Compatibility Study of Water-Based Lubricants and Insulation Systems in Low-Voltage Electrical Machines for Automotive Applications

1st Hujun Peng
Institute of Electrical Machines (IEM)
RWTH Aachen University
Aachen, Germany
hujun.peng@iem.rwth-aachen.de

2nd Jingning Wu
Institute of Electrical Machines (IEM)
RWTH Aachen University
Aachen, Germany
Jingning.wu@rwth-aachen.de

3rd Hakim El Bahi
Fuel & Lubricant Division
TotalEnergies One Tech
Solaize, France
hakim.el-bahi@totalenergies.com

4th Catherine Charrin
Fuel & Lubricant Division
TotalEnergies One Tech
Solaize, France
catherine.charrin@totalenergies.com

5th Andreas Thul
Institute of Electrical Machines (IEM)
RWTH Aachen University
Aachen, Germany
andreas.thul@iem.rwth-aachen.de

6th Kay Hameyer
Institute of Electrical Machines (IEM)
RWTH Aachen University
Aachen, Germany
hameyer@iem.rwth-aachen.de

7th Simon Steentjes
Institute of Electrical Machines (IEM)
RWTH Aachen University
Aachen, Germany
simon.steentjes@iem.rwth-aachen.de

2025 IEEE International Electric Machines & Drives Conference (IEMDC) | 979-8-3503-7659-3/25/$31.00 ©2025 IEEE | DOI: 10.1109/IEMDC60492.2025.11060975

***Abstract*—Direct oil cooling is widely employed in electric drive systems to enhance power density. However, conventional oils' thermal limitations restrict their cooling efficiency. To overcome this challenge, *TotalEnergies* has developed a water-based lubricant (WBL) as an alternative direct cooling medium. This study investigates the compatibility and electrical behavior of insulation components in electrical machines exposed to WBL, focusing on enameled wires and insulation paper at temperatures up to 100 °C. Two WBL formulations with different additive compositions are tested to assess their impact on insulation compatibility. The results indicate that WBLs demonstrate compatibility with insulation components at 70 °C. Furthermore, compared to the first kind of WBL, the second WBL shows better compatibility than the first WBL in various indexes. It clarifies that the additives in the WBL can be optimized to enhance its compatibility with insulation systems at higher temperatures, offering a promising avenue for improving the cooling performance of electric drive systems.**

***Index Terms*—Electrical machine, Direct oil cooling, Water-based lubricant, Insulation system, Material compatibility.**

I. Introduction

With the rapid adoption of electric vehicles and the growing demand for high-efficiency electrical machines, achieving higher power density while reducing machine size has become a critical challenge in modern electromechanical systems. However, increasing power density leads to elevated heat generation, which can degrade insulation materials, reduce efficiency, and shorten the operational lifespan of electrical machines.

Effective cooling strategies are essential to managing high temperatures in high-power-density electrical machines [1]. Among various cooling techniques, direct oil cooling has emerged as a widely used approach for improving thermal management, particularly in automotive applications where space and weight constraints are significant [2]–[4]. Furthermore, the corrosion performance between copper and the classical ATF is studied in [5]. The work of [6] explores the material compatibility of various polymer materials with different machine lubricants. However, conventional oil-based cooling media exhibit inherent limitations, such as low thermal capacity and high viscosity, which restrict their cooling performance. To address these challenges, *TotalEnergies* has developed water-based lubricants (WBLs) that combine the high thermal conductivity of water with the dielectric properties of oils [7], [8]. Before WBLs can be widely adopted in electrical machine cooling systems, their compatibility with insulation materials must be thoroughly evaluated [9], [10]. Since insulation materials in low-voltage electric machines are directly exposed to the coolant, it is crucial to ensure that these lubricants do not degrade insulation performance over time.

This study investigates the compatibility of two water-based lubricants, WBL1 and WBL2, as cooling media for electrical machines. These lubricants differ in additive composition, which may influence their interaction with insulation materials. The research assesses their effects on enameled wires and insulation paper under thermal aging conditions, determining whether WBLs are viable for use in electrical machine insulation systems. Additionally, this study explores how modifications in WBL additives can enhance their compatibility with insulation materials, offering insights into potential improvements for next-generation cooling solutions in electrical machines.

