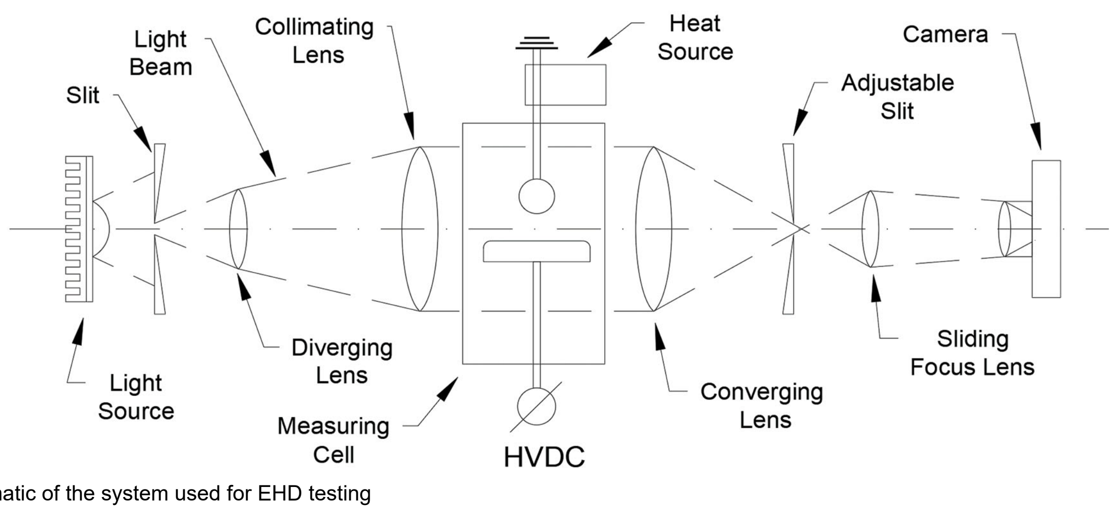

Fig.1. Schematic of the system used for EHD testing

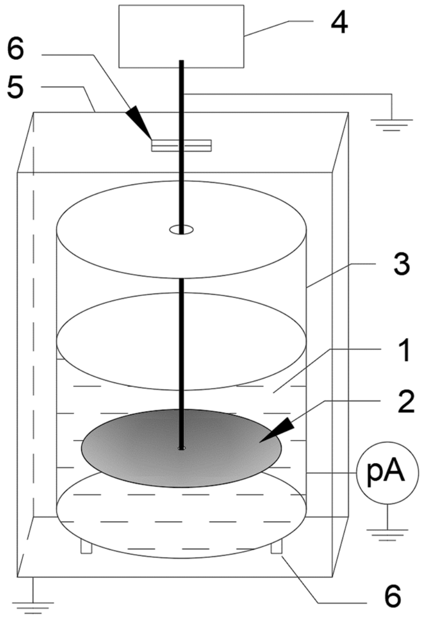

Fig. 2. Scheme of the system of spinning disk method for ECT measurements: (1) liquid, (2) disk, (3) measuring vessel, (4) motor, (5) Faraday's cage, and (6) Electrical separators

Results

A. EHD

The results of the EHDIV measurements with standard deviation are shown in fig. 3. It shows the most significant effect of ZnO on the initiation voltage, the value of which was 1.23 kV and is 9.82% higher than the pure ester voltage of 1.12 kV. For the other nanoparticles, slightly lower values of 1.16 and 1.18 kV are obtained for TiO_2 and CuO, respectively. An example of the image obtained from the test is shown in fig. 4.

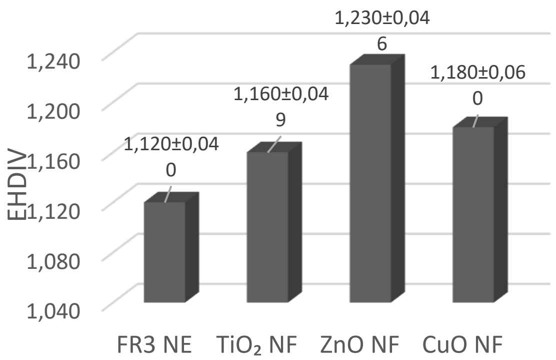

Fig. 3. EHDIV graph for the samples tested

B. ECT

The ECT measurement results of the NFs are presented relative to pure NE in Fig.5. The selected speed range is widely used in publications using the rotating disk method. They show that the tested nanoparticles maintain different charging tendencies for the tested disk speeds. The presence of TiO_2 nanoparticles significantly enhances the charging tendency, while CuO decreases it. However, the effect of ZnO is worth attention, the direction of current flow was opposite, and the measured current values were characterized by very high variability, what is more, the sample for 400 rpm speed achieved lower values. The obtained trends were characterized by a slight value increase during the measurement procedure.

