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Comparison of the Thermal Performance of Mineral Oil and Natural Ester for Safer Eco-Friendly Power Transformers

A Numerical and Experimental Approach

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Abstract. At present, most of the worldwide transformer fleet uses mineral oil as insulation fluid. However, the use of natural ester is playing an increasing role as safer and eco-friendly alternative to mineral oil. From the utilities' perspective, the change in the mineral oil paradigm can be approached by replacing their assets by new eco-friendly transformers or refurbishing their assets, substituting only the insulating fluid. To make an informed decision, guidelines indicating how a transformer designed for mineral oil would behave when operating with natural ester, are of paramount importance.

In the present research, temperature rise tests were carried out in a 15MVA ODAF core-type power transformer, under different operating conditions. Tests were run for mineral oil as insulating fluid and subsequently repeated for natural ester.

To gain further insights on experimental results, thermal modelling of the transformer under the same test conditions was carried out, using Thermal-Hydraulic Network Models and Computational Fluid Dynamics techniques.

From the present work it was found that the relationship between the thermal behaviour of the transformer using natural ester or mineral oil is not simple as it depends on the operating conditions of the transformer and on the geometry of the windings.

Key words. Mineral Oil, Natural Ester, Thermal Modelling, Power Transformers

1. Introduction

Transformers are one of the most important and expensive equipment used in electrical energy networks. Nowadays, most of the worldwide transformer fleet uses mineral oil as insulation fluid because of its excellent and well-known dielectric and thermal properties. However, global energy sector is converging towards sustainability while mineral oil has low biodegradability compared to other emerging insulation fluids.

The electric network is changing: while emerging smart grids contribute to a more efficient energy distribution, the increased migration of people from rural to urban areas drives higher demand on the city energy consumption – there are more users and they each require relatively more energy [1]. In urban substations, where there is lack of space to place larger power transformers, they are often overloaded to serve the energy demand. In these urban areas, safety is of major importance: mineral oil increases the probability of fire in case of equipment failure, exposing public to risk. In addition, because it is considered a hazardous material, a mineral oil leakage event creates health issues and requires special cleaning.

The use of natural ester is playing an increasing role as an alternative to mineral oil. Besides the biodegradability, natural ester exhibits additional advantages over mineral oil, such as fire safety, aging rate reduction of cellulose insulation and moisture tolerance [1], [2].

From the utilities perspective, the change in the mineral oil paradigm can be approached by i) replacing their assets by new eco-friendly transformers or ii) refurbishing their assets, substituting only the insulating fluid [3]. To make an informed decision, guidelines indicating how a transformer designed for mineral oil would behave when operating with natural ester as insulation fluid, are of major importance [2].

The present research was developed under the scope of *GreenEst* project (https://projects.efacec.com/greenest/). One objective of this project was to provide insights on the improvement of transformers design when using natural ester as insulation fluid. Temperature is one of the most important factors influencing the transformer lifetime, and consequently its operation planning (e.g. loading) [4]. Bearing this in mind, the present investigation was firstly focused on the comparison of the thermal hydraulic performance of mineral oil and natural ester as insulating fluids.

Thermal-Hydraulic Network Models tools (THNM) and Computational Fluid Dynamics techniques (CFD) were used to predict the thermal-hydraulic behaviour of the mineral oil and natural ester. The numerical simulations were applied to a practical case with a 15 MVA prototype transformer.

Experimental and numerical results from temperature rise tests were obtained, corresponding to different loading conditions and insulation fluid flowrate. These tests were run for mineral oil as insulating fluid (Nynas Nytro Taurus®) and subsequently repeated for natural ester (Cargill FR3®).

From the present work it was found that the relationship between the thermal behaviour of the transformer using natural ester or mineral oil is not simple as it depends on the operating conditions of the transformer and on the geometry of the windings. For each test conditions and winding geometry, a detailed comparative analysis of the thermal performance of mineral oil and natural ester is presented. The experimental results are complemented with local thermal-hydraulic analysis provided by the numerical tools. These findings are intended to, in one hand, provide insight on the adaptation of transformers design when using natural ester as insulation fluid and, on the other hand, support the utilities on the decisions regarding an eco-friendly transformation of their transformers fleets.

