Thermal properties of mixtures of mineral oil and natural ester in terms of their application in the transformer

Zbigniew Nadolny[1,*], and *Grzegorz* Dombek[1]

[1]Poznan University of Technology, Institute of Electrical Power Engineering, 60965 Poznan, Poland

Abstract. The article describes research results of thermal properties of mineral oil and natural ester. Percentage proportions of both the liquids were as follows: 100/0, 95/5, 80/20, 50/50, 20/80, 0/100. The authors present measurement results of thermal conductivity, viscosity, specific heat, density, and thermal expansion of the created mixtures. The measurements were taken in a relatively wide temperature range: 25 ºC, 40 ºC, 60 ºC, and 80 ºC. On the basis of the measurement results, convection heat transfer coefficient α was calculated and the most advantageous proportion of both the components of the mixture was pointed in terms of cooling effectiveness of the transformer.

1 Introduction

Insulating liquids are an integral part of the insulating system of most power transformers in the world. Due to their good properties, they have a role of an electric insulation and cooling medium [1-3]. Keeping in mind that heat transport in the transformer proceeds the following way: heat source → paper impregnated with liquid → insulating liquid → tank → air; it is liquid properties that will substantially decide about the efficiency of heat transfer [2, 4-6].

The properties which determine the ability of a liquid to heat transfer are: thermal conductivity λ, kinematic viscosity υ, specific heat c_p, density ρ, and thermal expansion β. These properties determine the ability of a liquid to cool the device, i.e. coefficient α [7-9]. The greater this ability is, the higher the value of coefficient α. In turn, coefficient α is greater when thermal conductivity, specific heat, density, and liquid thermal expansion are higher and its viscosity is lower [1, 2, 5].

The most frequently used insulating liquid in power engineering devices is mineral oil [1, 10, 11]. The popularity of applying mineral oil results from its low price and properties which have been well known for decades. Lately, stricter and stricter requirements concerning reliability of power engineering devices and a prospect of a real deficit of petroleum have contributed to search for insulating liquids alternative to mineral oil [12-16].

In the early 1990s, research on transformer liquids of plant origin was initiated. After less than ten years later, commercial application of natural esters was started in distribution transformers. Now we are observing their wider and wider application, including power transformers [11]. The advantages of applying natural esters instead of mineral oil are very good fire properties (high flash and fire point, and low net calorific value)

and environmental ones, which include first of all full biodegradability and low toxicity [17-19]. Undoubtedly, another advantage resulting from applying natural esters is also retarding the process of paper insulation ageing of the transformer [12, 20, 21]. Unfortunately, these esters, in comparison to mineral oil, are also characteristic of much higher viscosity and higher solidification temperature [2, 11].

Recently research on properties of insulating liquid mixtures has been conducted in many scientific centers in the world. These mixtures can be obtained in two ways. The first one is the so-called retrofilling, which consists in intentional replacing one insulating liquid (most often mineral oil) by another (natural or synthetic esters). This allows, among others, prolonging the remaining operation time of the power device [22]. This process, however, does not guarantee full removing the liquid which filled the transformer before. A small amount of it (not exceeding 8%) can be deposited in, for example, saturated paper insulation, windings, the core, and other hardly accessible places [23]. Thus as a result of filling the modernized unit with a new insulating liquid, we unintentionally obtain a mixture with the liquid which previously filled the transformer. The other way consists in applying an intended mixture in the new transformer, which consists of two or more insulating liquids of a known proportion. This results in obtaining a mixture, which is characteristic of improvement of some, selected properties in reference to the base liquids [10, 13-15, 24, 25].

