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Investigation of Natural Ester Insulating Fluid Properties and Thermal Model of a Transformer in Wide Temperature Range

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***Abstract*—Currently, a significant number of transformers are designed and used in the electricity distribution network. Since these machines are commonly based on an oil-paper electrical insulation system, it is crucial to know how certain important parameters of an oil behave within a wide range of ambient temperatures. Therefore, the range of temperatures should also include low temperature region as these conditions might occur in real application. The aim of this paper is to focus on the temperature dependent viscosity, density, thermal conductivity and specific heat of an oil in order to develop a strongly coupled thermal model of a transformer which is filled with biodegradable natural ester insulation fluid. Obtained results can be well applied within the design, operation and diagnostics phase of these types of electrical machines.**

***Keywords*—Transformer, Electrical Insulation System, Natural Ester, Thermal Properties, Thermal Model**

I. INTRODUCTION

The number of transformers filled with environment-friendly insulation fluids as an alternative to conventional mineral oils had increased over the last decades. For instance, this could be shown in case study [1] which states that there are over 3,000 of such distribution transformers only in the US. The Brazil and China market is mentioned as well. Reference [1] along with [2],[3],[4],[5] also points out several benefits of natural esters such as significantly higher biodegradability, fire resistance and water saturation point compared to the mineral oil. Moreover, the lower price might be also mentioned in comparison to the mineral oils [5]. Nonetheless, few disadvantage can be noticed according to aforementioned references as well. These are mainly higher viscosity or temperature of the pour point.

As many transformers are retrofitted with or designed for natural ester oils and operates within various ambient conditions and under variable loading, not only dielectric properties are the important ones but also thermal properties have to be taken into account. This paper focuses on investigation of such properties and their implementation into thermal model of particular distribution transformer which has been designed exclusively for the electrical insulating liquid which can be found under the product name ”Envitrafol” [6].

II. SELECTED PROPERTIES OF THE FLUID

In order to develop a sufficient thermal model of the transformer, temperature dependence of a few selected parameters must be explored. Moreover, thermal dependence of these parameters allows to develop thermal model considering natural convection heat exchange by means of insulating oil. Thermal solver requires temperature defined in Kelvins, therefore all of measured data were recalculated from degrees of Celsius. For specified rapeseed based oil Envitrafol, measurement of viscosity and density was carried out, while thermal conductivity and specific heat had to be found in similarly oriented studies.

A. Dynamic viscosity

Dynamic viscosity of pure oil has been measured via vibration viscometer A&D SV-10 and laboratory thermostat Krüss PT80 which provided controlled warming of the sample.

Measurement has been carried out for the temperature range starting at -1 °C continuing up to 60 °C. Acquired values are presented in the Fig. 1.

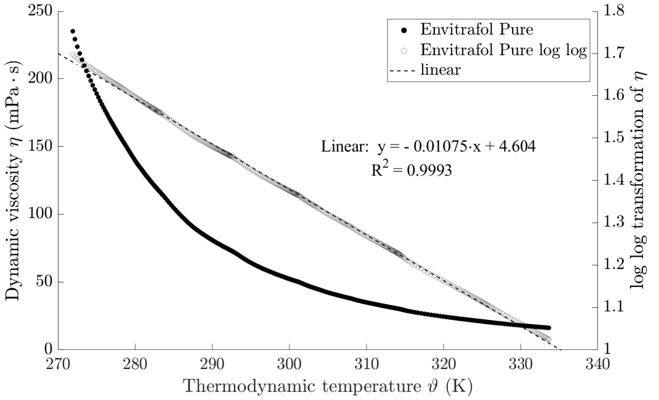

Fig. 1. Temperature dependence of Envitrafol dynamic viscosity

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For extrapolation purposes, it has been discovered that the best fit of the measured data is double exponential. This can be described by (1), where η means dynamic viscosity, ϑ stands for temperature, while a_η and b_η are regression coefficients. These regression coefficients has been determined after double logarithmic transformation and exponential and linear regression has been applied. It was observed that coefficient of determination is higher for a linear fit compared to exponential one and thus double exponential fit has been marked as the most suitable one. The coefficient of determination R^2 has been determined for linear fit after double logarithmic transformation of measured data.