2. Experimental Setup and Tests Conditions

An experimental setup of a real scale 15MVA ODAF core-type three-phase power transformer (Fig. 1) was used to perform temperature rise tests under different operating conditions (**Table 1**), for mineral oil (Nynas Nytro Taurus ®) and natural ester (Cargill FR3 ®).

Table 1. Temperature rise tests and operating conditions

Total nominal	Heat losses		
flowrate	220 kW	165 kW	110 kW
90 ($m^3 \cdot h^{-1}$)	E1	E2	-
30 ($m^3 \cdot h^{-1}$)	E3	E4	E5

This transformer has characteristics which allow it to be used as an experimental setup. Its six windings are all different from the thermal-hydraulic point of view (Fig. 2). It was expected that different fluid flow paths in the windings would result in different average winding temperatures. Consequently, for each test conditions (E1 to E5), three temperature rise tests were performed so the average winding temperatures were measured, by resistance method, in each phase.

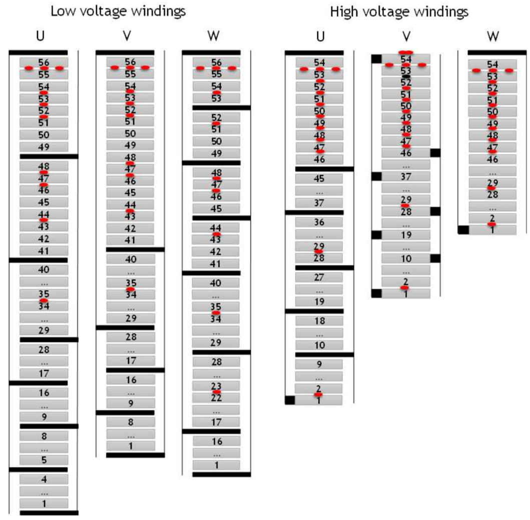


Fig. 2. Geometry of the windings and fiber optics location (in red)