Independently of the method how the mixture is created, the purpose of the application is to improve properties of the insulating liquid, which consequently affects the operation period of the transformer. Research on mixtures of insulating liquids which is conducted in many scientific centres all over the world refer mainly to electric properties. The remaining properties, including

---

* Corresponding author: zbigniew.nadolny@put.poznan.pl

thermal properties, attract much less attention, which is not a proper approach. Thus we should take into consideration that applying mixtures of insulating liquids which are characteristic of better electric properties and worse thermal properties in reference to the base liquids, will result in accelerating ageing processes taking place in the insulating system of the transformer and reducing the time of its operation. Therefore, this article presents research results concerning properties that influence the efficiency of transformer cooling properties.

2 Purpose and range of the research

The purpose of the undertaken research was to determine the influence of proportions of mineral oil with natural ester on thermal properties of a created mixture. The research range covered the measurement of thermal conductivity λ, kinematic viscosity υ, specific heat c_p, density ρ, and thermal expansion β. On the basis of the measured properties and the equation presented below, coefficient α was determined [8, 9]:

$$\alpha = n+1\sqrt{c \cdot \lambda^{1-n} \cdot g^n \cdot \delta^{3n-1} \cdot \beta^n \cdot \rho^n \cdot c_p^{\ n} \cdot \upsilon^{-n} \cdot q^n} \quad (1)$$

where: α – convection heat transfer coefficient of the liquid [W·m^{-2}·K^{-1}], c, n – constants dependent on the character of the flow, λ – thermal conductivity [W·m^{-1}·K^{-1}], g – acceleration of gravity [m·s^{-2}], δ – characteristic dimension connected with liquid flow [m], β – thermal expansion [K^{-1}], ρ – density [g·l^{-1}], c_p - specific heat [J·kg^{-1}·K^{-1}], υ – kinematic viscosity [mm^2·s^{-1}], q – surface thermal load [W·m^{-2}]. The characteristic dimension δ was equal to 1 m. By contrast, the values of constants c and n were assumed according to the figures listed in Table 1.

Table 1. Values of constants c and n dependent on the flow type [8,9].

Flow type	$Gr \cdot Pr$	c	n
No flow	$< 10^{-3}$	0.45	0
Laminar flow	$10^{-3} - 5 \cdot 10^2$	1.18	0.125
Transitional flow	$5 \cdot 10^2 - 2 \cdot 10^7$	0.54	0.25
Turbulent flow	$> 2 \cdot 10^7$	0.135	0.333

For measurements of thermal properties, the authors used mineral oil named Nytro Taurus manufactured by Nynas and natural ester named Envirotemp FR3 made by Cargil. Both liquids in investigations were new and unused. Water content was 2 ppm in case of mineral oil, and 34 ppm in case of natural ester. Acid number was less than 0,010 mg$_{KOH}$·g$^{-1}_{liquid}$ for mineral oil, and 0,020 mg$_{KOH}$·g$^{-1}_{liquid}$ for natural ester. Measurements of thermal conductivity of the mixtures were done using authorial measurement system, described in [26]. Measurements of kinematic viscosity, density, and thermal expansion of

the mixtures were done using authorial measurements systems according to obligatory standards [27-29]. Measurement of specific heat of the mixtures were done using the differential scanning calorimeter Mettler Toledo DSC1. In order to do the investigations, the authors prepared mixtures of mineral oil and natural ester of the following percentage concentrations of both the liquids: 100/0, 95/5, 80/20, 50/50, 20/80, 5/95, and 0/100. The measurements were taken at the temperature of 25 ℃, 40 ℃, 60 ℃, and 80℃. The results of the investigations are presented in the following section.

3 Results and discussion

3.1 Thermal conductivity of the mixture of mineral oil and natural ester

Table 2 and Fig. 1 contain measurement results of thermal conductivity λ of a mixture of mineral oil (MO) and natural ester (NE) depending on ester concentration. As we can observe, with increase of natural ester content, thermal conductivity λ considerably increases.

Table 2. Measurement results of thermal conductivity λ of the mixture of mineral oil (MO) and natural ester (NE).