The organization of this work is as follows: Section II introduces the experimental setup, including the choice of insulation materials and thermal aging tests. Section III emphasizes the results presentation and analysis. Section IV gives conclusions and outlooks on further research points.

II. Experiemntal Setup and Methodology

This section introduces the insulation materials for the compatibility test, including two kinds of enameled wires and one slot liner. It then introduces the experimental setup for the thermal aging test. Next, it presents the measurement devices available for measuring various parameters.

A. Enameled wires

In this study, two types of enameled wires are selected: Damid wires with a double-layer coating and wires coated with PEEK (polyether ether ketone) insulation. The Damid wire, featuring a polyamide-imide overcoat, is chosen for its excellent mechanical strength, thermal stability, and electrical insulation properties, making it a standard option for electrical machines operating under moderate temperature conditions [7]. In contrast, the PEEK-coated wire is selected for its exceptional mechanical and chemical resistance, even at elevated temperatures, making it suitable for more demanding environments. To evaluate the electrical properties of enameled wires exposed to WBL, the wires are prepared into twisted pairs, as shown in Fig. 1, following the IEC 60317-0-1 standard [11].

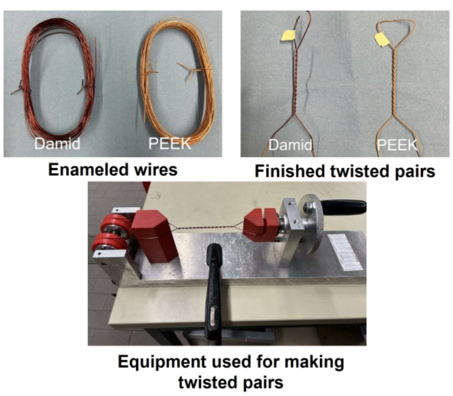
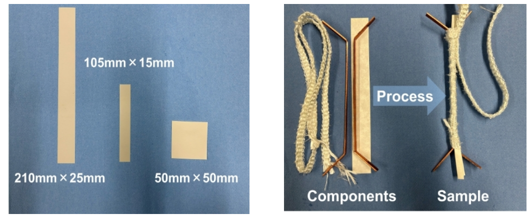


Fig. 1. Manufacturing twisted pairs from wires including materials and tools.

B. Slot insulation paper

This study selects Nomex paper from the company *DuPont* as the slot-insulating material due to its excellent electrical insulation, thermal stability, and mechanical strength. The paper used in this experiment has a thickness of $0.25\,\mathrm{mm}$ and is prepared in various sizes, as shown in Fig. 2a. To facilitate the measurement of insulation resistance and Partial Discharge Inception Voltage (PDIV), the insulating paper is processed into standardized test specimens, as illustrated in Fig. 2b. Specifically, strip-shaped specimens are used for capacitance, PDIV, and dielectric loss factor measurements, while square-shaped specimens are designated for Comparative Tracking Index (CTI) testing.



(a) (b)

Fig. 2. Manufacturing specimen from insulation paper: (a) Various Size for different specimens, (b) Finished specimen.

C. Experimental setup of thermal aging process

To evaluate material degradation when exposed to WBL1 and WBL2, enameled wires and Nomex papers are immersed in the respective lubricants. The key physical properties of the WBLs used in this study are summarized in Table I, along with a comparison to automatic transmission fluid (ATF). Both WBL1 and WBL2 exhibit identical physical characteristics, including viscosity, density, thermal conductivity, and specific heat capacity. The primary distinction between them lies in their additive composition, which is specifically formulated to enhance compatibility with insulation materials. However, due to commercial confidentiality, the exact composition of these additives cannot be disclosed.

TABLE I
Shared physical properties of WBLs and ATF at 40 °C [7]

Parameter	WBLs	ATF
Viscosity in $\mathrm{mm^2/s}$	24.0	31.29
Density in $\mathrm{kg/m^3}$	1060.0	828.9
Thermal conductivity in $\mathrm{W/(m\cdot K)}$	0.3840	0.1398
Specific heat capacity in $\mathrm{J/(kg\cdot K)}$	3200	2110

The compatibility study is conducted at 70 °C and 100 °C to simulate both typical operational conditions and extreme scenarios. A temperature of 70°C represents the upper-limit working temperature of cooling liquids in low-voltage electrical machines, while 100 °C serves as an accelerated aging condition, enabling the assessment of insulation stability under extreme thermal stress. The WBLs are stored in sealed heating pots during the tests, as illustrated in Fig. 3.