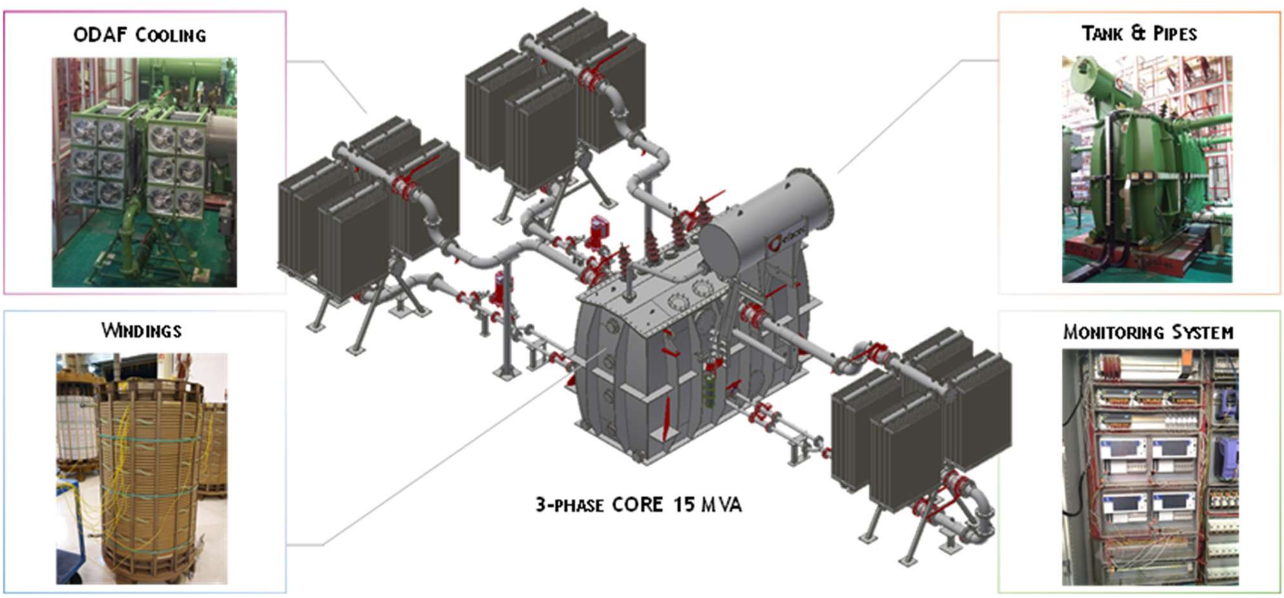


Fig. 1. Experimental setup of a real scale 15 MVA ODAF core-type three-phase power transformer

Another feature of the real-scale experimental setup is the insulating fluid guidance (Fig. 3): the fluid is separately directed to each winding so the flowrate can be measured for each of the six windings, using six ultrasonic flowmeters (as described in Table 2).

Fig. 3. Oil separately directed to low-voltage and high-voltage windings

Additionally, the experimental setup has a thorough monitoring system (Table 2) to allow a detailed thermal-hydraulic analysis.

Table 2. List of sensors composing the monitoring system

Location	Measured property	Sensor	Qty.
Active part: windings and magnetic circuit	Temperature	Fiber optics	72
External hydraulic circuit: pipes	Temperature	RTDs PT1000	17
	Temperature e moisture	Vaisala MMT 162	1
	Flowrate	Ultrassonic flowmeters	6
	Pressure difference	Differencial pressure transmitter	3

3. Results

A. Experimental Results

This section describes steady-state experimental results obtained for different fluid flowrates and loading conditions, according to Table 1.
After the first stage, when temperature rise tests were run for mineral oil as insulating fluid, it was found that the geometry of the high voltage winding of phase V (as shown in Fig. 2) was the most promising from the thermal performance point of view. Bearing this in mind, in the second stage of the temperature rise tests, when natural ester was the insulating fluid, focus was put on phase V: test conditions E1 to E5 were run and the average winding temperature was obtained for phase V only. Yet, in order to have insights on the effect of the windings geometry when using ester as insulating fluid, the E3 test was repeated and the average winding temperature was obtained for all three phases.

The operation conditions imposed to the pumps (by controlling the frequency) were maintained for the first and second stage of tests. Due to the higher viscosity of natural ester, the resulting flowrate was lower, as shown in table 3.

Table 3. Inlet measured conditions

		Inlet temperature (ºC)						Flowrate (m3/s)					
		U		V		W		U		V		W	
		LV	HV	LV	HV	LV	HV	LV	HV	LV	HV	LV	HV
M.O.	E1	48.4	48.4	49.7	49.1	46.8	46.9	14.9	15.8	16.7	15.2	14.7	16.4
	E2	39.8	40.0	39.2	39.0	42.0	41.9	14.6	15.6	15.7	14.7	14.5	16.2
	E3	43.2	43.3	40.7	40.4	42.7	42.6	5.7	5.8	4.7	5.3	4.1	4.8
	E4	33.5	33.5	33.4	33.2	33.2	33.0	5.2	4.3	5.1	5.6	5.2	5.1
	E5	30.9	30.9	29.0	29.1	30.5	30.4	5.2	4.3	5.2	5.7	5.2	4.3
N.E.	E1			43.0	42.3					13.6	13.6		
	E2			39.0	38.5					12.9	12.9		
	E3	38.7	38.5	41.1	40.8	39.2	38.9	4.3	4.3	5.0	5.0	4.2	4.2
	E4			37.5	37.1					5.0	5.0		
	E5			29.9	29.6					4.1	4.1		

The differences of temperature rises and the gradient ratios, between natural ester and mineral oil, are shown in Fig. 4, 5, 7 and 8.