Proportion of mineral oil (MO) and natural ester (NE)		Temperature T			
		25 ℃	40 ℃	60 ℃	80 ℃
		Thermal conductivity λ [W·m^{-1}·K^{-1}]			
100% MO	0% NE	0.133	0.130	0.128	0.126
95% MO	5% NE	0.136	0.134	0.132	0.130
80% MO	20% NE	0.144	0.141	0.139	0.137
50% MO	50% NE	0.158	0.156	0.153	0.152
20% MO	80% NE	0.173	0.171	0.168	0.166
5% MO	95% NE	0.179	0.177	0.174	0.172
0% MO	100% NE	0.182	0.180	0.178	0.175

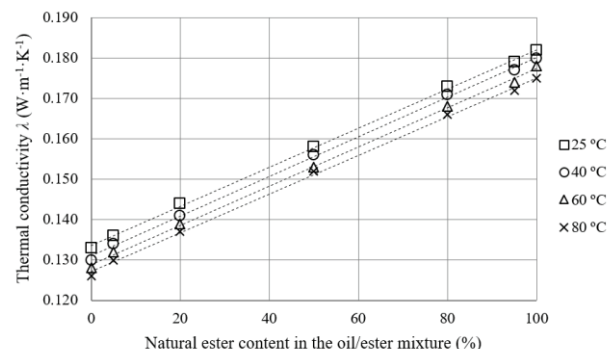**Fig. 1.** Thermal conductivity λ of the mixture of mineral oil and natural ester.

This increase is practically linear. The increase of λ was equal to 36.8% (for 25 °C), 38.5% (for 40 °C), 39.1% (for 60 °C), and 38.9% (for 80 °C). As we can see, this increase was at a constant level and it practically did not depend on temperature. Summing up, we can say that natural ester increases thermal conductivity of the mixture of mineral oil and natural ester, and consequently they can improve cooling properties of such a mixture.

3.2 Viscosity of the mixture of mineral oil and natural ester

Table 3 and Fig. 2 present research results of kinematic viscosity v of the mixture of mineral oil and natural ester, depending on the ester concentration.

Table 3. Measurement results of kinematic viscosity v of the mixture of mineral oil (MO) and natural ester (NE).

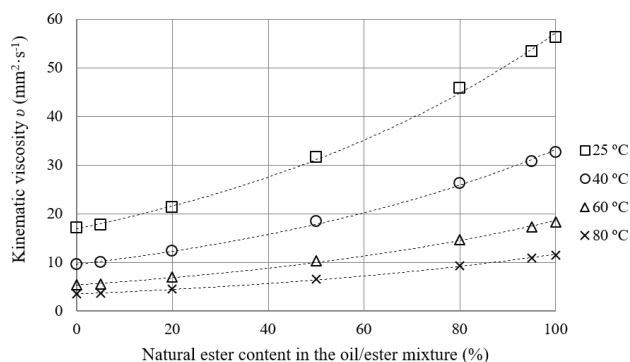| Proportion of mineral oil (MO) and natural ester (NE)		Temperature T			
		25 °C	40 °C	60 °C	80 °C
		Kinematic viscosity v [mm²·s⁻¹]			
100% MO	0% NE	17.08	9.59	5.37	3.43
95% MO	5% NE	17.67	9.93	5.44	3.59
80% MO	20% NE	21.34	12.25	6.89	4.46
50% MO	50% NE	31.68	18.48	10.28	6.50
20% MO	80% NE	45.81	26.23	14.67	9.25
5% MO	95% NE	53.42	30.78	17.24	10.88
0% MO	100% NE	56.29	32.66	18.29	11.50

Fig. 2. Kinematic viscosity v of the mixture of mineral oil and natural ester.

As it was shown, increase of natural ester content increases viscosity of the mixture very significantly. Initially, this increase is tiny (up to 5% of ester content) and next it is very clear (over 5% of ester content). Increase of viscosity v was equal to 230% (for 25 °C), 241% (for 40 °C), 241% (for 60 °C), and 235% (for 80 °C). This increase, caused by increase of natural ester

content in the mixture, was practically independent of temperature. Summing up, we can state that natural ester clearly increases viscosity of the mixture. This fact can result in substantial deterioration of thermal properties of the mixture.