The thermal aging test extends over eight weeks, with sampling points at 1 day, and at 2, 4, 6, and 8 weeks. This approach enables the evaluation of both short-term and long-term aging effects of WBL on insulation materials at 70 °C and 100 °C. To ensure statistical reliability, seven specimens are tested for each sampling point and specimen type.

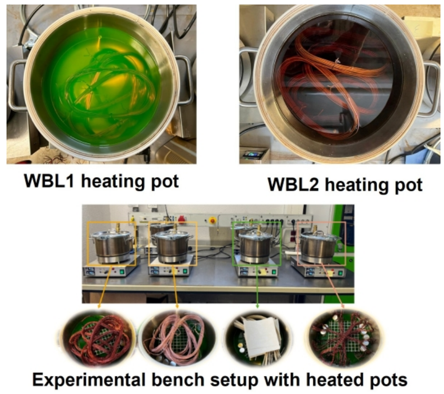


Fig. 3. Experimental setup for thermal aging of insulation materials in pots.

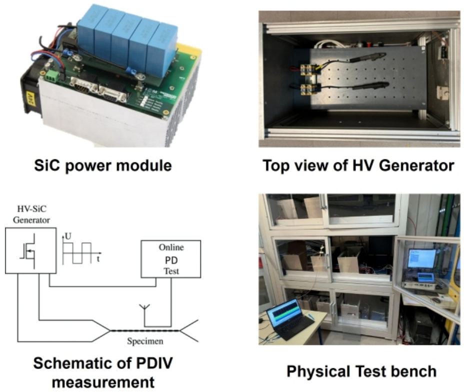


Fig. 4. Illustrations of the IEM high-voltage impulse generator for PDIV measurement.

D. Measurement equipment and setup

Partial Discharge Inception Voltage (PDIV) testing is performed on twisted pair samples using the IEM impulse generator, as used in [12], and the EW600.B measurement device from Stahl, following the IEC 60034-1 standard [13]. A schematic of the PDIV test setup using the IEM impulse generator is shown in Fig. 4.

The Comparative Tracking Index (CTI) test evaluates the resistance of insulating materials to surface electrical breakdown. In this experiment, a CTI instrument from company *FISCHER ELEKTRONIK* is used to measure the CTI of Nomex paper in accordance with IEC 60112 [14].

III. Result Analysis

The impact of WBL on the insulation system is assessed by measuring PDIV, capacitance, and dielectric loss factors for various specimens over time. These measurements are taken at different sampling intervals under two temperature conditions (70 °C and 100 °C) to evaluate the aging effects of WBL1 and WBL2 on the insulation materials.

A. Compatibility performance of enameled wires in WBLs

At 70 °C, both Damid and PEEK enameled wires maintain stable PDIV values throughout the 8-week aging period in both WBL1 and WBL2, as shown in Fig. 5a and Fig. 5b. The relatively small standard deviations across measurements indicate that both WBLs exhibit good compatibility with these insulation materials under moderate temperature conditions. However, at 100 °C, significant differences in degradation behavior emerge. Damid enameled wires exposed to WBL1 experience severe insulation failure, with the enamel coating completely dissolving after six weeks, leaving the conductor exposed, as illustrated in Fig. 6a. In contrast, Damid wires in WBL2 degrade more gradually, with the enamel progressively peeling off but not fully dissolving, as shown in Fig. 6b. This suggests that WBL2 offers better insulation protection compared to WBL1. For PEEK wires at 100 °C, those immersed in WBL1 also fail after six weeks, as shown in Fig. 5c, indicating insulation breakdown at elevated temperatures. However, PEEK wires in WBL2 retain their PDIV values even after prolonged aging, demonstrating significantly better thermal stability and compatibility.