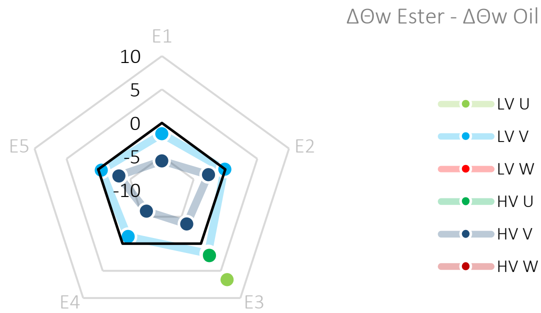


Fig. 4. Average Winding Rise (K) – difference between natural ester and mineral oil

From Fig. 4, for both windings of phase U (in E3 test conditions), the average winding rise is higher when using natural ester as insulating fluid. In opposite, average rises of phase V windings are lower when using natural ester instead of mineral oil (except for E3 test condition).

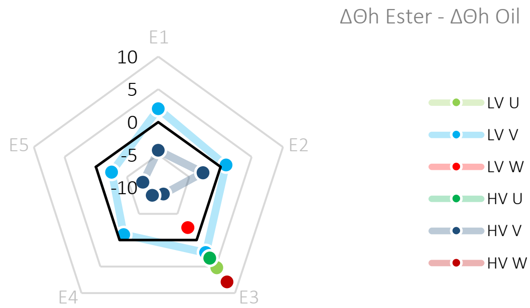


Fig. 5. Hotspot Rise (K) – difference between natural ester and mineral oil

According to Fig. 5, the high voltage winding of phase V presents lower hotspot rises, for all test conditions, when using natural ester. For other winding geometries, the hotspot variation is not linear - it varies with test conditions. It is important to notice that, not only the hotspot temperature, but also the hotspot location, can vary with the test conditions. Also, for the same test conditions and winding geometry, the hotspot location can vary with the type of fluid. These results are shown in Fig. 6.

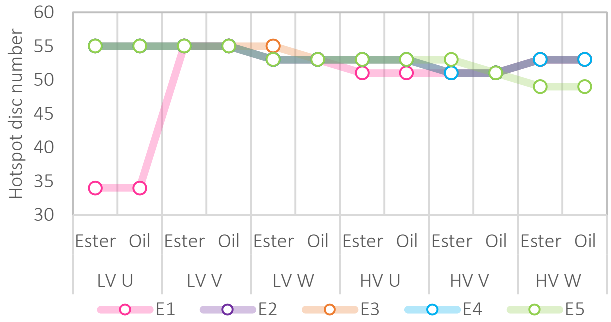


Fig. 6. Hotspot disc number

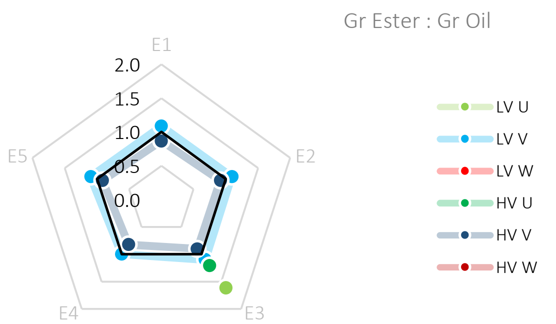


Fig. 7. Average Gradient – ratio between natural ester and mineral oil

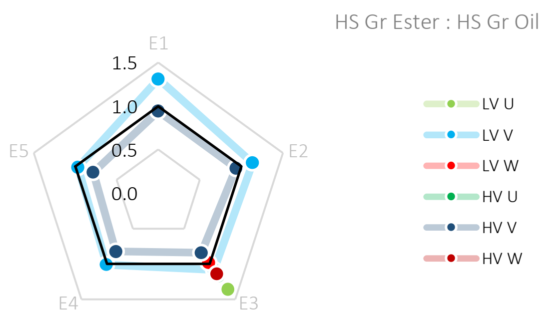


Fig. 8. Hotspot Gradient – ratio between natural ester and mineral oil

From Fig. 7 and Fig. 8, the gradients of the high voltage winding of phase V and low voltage winding of phase W present lower gradients with natural ester than with mineral oil. The opposite occurs with the remaining windings.

In Fig.9, a comparison of the difference between top and bottom oil is given, for each phase and for each test.