3.3 Specific heat of the mixture of mineral oil and natural ester

Table 4 and Fig. 3 present measurement results of specific heat c_p of the mixture of mineral oil and natural ester depending on ester concentration. Increase of the natural ester content caused a certain increase of the specific heat of the mixture. This increase was linear. The increase of c_p was equal to 6.6% (for 25 °C), 5.4% (for 40 °C), 4.3% (for 60 °C), and 5.7% (for 80 °C). As we can see, the increase of specific heat caused by the increase of the natural ester content in the mixture practically did not depend on temperature. Summing up, we can say that natural ester can slightly improve cooling properties of the mixture of mineral oil and natural ester.

Table 4. Measurement results of specific heat c_p of the mixture of mineral oil (MO) and natural ester (NE).

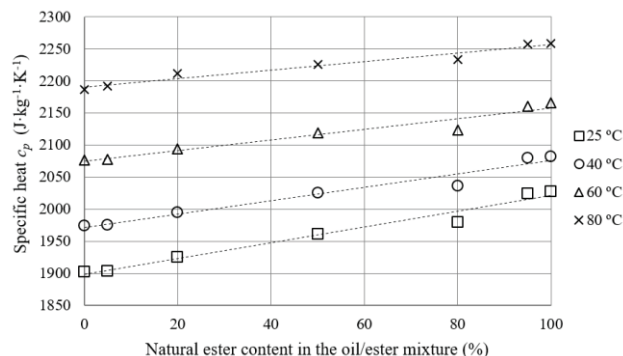| Proportion of mineral oil (MO) and natural ester (NE)		Temperature T			
		25 °C	40 °C	60 °C	80 °C
		Specific heat c_p [J·kg⁻¹·K⁻¹]			
100% MO	0% NE	1902	1974	2077	2187
95% MO	5% NE	1904	1975	2078	2192
80% MO	20% NE	1925	1995	2094	2212
50% MO	50% NE	1961	2025	2119	2226
20% MO	80% NE	1980	2036	2123	2233
5% MO	95% NE	2024	2080	2160	2257
0% MO	100% NE	2028	2082	2166	2259

Fig. 3. Specific heat c_p of the mixture of mineral oil and natural ester.

3.4 Density of the mixture of mineral oil and natural ester

Table 5 and Fig. 4 present measurement results of density ρ of a mixture of mineral oil and natural ester, depending on ester concentration. As it was shown, the increase of natural ester content caused the linear increase of mixture density. Increase of density ρ was equal to 5.8% (for 25 ºC), 6.0% (for 40 ºC), 5.6% (for 60 ºC), and 5.8% (for 80 ºC). This increase by a few percent, caused by the increase of natural ester content in the mixture, was practically independent of temperature. Summing up, we can say that increase of natural ester content can cause a slight improvement of cooling abilities of the mixture of mineral oil and natural ester.

Table 5. Measurement results of density ρ of the mixture of mineral oil (MO) and natural ester (NE).

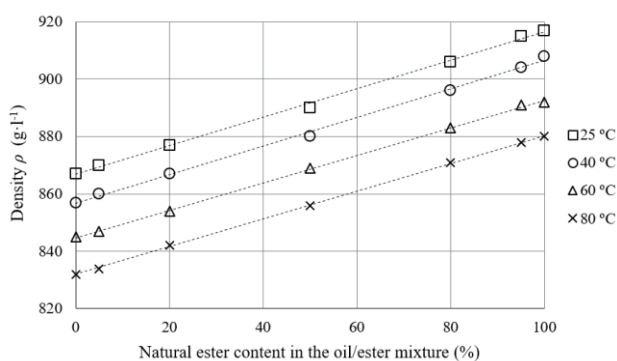| Proportion of mineral oil (MO) and natural ester (NE) | | Temperature T | | | |
		25 ºC	40 ºC	60 ºC	80 ºC
		Density ρ [g·l^{-1}]			
100% MO	0% NE	867	857	845	832
95% MO	5% NE	870	860	847	834
80% MO	20% NE	877	867	854	842
50% MO	50% NE	890	880	869	856
20% MO	80% NE	906	896	883	871
5% MO	95% NE	915	904	891	878
0% MO	100% NE	917	908	892	880