These results emphasize the critical role of temperature in determining the compatibility between WBLs and enameled wires. Moreover, WBL2, with its modified additive composition, significantly enhances the long-term performance of insulation materials at high temperatures. The superior performance of WBL2 over WBL1 is evident not only in PDIV measurements (Fig. 5) but also in the observed physical degradation trends. This confirms that additive optimization plays a key role in improving the compatibility of WBLs with

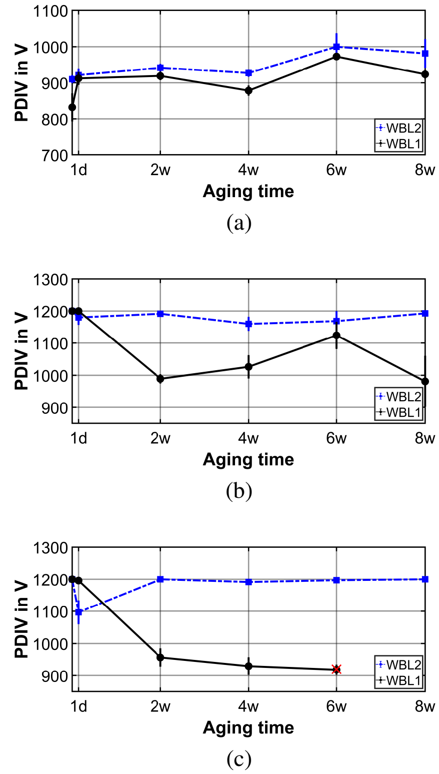
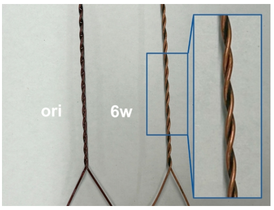
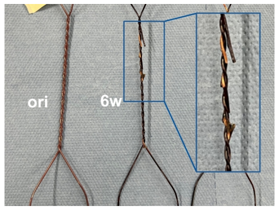


Fig. 5. Change in PDIV values of twisted pairs after 8-week aging in WBLs: (a) Damid wires at 70 °C, (b) PEEK wires at 70 °C, (c) PEEK wires at 100 °C.



(a)



(b)

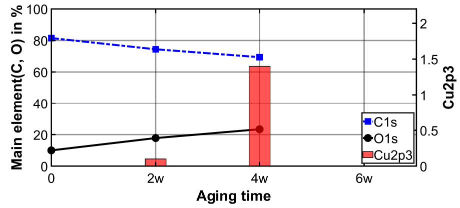
Fig. 6. Comparison of Damid enameled wires immersed in different WBLs after 6 weeks at 100 °C: (a) Damid wire in WBL1 with insulation coating entirely detached from the copper core, (b) Damid wire in WBL2 with insulation coating gradually detached.

enameled wires.

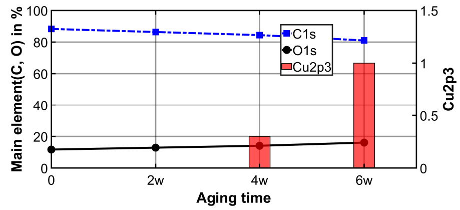
X-ray photoelectron spectroscopy (XPS) is conducted on reference enameled wires laid in air and aged ones in WBL1 after 2, 4, and 6 weeks to understand the degradation behavior further. Prior to measurement, the wire surfaces were etched for 600 seconds to remove surface contaminants. As shown in TABLE II, the analyzed elements are mainly composed of two categories: polymer composition of the insulation coating, including elements of carbon (C), nitrogen (N), and oxygen (O), as well as representative lubricant elements such as sulfur (S), phosphorus (P), and silicon (Si). Significant differences in the change of the elemental amount between Damid and PEEK wires are observed for the specimen in WBL1 at 100,°C.