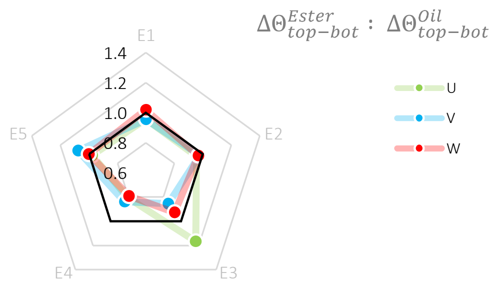


Fig. 9. Top Oil to Bottom Oil Temperature Gradient - ratio between Natural Ester and Mineral Oil

The ratio between top and bottom oil also varies according to the test conditions.

From the experimental point of view, it was possible to conclude that the fluid properties alone will not suffice to infer about the transformer thermal behavior. In order to correctly predict the thermal performance of a natural ester retro-filled transformer, data on the operation conditions and on the design of the transformer should be considered. To further understand the local phenomena dictating this non-linear thermal-hydraulic response between natural ester and mineral oil operated transformer, numerical analyses were performed.

B. CFD and THNM Results

Computational fluid dynamics (CFD) was used to analyze the fluid flow and heat transfer inside the windings. The simulations were carried out using the commercial software ANSYS Fluent®. These models provide deep insight about how the heat transfer and fluid flow is done. Because the six windings of the experimental setup are all geometrically different, six winding models were built. Each winding is tangentially divided in 16 sections (as shown in Fig. 10). Taking advantage of the tangential symmetry and to save computational resources, only 1/32 of the winding domain was modelled.

The number of elements composing the mesh used to discretize the domain of each winding is given in table 3.

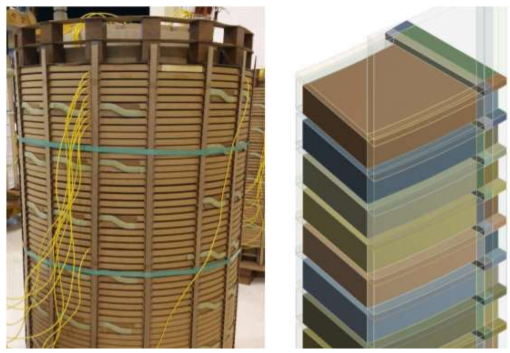


Fig. 10. Example of winding tangential sections and modelled winding domain

Table 4. Number of mesh elements of each 1/32 winding

Phase:	U	V	W
Low voltage winding:	18.6M	18.6M	18.4M
High voltage winding:	20.9M	20.4M	20.6M

When comparing the thermal behavior of the transformer between two fluids, mineral oil (M.O.) and natural ester (N.E.) need to be modelled as close as possible to reality. Several user-defined functions were used to describe the fluid properties.

The properties of the fluids vary with temperature as given in table 5.

Table 5. Properties of the fluids

Density (kg·m⁻³)	$\rho_{oil} = -0.6585 \times T + 1065.8010$ $\rho_{ester} = -0.6720 \times T + 1117.557$
Specific Heat (J·kg⁻¹·K⁻¹)	$Cp_{oil} = 3.3478 \times T + 948.1248$ $Cp_{ester} = 3.95387 \times T + 991.8322$
Thermal Conductivity (W·m⁻¹·K⁻¹)	$k_{oil} = -1.126893 \times 10^{-7} \times T^2 + 9.073702 \times 10^{-6} \times T + 0.1392663$ $k_{ester} = 9.275026 \times 10^{-7} \times T^2 - 8.762896 \times 10^{-6} \times T + 0.3417096$
Viscosity (Pa·s)	$\mu_{oil} = e^{574840600 \times T^{-3} - 4122209 \times T^{-2} + 12078.37 \times T^{-1} - 20.04413}$ $\mu_{ester} = e^{118847700 \times T^{-3} - 351469.9 \times T^{-2} + 1981.899 \times T^{-1} - 9.795988}$

For the solid domains (conductor and solid insulation), equivalent thermal conductivities were assumed and imposed as cylindrical orthotropic conductivities, according to table 6.