$$\eta = \exp(\exp(a_\eta \cdot \vartheta + b_\eta) \tag{1}$$

The solid state of this particular batch of oil has been found approximately at -15 °C during the experiment. This value is corresponding with the pour point of the natural ester presented in [1]. Thus, extrapolation of dynamic viscosity has its meaning only down to this value. However, for the dried batch of Envitrafol the pour point can be reported even around the value of -20 °C. It should be noted that a pour point is dependent on the water content and thus may vary batch to batch of the manufactured oil.

Kinematic viscosity can be calculated based on the collected data of the dynamic viscosity and density via (2) according to ISO 3104:2020. Here, the ν is the kinematic viscosity, the η represents already mentioned dynamic viscosity and ρ stands for the density.

$$\nu = \frac{\eta}{\rho} \tag{2}$$

B. Density

Density has been measured and calculated using the method which is based on the weight difference of submerged element of known volume in the air and in the liquid (Archimedes' principle). Laboratory scales and a multimeter with thermocouple sensor were used as the measurement devices.

Measured values of density were compared with those in [1, 2, 3] and [7] in order to validate results' verity. Despite the fact that mentioned oils are not identical, all of them are still nature ester or rapeseed oil and therefore their parameters are quite similar.

Density can be calculated according to (3) afterwards. In this equation, ρ stands for density, A is the weight of the submerged element in the air, B is the weight of submerged element in the liquid, V represents the volume of the element and finally d stands for the density of air at certain level of relative humidity in the lab. Dry air condition (30-40% RH) has been met during measurement.

$$\rho = \frac{A - B}{V} + d \tag{3}$$

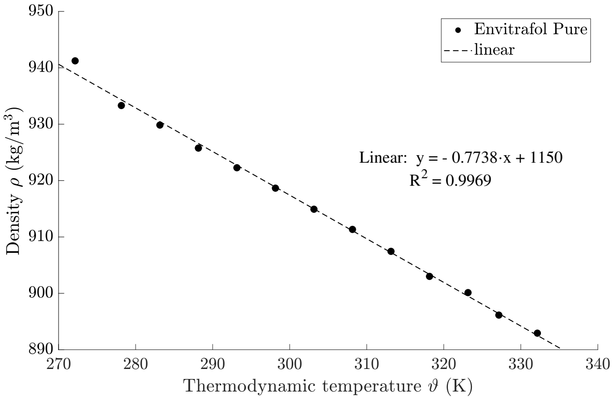

Fig. 2. Temperature dependence of Envitrafol density

The density of an oil sample has been determined for the same temperature range as the dynamic viscosity has been. The trend of the curve is decreasing as the temperature increases. This is shown in Fig. 2.

Linear regression (4) has been applied and the coefficient of determination R^2 is sufficient.

$$\rho = a_\rho \cdot \vartheta + b_\rho \tag{4}$$

Calculated values at certain temperatures were again compared with similar studies [1, 2, 3, 7, 8] in order to confirm validity of the measurement. Results slightly differ since compared oils are not exactly the same type.

C. Thermal conductivity

This parameter has been implemented in accordance with (5) where the λ represents thermal conductivity, ϑ still means the temperature and a_λ, b_λ, c_λ are the regression coefficients.

$$\lambda = a_\lambda \cdot \vartheta^2 + b_\lambda \cdot \vartheta + c_\lambda \tag{5}$$

This equation and corresponding coefficients have been taken from [9] and partially confirmed by the data contained in [2]. For the purposes of this work, the regression coefficients for rapeseed oil from [9] has been used since worst-case is considered in the thermal model.

The regression shown in Fig. 3 has been made in order to fit the data used from [2]. Although the equation of quadratic regression fits data perfectly, the linear regression might be also sufficient in the range of shown temperatures.