Fig. 4. Density ρ of the mixture of mineral oil and natural ester.

3.5 Thermal expansion of the mixture of mineral oil and natural ester

Table 6 and Fig. 5 show measurement results of thermal expansion β of a mixture of mineral oil and natural ester depending on ester concentration. As we can see, increase of natural ester content practically did not cause any changes of thermal expansion of the mixture. The lack of expansion changes was noted for all the

temperature α values. Thus we can say that increase of natural ester content does not result in any changes of cooling abilities of an analyzed mixture.

Table 6. Measurement results of thermal expansion β of the mixture of mineral oil (MO) and natural ester (NE).

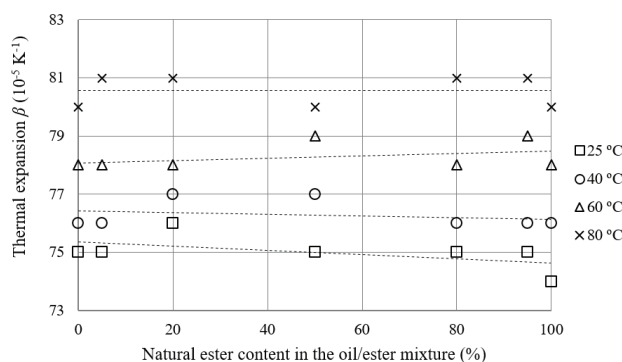| Proportion of mineral oil (MO) and natural ester (NE) | | Temperature T | | | |
		25 ºC	40 ºC	60 ºC	80 ºC
		Thermal expansion β [K^{-1}]			
100% MO	0% NE	0.00075	0.00076	0.00078	0.00080
95% MO	5% NE	0.00075	0.00076	0.00078	0.00081
80% MO	20% NE	0.00076	0.00077	0.00078	0.00081
50% MO	50% NE	0.00075	0.00077	0.00079	0.00080
20% MO	80% NE	0.00075	0.00076	0.00078	0.00081
5% MO	95% NE	0.00075	0.00076	0.00079	0.00081
0% MO	100% NE	0.00074	0.00076	0.00078	0.00080

Fig. 5. Thermal expansion β of the mixture of mineral oil and natural ester.

3.6 Convection heat transfer coefficient of the mixture of mineral oil and natural ester

Table 7 and Fig. 6 present calculation results of the convection heat transfer coefficient α of a mixture of mineral oil and natural ester depending on ester concentration. The calculations of coefficient α were done on the basis of the measurement results presented in the previous subsections (3.1-3.5).

As it results from the table and the figure, with increase of natural ester content in the mixture, its coefficient α was initially rising a little (up to 5% of ester content) and next it was clearly decreasing (starting from 5% of ester content). This trend could be observed independently of temperature. The initial increase of coefficient α (up to 5% of ester content) was very small and it was merely 0.4% (for 25 ºC), 0.8% (for 40 ºC), 1.3% (for 60 ºC), 0.9% (for 80 ºC). In turn, the drop of coefficient α (starting from 5% of ester content) was

more significant and it was 4.5% (for 25 ºC), 4.8% (for 40 ºC), 5.4% (for 60 ºC), and 8.1% (for 80 ºC).

Table 7. Measurement results of convection heat transfer coefficient α of the mixture of mineral oil (MO) and natural ester (NE).