Table 6. Thermal conductivity of solid domain (W·m⁻¹·K⁻¹)

	High Voltage Winding	Low Voltage Winding
Axial	1.18	17.17
Radial	0.35	3.84
Tangential	300	270

At the inlet of the windings, temperature and flowrate boundary conditions were imposed, following the quantities measured in the temperature rise tests as shown in table 3. At the winding outlet, a relative zero-pressure outlet condition was assumed.

The numerical analyses (CFD and THNM) applied in the present work generated a large amount of data. To facilitate the analyses of both experimental and numerical outcomes, representative results are presented hereafter.

As an example, Fig. 11 shows a comparison between average gradients obtained experimentally and by CFD.

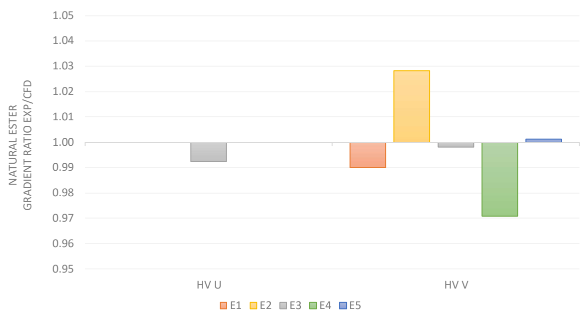
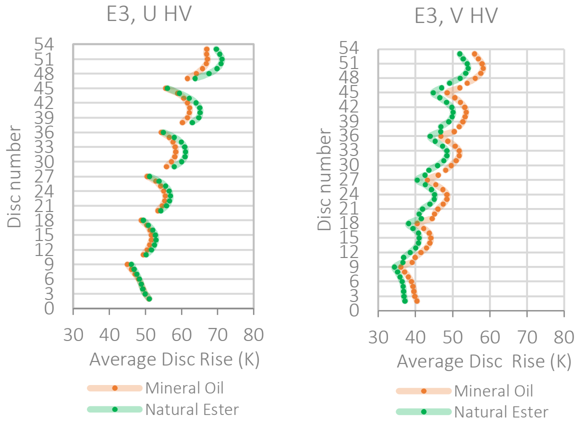


Fig. 11. Ratio of Experimental and CFD average gradients for high-voltage winding of phase U and V, when natural ester is the insulating fluid

From Fig. 11, the variation between experimental and simulation average gradients are within the range of 3%.

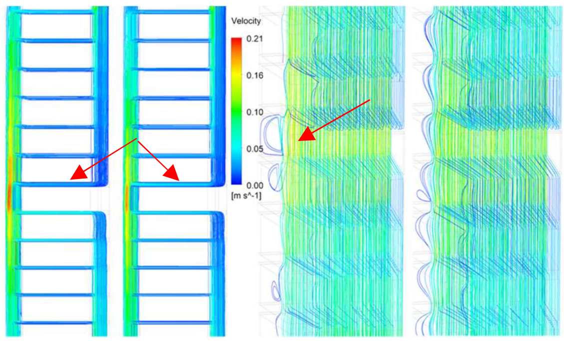
In Fig. 12, the discs temperature rise of high-voltage winding of phase U and V, for E3 test conditions and for natural ester and mineral oil, are shown.



a b

Fig. 12. High-voltage windings discs temperature rise a) phase U and b) phase V, for E3 test conditions, from CFD

Fig. 12a shows an increasing deviation in the discs' temperature rise between mineral oil and natural ester insulating fluid. For the high voltage winding of phase U, the average winding rise is higher when the natural ester is the insulating fluid. On the contrary, for the high voltage winding of phase V, the average winding rise is lower when the natural ester is the insulating fluid (Fig 12b).
These results follow the results obtained experimentally.
To investigate the source of this deviation, a local analysis is performed.



a b

Fig. 13. Flow path-lines of mineral oil (left) and natural ester (right) for the high-voltage winding of phase V and E3 test conditions: a) velocity profile and b) details of recirculation zones

Recirculation zones cause zero velocity zones and reduce the heat transfer. As seen in Fig.13, mineral oil path-lines include recirculation zones near the flow barriers. This phenomenon can be explained by the lower viscosity of mineral oil when compared to ester.
The higher viscosity of ester also helps the flow to be more evenly distributed through the radial channels of each pass (Fig. 13a). The increased radial flowrate between the discs benefits the cooling performance, uniformizing and maximizing heat transfer from the discs.