D. Specific heat capacity

Values of lower specific heat capacity has been applied in the thermal solver as more pessimistic scenario was taken into account (according to Calorimetry formula). Thermal dependency of specific heat is depicted in Fig. 4. Data available in [2] and [8] have been used. For the chosen temperature range, the coefficient of determination R^2 is sufficient even for linear regression. However, quadratic regression (6) has been used.

$$c_p = a_{c_p} \cdot \vartheta^2 + b_{c_p} \cdot \vartheta + c_{c_p} \tag{6}$$

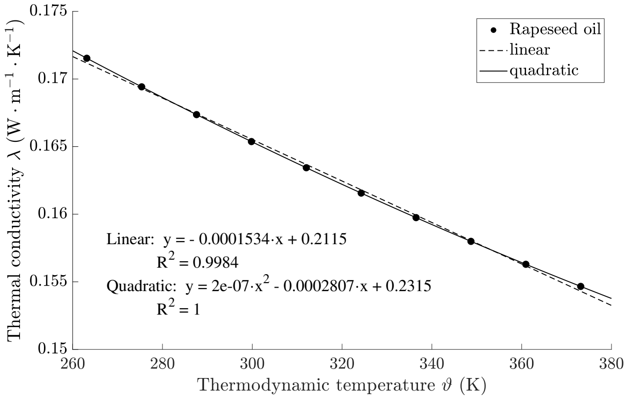

Fig. 3. Thermal conductivity of rapeseed oil

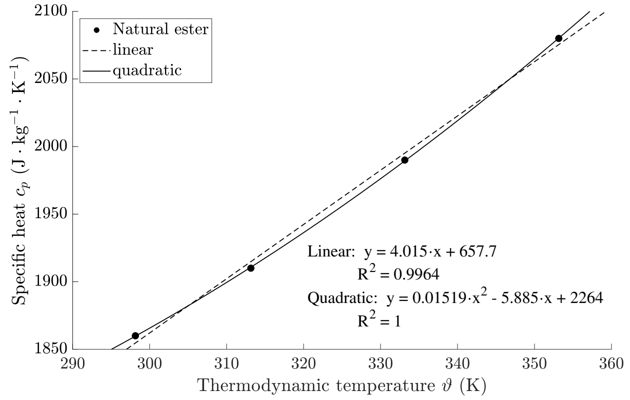

Fig. 4. Specific heat of natural ester

III. THERMAL MODEL OF THE TRANSFORMER

The thermal model was built using Ansys Fluent 2021 R1. In order to build a model including heat exchange by natural convection, it was necessary to insert the thermal dependence of the relevant parameters of the electrical insulating oil.

A. Setup

The thermal model was considered in a steady state with laminar flow. The Newton's boundary condition was placed on the transformer container with variable ambient temperature and constant heat transfer coefficient $h = 15$ W/(m^2·K). For the thermal solver setup, the continuous dependence of mentioned parameters has been entered via equations obtained through regression analysis. These equations are based either (i) on the measurement (in case of viscosity and density) or (ii) on the other publicly available data (for thermal conductivity and specific heat) shown in previous sections of this paper. Coefficients for aforementioned regression equations are summarized in Tab. I (temperature is considered in Kelvins).

Other materials' thermal parameters have been set via corresponding Ansys library, for example, insulation between coils or laminated electrical steel.

TABLE I
REGRESSION COEFFICIENTS AND R^2

Parameter	a	b	c	R^2
η (mPa·s)	-0.0108	4.604	0	0.9993
ρ (kg/m^3)	-0.7738	1150	0	0.9969
λ (W·m^{-1}·K^{-1})	$2.00 \cdot 10^{-7}$	$-2.807 \cdot 10^{-4}$	0.2315	1
c_p (J·kg^{-1}·K^{-1})	0.01519	-5.885	2264	1

The three-phase core type distributional transformer has rated power 160 kVA, no-load losses 181 W, full-load losses 1 600 W and designed maximum temperature 105 °C. Voltage rating is 22 kV (HV) and 0.4 kV (LV).