Due to aging in WBL, the amount of carbon decreases, while the amount of oxygen increases with aging time in WBL1, as shown in TABLE II. For Damid wires in Fig. 7a, the amount of oxygen rises from the initial 10 % to 23.4 % after four weeks of aging, and the data for the aging time of six weeks does not exist since the insulation layer has detached from the copper core after 6 weeks, and an XPS measurement is not available. Accompanied by that, the amount of carbon element decreases from the initial 81.5 % to 69.6 % after four weeks of aging in WBL1. This increase in oxygen at the expense of carbon is likely due to the penetration of WBL into the polymer matrix. This hypothesis is supported by the detection of lubricant-related elements even deeper within the polymer, indicating that additive components are not only interacting at the surface but infiltrating the bulk material. Moreover, the substitution of the polymer matrix by the hydro-lubricant is also evident from the nitrogen content, which is substantially present in Damid due to its polyamide-imide structure. The nitrogen level is reduced from 8.6 % to 3.7 % after 6 weeks of aging, suggesting that the original polymer chains are being degraded or displaced.

Compared to the Damid wires, PEEK wires show better stability regarding the change in element amount, as shown in Fig. 7b. Thereby, the carbon amount of PEEK wires decreases from the initial 88.3 % to 81 % after six weeks of aging, and the oxygen amount increases from the initial 11.7 % to 16.1 %. Furthermore, the amount of copper detected in PEEK after 6 weeks is comparable to that found in DAMID after 4 weeks, which indicates a higher permeability of DAMID than PEEK in WBL. Overall, the chemical analysis results correlate well with the PDIV measurements, where Damid failed as early as the second week at 100 °C, while PEEK maintained performance until the sixth week, as shown in Fig. 5.



(a)



(b)

Fig. 7. XPS results of the evolution of the surface element composition in Damid and PEEK wires after aging in WBL1 at 100 °C: (a) Damid wires up to 4 weeks, (b) PEEK wires up to 6 weeks,

Another interesting point is that the XPS analysis detects the copper element, which does not belong to the WBL. One hypothesis is that the copper in the core of enameled wires diffuses from the inside to the outside. In order to clarify it, another in-depth XPS analysis is conducted for the wires to study the amount profile of Cu at different depths by etching for different times. A longer etching time represents more depth from the exterior surface of enameled wires. The result for the Damid wire is presented in Fig. 8. The amount of Cu gradually decreases with increasing depth from the wire surface, the same trend as the phosphorus and sulfur lubricant elements. Therefore, the copper penetration into the polymer layer of enameled wires is believed to happen towards the inside instead of diffusion from the copper core of wires towards the outside. Moreover, the Cu element and other elements from WBL1, such as sulfur, phosphorus, and silicon, are no longer detectable at depth in the case of PEEK, whereas they remain present in Damid. It indicates that copper, like other WBL-derived elements, penetrates significantly deeper into Damid than into PEEK, further confirming the higher permeability of Damid. One possible explanation is that during the thermal aging test, the cut edge of wires in the coils, immersed in the WBL, lets the copper be directly exposed to WBL, as shown in Fig. 3. In practical electrical machines, there is no such kind of cut edge in wires, which suggests a direction for improving the measurement setup for the future.

The evolution of capacitance and dielectric loss factor ($\tan\delta$) in Damid and PEEK enameled wires under thermal aging at 70 °C, as shown in Fig. 9 and Fig. 10, illustrates the impact of WBL1 and WBL2 on stability of enameled wires. At 70 °C, both Damid and PEEK enameled wires maintain stable capacitance and dielectric loss factor values in WBL1 and

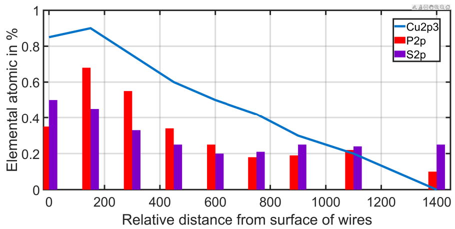
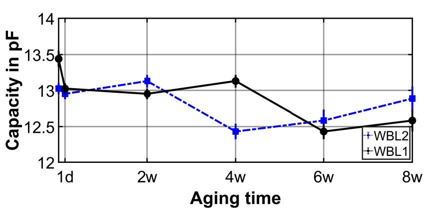


Fig. 8. Quantity profile of different elements corresponding to different depths in Damid wires after aging for four weeks in WBL1.