CFD is a powerful tool to give thorough insights on the thermal-hydraulic phenomena occurring inside the windings. However, such detailed analysis results in large time and resources consumption (in the magnitude of days). For this reason, a proprietary THNM tool

(FluCORE) was used to enable a faster prediction of the thermal hydraulic behavior of the windings. This tool presents valuable advantages once it represents lower computational effort, lower model preparation time and lower simulation time (in the magnitude of minutes).

In Fig. 14 and Fig. 15, a comparison between results obtained with CFD and FluCORE is shown.

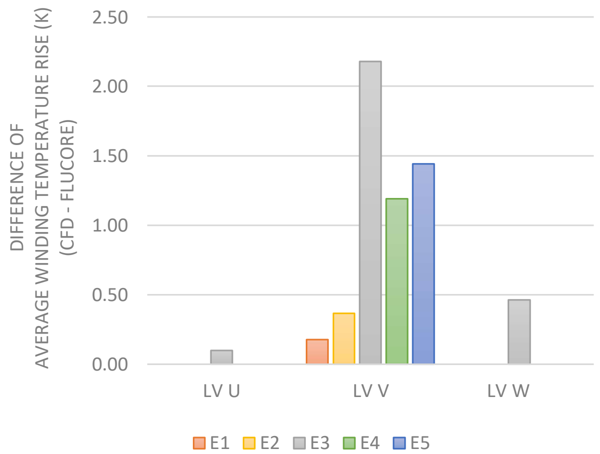


Fig. 14. Difference of average winding temperature rise between CFD and FluCORE, for Natural Ester

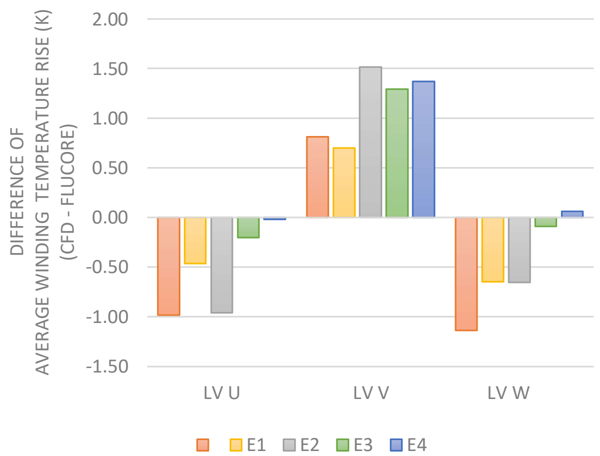


Fig. 15. Difference of average winding temperature rise between CFD and FluCORE, for Mineral Oil

From Fig. 14 and 15, a maximum deviation 2.2 K in the average winding temperature rise is obtained, between CFD and FluCORE.

4. Conclusions

From the present work it was found that the relationship between the thermal behaviour of the transformer using natural ester or mineral oil is not simple - it depends on the operating conditions of the transformer and on the geometry of the windings. As an example, it was experimentally found that, for E3 test conditions, the hotspot rise can be increased by 4 K (in high voltage winding of phase U) or be decreased by 9 K (in low voltage winding of phase W) by using natural ester instead of mineral oil. For each test conditions and winding geometry, a detailed comparative analysis of the thermal performance of mineral oil and natural ester is presented. The experimental results are complemented with local thermal-hydraulic analysis provided by the numerical tools. These findings are intended to, in one hand, provide insight on the adaptation of transformers design when using natural ester as fluid insulation and, on the other hand, support the utilities on the decisions regarding an eco-friendly transformation of their transformers fleets.

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