Proportion of mineral oil (MO) and natural ester (NE)		Temperature T			
		25 ºC	40 ºC	60 ºC	80 ºC
		Convection heat transfer coefficient α [W·m^{-2}·K^{-1}]			
100% MO	0% NE	93.56	107.89	125.70	141.65
95% MO	5% NE	93.92	108.70	127.32	142.86
80% MO	20% NE	92.94	106.63	123.67	139.56
50% MO	50% NE	88.65	101.98	118.64	134.15
20% MO	80% NE	85.18	97.98	113.91	129.43
5% MO	95% NE	84.04	96.60	112.44	127.12
0% MO	100% NE	83.46	96.12	111.80	126.17

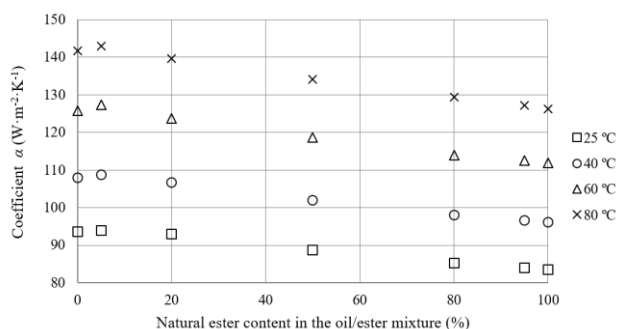**Fig. 6.** Convection heat transfer coefficient α of the mixture of mineral oil and natural ester.

The initial increase of coefficient α caused by increase of ester content in the mixture (up to 5%) resulted from many effects. These include the increase of thermal conductivity, specific heat, and density, despite a slight increase of viscosity. In turn, the drop of coefficient α (over 5% of ester content) was caused by a violent viscosity increase, despite resulting increase of thermal conductivity, specific heat, and density. We can say on this basis that the best combination of the mixture components is 95% of mineral oil and 5% of natural ester.

4 Conclusions

The increase of natural ester content in the mixture of mineral oil and natural ester resulted in increase of thermal conductivity by almost 40%, viscosity increase by over 200%, specific heat increase by about 5%, density increase by about 5%, and no changes of thermal expansion. In contrast, coefficient α has its maximum for a mixture of 95% of mineral oil and 5% of natural ester.

Coefficient α was 141.65 W·m^{-2}·K^{-1} in case of pure mineral oil and 142.86 W·m^{-2}·K^{-1} in case of mixture with maximal convection heat transfer coefficient, for 80 ºC (Table 7). Temperature decrease ΔT (between windings and tank) for pure oil is 24.7 ºC, and for mixture with maximal α is 24.5 ºC (surface heat density equals 3500 W·m^{-2}). It means that difference of ΔT between pure oil and mixture whit maximal α is just 0.2 ºC.

From the practical point of view we can say that it makes no sense to apply the mixture (95% of mineral oil and 5% of natural ester) of the maximum coefficient α. This results from the fact that for such a mixture, this coefficient is only by 1-2% higher than for the coefficient α of pure mineral oil.

In the case of retrofilling, i.e. replacing mineral oil with ester (e.g. natural ester), we can expect that a few percent of oil will remain in the transformer in its hardly available parts (paper insulation, crevices). In this way, a mixture of oil and ester is created of the proportion 5/95. The coefficient α of such a mixture (Table 7, Figure 6) is much lower than the coefficient α of pure mineral oil or the mixture of the maximum value of α. Thus we can expect that after retrofilling the transformer, the created mixture will have worse cooling properties. On the other hand, the coefficient α of the mixture is a slightly higher than the coefficient α of pure natural ester. Thus we can expect that after retrofilling the transformer, the created mixture will have better cooling properties than natural ester.

Measured values of thermal properties of mixtures (thermal conductivity, kinematic viscosity, specific heat, density, and thermal expansion) were intermediate values of pure oil and pure natural ester. But coefficient α values, calculated using formula (1), were not intermediate values of pure oil and pure natural ester. The coefficient α had some unexpected maximum, what is important results.