Fig. 4. EHD motion image obtained by the described method, for FR3 TiO_2 sample

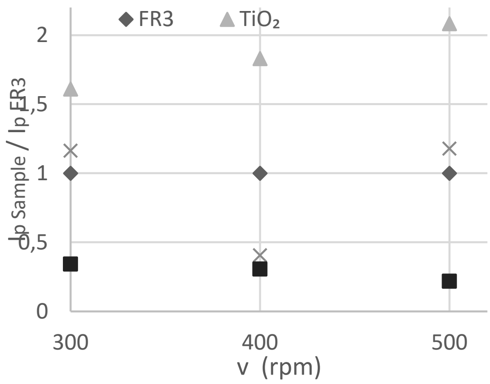

Fig. 5. The ratio of the average ECT NF current values to the base NE, for different disk rotation speeds v in rpm

Conclusions and discussion

This preliminary study was designed to test the existence of the effect of different types of nanoparticles on the EHD and ECT of the tested nanofluid. Conducting physical experiments to measure and observe the behaviour of fluids can gain a comprehensive understanding of fluid flow and analyse the impact of nanoparticles.

During the study, a dependence of EHD phenomena on nanoparticles was demonstrated indicating the need for further research on the topic. Among the liquids studied, the nanofluid with TiO_2 showed the highest tendency to charge, which is an unfavorable phenomenon. In contrast, the nanofluid with CuO addition has the best properties, lowering the tendency to electrification of the nanoester. All nanofluids under the test system conditions showed an increase in the value of the initiation voltage of EHD motion. It is worth noting that due to the possibility of different interactions of nanoparticles from their concentration in the liquid, as confirmed by the previously cited studies, future studies should be carried out with different concentrations of nanoparticles.

Experimental techniques, such as flow visualization provide valuable data that can be used to understand complex electrohydrodynamic phenomena in ester based nanofluids. With the concentration of nanoparticles in the liquid ester, its transparency changes. During visualization studies of EHD, at high concentrations this problem is noticeable and makes measurement difficult or even impossible.

The knowledge of the EHD and ECT phenomena of the studied nanofluids can contribute to the structural requirements for future designed transformers. The observed flow transitions are due to the strong interaction between the electric field and flow that characterizes EHD flow phenomena.

The aim of further research should be to determine the existence of correlations between ECT and EHD motion for different types and kinds of nanofluids dispersed in the ester volume.

Although nanoparticles may offer clear advantages in improving the properties of transformer esters, their long-term consequences and specific behaviour require further research attention.

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REFERENCES

[1] W. Ziomek, “Transformer electrical insulation [editorial],” IEEE Transactions on Dielectrics and Electrical Insulation, vol. 19, no. 6, pp. 1841–1842, 2012, doi: 10.1109/TDEI.2012.6396938.

[2] I. Fofana, “50 years in the development of insulating liquids,” IEEE Electrical Insulation Magazine, vol. 29, no. 5, pp. 13–25, 2013, doi: 10.1109/MEI.2013.6585853.

[3] X. Peng et al., “Research progress in modified mineral oil, natural ester and mixed oil in transformers,” Electrical Materials and Applications, vol. 1, no. 1, p. e12005, Apr. 2024, doi: 10.1049/EMA3.12005.

[4] A. A. Mohammed, H. I. Dawood, and H. N. Onyeaka, “A Review Paper on Properties and Applications of Nanofluids,” IOP Conf Ser Earth Environ Sci, vol. 1232, no. 1, 2023, doi: 10.1088/1755-1315/1232/1/012009.

[5] A. J. Amalanathan, R. Sarathi, and M. Zdanowski, “A Critical Overview of the Impact of Nanoparticles in Ester Fluid for Power Transformers,” Energies 2023, Vol. 16, Page 3662, vol. 16, no. 9, p. 3662, Apr. 2023, doi: 10.3390/EN16093662.

[6] J. Jacob, P. Preetha, and S. T. Krishnan, “Review on natural ester and nanofluids as an environmental friendly alternative to transformer mineral oil,” IET Nanodielectrics, vol. 3, no. 2, pp. 33–43, Jun. 2020, doi: 10.1049/IET-NDE.2019.0038.