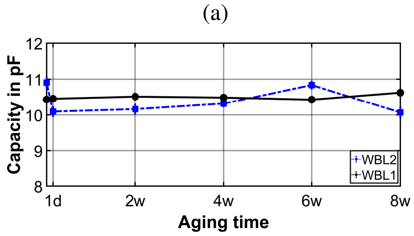
TABLE II
COMPARISON OF ELEMENT ANALYSIS RESULTS OF ENAMELED WIRES AT DIFFERENT AGING STAGES IN WBL1 AT 100 °C.

Category	Element	Reference (0 h)		Aged wire (336 h, 672 h, 1008 h)	
		Damid	PEEK	Damid	PEEK
Polymer composition in atom%	C	81.5	88.3	74.4, 69.6, -	-, 84.4, 81
	N	8.6	0.7	6.3, 3.7, -	-, 0.2, 0.3
	O	10.0	11.7	17.8, 23.4, -	-, 14.1, 16.1
Lubricant element in atom%	S	–	< 0.1	0.3, 0.7, -	-, 0.3, 0.7
	P	< 0.1	< 0.1	0.3, 0.6, -	-, 0.1, 0.2
	Si	0.5	0.5	0.2, 0.2, -	-, 0.2, 0.3

WBL2 throughout the 8-week aging period, indicating good insulation compatibility with these cooling lubricants. While minor fluctuations in capacitance and dielectric loss factor ($\tan\delta$) are observed, these variations do not suggest significant and continuous material degradation. These results indicate that both WBL1 and WBL2 effectively maintain insulation stability at 70 °C. Furthermore, WBL2 demonstrates slightly more stable dielectric properties with aging time, potentially enhancing long-term insulation performance. This highlights the crucial role of additive formulation in optimizing insulation behavior, even under moderate thermal conditions.

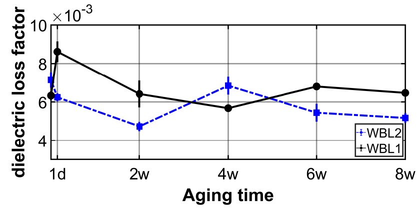


(a)

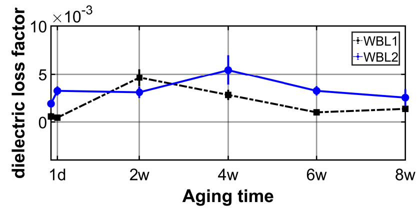


(b)

Fig. 9. Capacitance of Damid and PEEK twisted wires in WBLs after 8 weeks at 70 °C: (a) Damid wires, (b) PEEK wires.

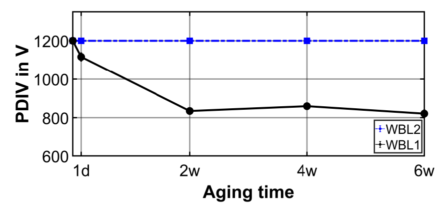


(a)

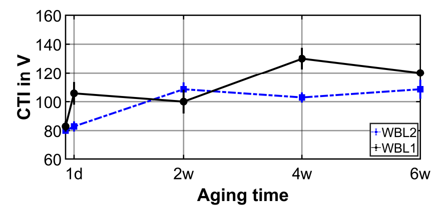


(b)

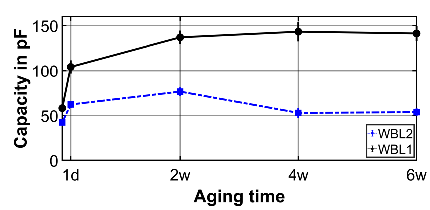
Fig. 10. Dielectric loss factor ($\tan\delta$) of Damid and PEEK twisted wires in WBLs after 8 weeks at 70°C: (a) Damid wires (b) PEEK wires.



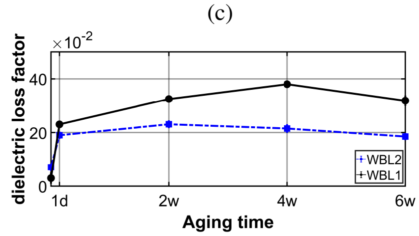
(a)



(b)



(c)



(d)

Fig. 11. Electrical performance of Nomex in WBL1s after 6 weeks at 100 °C: (a) PDIV Values, (b) CTI Values, (c) Capacitance Values, (d) Dielectric loss $\tan\delta$.