Future investigations of a mixture with used mineral oil and unused natural ester should be made in order to better understanding of thermal consequence of retrofilling the transformer.

References

1. T.O. Rouse, IEEE Electr. Insul. Mag. **14** (1998)
2. G. Dombek, Z. Nadolny, Eksploatacja i Niezawodnosc – Maintenance and Reliability **18** (2016)
3. Z. Nadolny, G. Dombek, P. Przybylek, IEEE 2016 Conf. Electr. Insul. Dielectr. Phenom., 857-860 (2016)
4. R. Lopatkiewicz, Z. Nadolny, Prz. Elektrotechniczny **84** (2008)

5. Z. Nadolny, G. Dombek, P. Przybylek, D. Przadka, IEEE 2016 Conf. Electr. Insul. Dielectric Phenom., 538-541 (2016)

6. R. Lopatkiewicz, Z. Nadolny, P. Przybylek, W. Sikorski, Prz. Elektrotechniczny **88** (2012)

7. F.B. Waddington, GEC J. Sci. Technol. **49** (1983)

8. F.P. Incropera, D.P. DeWitt, T.L. Bergman, A.S. Lavine, *Fundamental of heat and mass transfer* (Willey, 2007)

9. R. Rudramoorthy, K. Mayilsamy, *Heat and mass transfer* (Pearson, 2011)

10. R. Liao, J. Hao, S. Grzybowski, IEEE 2011 Int. Conf. Dielectric Liq., 1-4 (2011)

11. Cigre WG A2.35, *Experience in service with new insulating liquids. Brochure 436* (Cigre, Paris, 2010)

12. Y. Bertrand, L.C. Hoang, Int. Conf. Prop. Appl. Dielectric Mater., 491-494 (2003)

13. I. Fofana, V. Wasserberg, H. Borsi, E. Gockenbach, IEEE Electr. Insul. Mag. **18** (2002)

14. I. Fofana, V. Wasserberg, H. Borsi, E. Gockenbach, IEEE Electr. Insul. Mag. **18** (2002)

15. C. Perrier, J.L. Beroual, L. Bessade, IEEE Trans. Dielectr. Electr. Insul. **13** (2006)

16. T. Boczar, A. Cichon, S. Borucki, IEEE Trans. Dielectr. Electr. Insul. **21** (2014)

17. K. Longva, Nordic Insul. Symp., 293-295 (2005)

18. T.V. OOmmen, IEEE Electr. Insul. Mag. **18** (2002)

19. C.P. McShane, J.L. Corkran, K.J. Rapp, J. Luksich, Conf. Electr. Insul. Dielectric Phenom., 124-127 (2003)

20. L. Ruijin, H. Jian, C. George, M. Zhigin, Y. Lijm, IEEE Trans. Dielectr. Electr. Insul. **18**, 1626-1637 (2011)

21. P. Trnka, V. Mentlik, M. Svoboda, IEEE Int. Conf. Dielectric Liq., 1-4 (2014)

22. C.P. McShane, J. Luksich, K.J. Rapp, IEEE-IAS/PCA Cem. Ind. Tech. Conf., 141-147 (2003)

23. I. Fofana, V. Wasserberg, H. Borsi, E. Gockenbach, IEEE Electr. Insul. Mag. **17**, 17-30 (2001)

24. R. Liao, J. Hao, L. Yang, S. Liang, J. Yin, Int. Conf. High Voltage Eng. Appl., 588-591 (2010)

25. C.P. McShane, IEEE-IAS/PCA Cem. Ind. Tech. Conf., 31-40 (2001)

26. G. Dombek, Z. Nadolny, P. Przybylek, Prz. Elektrotechniczny, 148-151 (2014)

27. ASTM D 1903-08

28. ISO 3675:1998

29. ISO 3104:1994