B. Results

Results have been evaluated once the model solver achieved convergence of conservation laws and specific physical quantities.

First of all, contour plot for transformer's cross-section view has been exported for each model setup in order to evaluate temperature distribution in the whole device. For instance, a plot for an ambient temperature 40 °C is shown in Fig. 5. It is noticeable that the highest temperature of the oil dwells in higher layers.

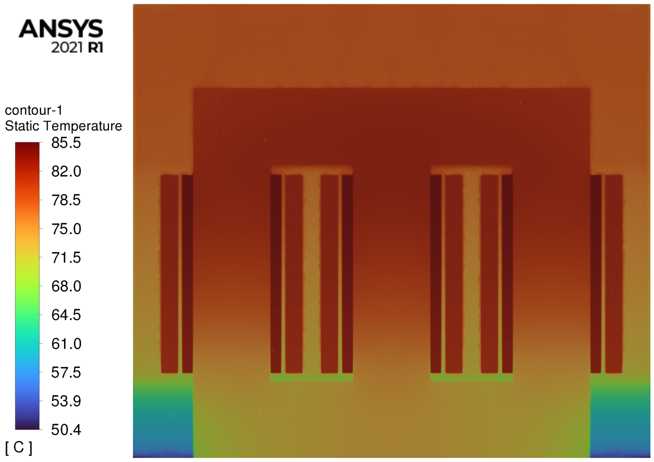

Fig. 5. Model results, cross-section view, ambient temperature 40 °C, full nominal power losses

The critical part of transformer in terms of cooling are turns of the coils. In order to evaluate whether the cooling is sufficient or not, temperature has been plotted in Fig. 6 along the vertical dimensions inside of both coils. Since the low voltage coil has a higher current density, the temperature is higher as well and vice versa in the case of coil with the higher voltage. The highest temperature is located at low voltage (LV) coils which is also the highest temperature observed according to Fig. 5.

Subsequently, the average oil flow velocity caused by the natural convection was evaluated. Maximum temperatures and average oil flow velocity increase with increasing ambient temperature. These values are summarized along with setups and other results in Tab. II.

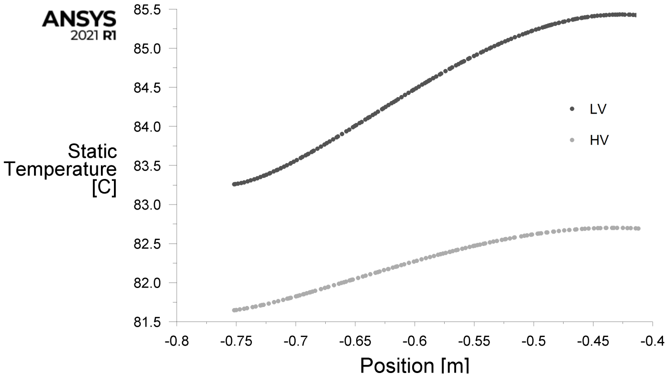

Fig. 6. Temperature of LV and HV side coil, ambient temperature 40 °C, full nominal power losses

TABLE II
SETUPS AND RESULTS OBTAINED FROM THE MODEL

Parameter	#1	#2	#3	#4	#5
Ambient temperature (°C)	-20	0	20	40	60
Highest temperature (LV coil) (°C)	29.4	46.5	65.4	85.5	106.7
Average oil velocity (mm/s)	1.1	1.4	1.5	2.0	2.5

CONCLUSION

Temperature dependence of dynamic viscosity and density have been investigated for particular type of transformer oil - Envitrafol. Subsequently, validation through results of similar published studies has been done successfully. Thermal conductivity and specific heat have been determined entirely through the literature review of similar types of transformer insulating liquid or oils. Oil's properties, regression equations, setups and results of the transformer's thermal model have been presented in the paper.