[7] D. Amin, R. Walvekar, M. Khalid, M. Vaka, N. M. Mujawar, and T. C. S. M. Gupta, “Recent progress and challenges in transformer oil nanofluid development: A review on thermal and electrical properties,” IEEE Access, vol. 7, pp. 151422–151438, 2019, doi: 10.1109/ACCESS.2019.2946633.

[8] J. Rouabeh, W. Nsibi, L. M’barki, S. Khmeilia, and B. Jallouli, “A study of correlation between the ect and ehd properties of different aged insulating oil mixtures that can Be an alternative to mineral oil for the insulation and cooling of power transformers,” Heliyon, vol. 9, no. 1, p. e12693, Jan. 2023, doi: 10.1016/J.HELIYON.2022.E12693.

[9] Kędzia J., “Zagrożenia izolacji transformatorów energetycznych wywołane elektryzacją statyczną,” Oficyna Wydawnicza Politechniki Opolskiej, 1999.

[10] M. Jaroszewski, A. Beroual, and M. Dziedziul, “Electro-convection in natural ester based transformer fluid,” IEEE Transactions on Dielectrics and Electrical Insulation, vol. 25, no. 6, pp. 2398–2404, Dec. 2018, doi: 10.1109/TDEI.2018.007267.

[11] J. Rouabeh, W. Nsibi, L. M’barki, S. Khmailia, and H. Mel, “Study of electrohydrodynamic properties in insulating liquids and research of an alternative mixture to mineral oil for energy transformers,” J Electrostat, vol. 115, p. 103684, Jan. 2022, doi: 10.1016/J.ELSTAT.2022.103684.

[12] J. G. Hwang, M. Zahn, F. M. O’Sullivan, L. A. A. Pettersson, O. Hjortstam, and R. Liu, “Effects of nanoparticle charging on streamer development in transformer oil-based nanofluids,” J Appl Phys, vol. 107, no. 1, p. 14310, Jan. 2010, doi: 10.1063/1.3267474/287254.

[13] H. Khelifa, P. Skotnicki, A. Beroual, E. Vagnon, and M. Jaroszewski, “Effect of MgO Nanoparticles on the AC Breakdown Voltage, Partial Discharge Activity, and Electrostatic Charging Tendency of Natural Ester,” IEEE Transactions on Dielectrics and Electrical Insulation, 2024, doi: 10.1109/TDEI.2024.3374244.

[14] M. Zdanowski, “Streaming Electrification of C60 Fullerene Doped Insulating Liquids for Power Transformers Applications,” Energies 2022, Vol. 15, Page 2496, vol. 15, no. 7, p. 2496, Mar. 2022, doi: 10.3390/EN15072496.

[15] A. J. Amalanathan, R. Sarathi, N. Harid, and H. Griffiths, “Investigation on flow electrification of ester-based TiO2nanofluids,” IEEE Transactions on Dielectrics and Electrical Insulation, vol. 27, no. 5, pp. 1492–1500, Oct. 2020, doi: 10.1109/TDEI.2020.008540.

[16] L. Kong, J. Sun, and Y. Bao, “Preparation, characterization and tribological mechanism of nanofluids,” RSC Adv, vol. 7, no. 21, pp. 12599–12609, Feb. 2017, doi: 10.1039/C6RA28243A.

[17] W. Merzkirch, AGARD-AG-302: Techniques of flow visualization, vol. 302. North Atlantic Treaty Organization, Advisory Group for Aerospace Research and Development, 1987. doi: 10.14339/AGARD-AG-302-pdf.

[18] Rouabeh Jilani, “Badania Elektrostatycznych i Elektrohydrodynamicznych Właściwości Olejów Izolacyjnych,” Politechnika Wrocławska, Wrocław, 1998.

[19] A. Sierota and J. Rungis, “Electrostatic Charging in Transformer Oils Testing and Assessment,” IEEE Transactions on Dielectrics and Electrical Insulation, vol. 1, no. 5, pp. 840–870, 1994, doi: 10.1109/94.326655.

[20] M. Jaroszewski, A. Beroual, and P. Rozga, “Electrostatic charging tendency of natural transformer ester - impact of the surface state of solid on electrification currents,” Proceedings - IEEE International Conference on Dielectric Liquids, vol. 2022-May, 2022, doi: 10.1109/ICDL49583.2022.9830947.