It has been verified that cooling is sufficient and the original thermal design of the transformer filled with Envitrafol can thus operate continuously up to almost 60 °C of ambient temperature, considering the presence electrical insulating materials of class A according to EN 60085:2008. The obtained oil parameters could be used in the design of similar transformers in the future, including information on behaviour over a wider temperature range, especially at low temperatures.

The manufacturing phase of the transformer prototype is currently underway. Once this is completed, relevant measurements should be carried out in order to verify and possibly modify or adjust the thermal model.

Another interesting direction of the research might be an implementation of the ferrofluids and their properties which are mentioned for instance in [10] and [11]. It could also be promising to build a complex model that would provide a digital twin of the device or to use a transient thermal model in order to evaluate whole process of oil heating. A solid state of the oil as the extreme situation together with different levels of power losses should be also investigated in the future work.

REFERENCES

[1] ABB Hefei Transformer Co. Ltd. *ABB nature ester distribution transformer*. Nov. 2016. URL: https://new.abb.com/docs/librariesprovider46/pw2016/seminars/r308-en-abb_nature_ester_distribution_transformer.pdf?sfvrsn=2.

[2] Grzegorz Dombek, Zbigniew Nadolny, and Agnieszka Marcinkowska. "Thermal properties of natural ester and low viscosity natural ester in the aspect of the reliable operation of the transformer cooling system". In: *Ekspolatacja i Niezawodnosc - Maintenance and Reliability* 21 (3 June 2019), pp. 384–391. ISSN: 15072711. DOI: 10.17531/ein.2019.3.4.

[3] George Frimpong, Jan Hajek, and Krzysztof Kulasek. *Eco-friendly ester liquid transformer designs*. URL: https://search.abb.com/library/Download.aspx?DocumentID=9AKK107046A6496.

[4] Pavel Trnka, Vaclav Mentlik, and Michal Svoboda. *Ecologically acceptable insulating liquids for electrical appliances*. 2014. ISBN: 9781479920631. DOI: 10.1109/ICDL.2014.6893121.

[5] Pavel Trnka et al. "Behavior of alternative electro insulating liquid at solidification process". In: *2016 IEEE International Conference on Dielectrics (ICD)*. Vol. 2. 2016, pp. 1175–1178. DOI: 10.1109/ICD.2016.7547827.

[6] Vaclav Mentlik et al. "Development of a Biodegradable Electro-Insulating Liquid and Its Subsequent Modification by Nanoparticles". In: *Energies* 11.3 (2018). ISSN: 1996-1073. DOI: 10.3390/en11030508.

[7] Milan Spohner. "A Study of the Properties of Electrical Insulation Oils and of the Components of Natural Oils". In: *Acta Polytechnica* 52 (5 Jan. 2012). ISSN: 1805-2363. DOI: 10.14311/1652.

[8] Melissa I Torregroza-Rosas, Edgardo Arrieta-Martinez, and Jorge I Silva-Ortega. "Thermal Behaviour of Natural Ester Based Oil Used in Distribution Transformers; Thermal Behaviour of Natural Ester Based Oil Used in Distribution Transformers". In: (2021). DOI: 10.1109/INTERCON52678.2021.9532650.

[9] J. F. Hoffmann et al. "Temperature dependence of thermal conductivity of vegetable oils for use in concentrated solar power plants, measured by 3omega hot wire method". In: *International Journal of Thermal Sciences* 107 (Sept. 2016), pp. 105–110. ISSN: 1290-0729. DOI: 10.1016/J.IJTHERMALSCI.2016.04.002.

[10] Stefan Hardon et al. "The Magneto-Dielectric Anisotropy Effect in the Oil-Based Ferrofluid". In: *International Journal of Thermophysics* 40 (2019), p. 24. DOI: 10.1007/s10765-019-2486-4. URL: https://doi.org/10.1007/s10765-019-2486-4.

[11] Lucian Pislaru-D et al. "Prototyping a Ferrofluid-Cooled Transformer". In: *IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS* 49 (3). DOI: 10.1109/TIA.2013.2252872.