B. Compatibility performance of slot insulating paper in WBLs

The Nomex insulation paper demonstrates good compatibility with both WBLs, as PDIV values remain stable after six weeks, as shown in Fig. 11a. Furthermore, WBL2 exhibits higher compatibility with Nomex paper than WBL1, as indicated by its more stable PDIV values. To further evaluate material integrity, Fig. 12 presents the visual appearance of Nomex paper after six weeks of immersion in WBL1 and WBL2 at 100°C. The WBL1-treated samples exhibit noticeable discoloration and darkening, suggesting a stronger interaction between the insulation paper and the coolant, which may affect long-term stability. In contrast, WBL2-treated samples show less discoloration, indicating reduced material degradation. Regarding CTI values, as shown in Fig. 11b, no significant difference is observed between the two WBLs. However, the insulation paper immersed in both WBLs exhibits increased CTI values. This may be attributed to oil penetration into the insulation paper, which enhances its CTI performance. Additionally, capacitance measurements in Fig. 11c reveal a strong increase in WBL1-treated samples, suggesting structural or dielectric modifications due to oil absorption. In contrast, WBL2-treated samples exhibit a gradual increase in capacitance, indicating better stability. The dielectric loss factor ($\tan\delta$), as shown in Fig. 11d, further supports this observation. WBL2-treated samples maintain lower loss factors, while WBL1-treated samples show a steady increase, indicating higher dielectric losses and potential aging effects.

Overall, Nomex paper remains compatible with both WBLs at 100 °C, with WBL2 providing superior insulation stability by maintaining higher PDIV values, increasing CTI, reducing dielectric losses, and ensuring more stable capacitance characteristics.

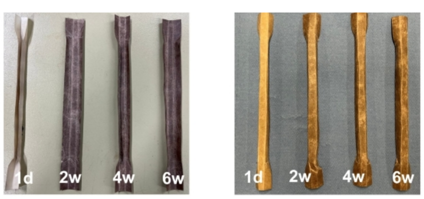


Fig. 12. Appearance comparison of Nomex insulation paper immersed in different WBLs after 6 weeks at 100 °C.

IV. Conclusions and Outlooks

This study investigates the compatibility of two water-based lubricants (WBL1 and WBL2) with insulation materials used in low-voltage rotating electrical machines at high temperatures. The results indicate that both WBLs exhibit promising compatibility with enameled wires at 70°C and with insulation paper at 100 °C. However, the compatibility between WBLs and enameled wires at 100 °C remains inconclusive. Additionally, WBL2, formulated with a different type of additive, demonstrates improved electrical performance and better overall compatibility with insulation materials compared to WBL1. This suggests that optimizing WBL additives can enhance insulation stability, a direction that will be further explored by TotalEnergies. For future research, compatibility testing will be conducted under more realistic operating conditions. Specifically, WBL application methods such as spraying onto motorettes or end windings will be evaluated to assess performance in practical cooling scenarios under operational stresses.

References

[1] P. Ponomarev, M. Polikarpova, and J. Pyrhönen, "Thermal modeling of directly-oil-cooled permanent magnet synchronous machine," in *2012 XXth International Conference on Electrical Machines*, 2012, pp. 1882–1887.

[2] M. Halwas, L. Hausmann, F. Wirth, J. Fleischer, B. Jux, and M. Doppelbauer, "Influences of design and manufacturing on the performance of electric traction drives," in *2020 International Conference on Electrical Machines (ICEM)*, vol. 1. IEEE, 2020, pp. 488–494.

[3] B. Assaad, K. Mikati, T. Tran, and E. Negre, "Experimental study of oil cooled induction motor for hybrid and electric vehicles," in *2018 XIII International Conference on Electrical Machines (ICEM)*, 2018, pp. 1195–1200.

[4] J. Montonen, J. Nerg, M. Polikarpova, and J. Pyrhönen, "Integration principles and thermal analysis of an oil-cooled and -lubricated permanent magnet motor planetary gearbox drive system," *IEEE Access*, vol. 7, pp. 69 108–69 118, 2019.

[5] G. J. Hunt, M. P. Gahagan, and M. A. Peplow, "Wire resistance method for measuring the corrosion of copper by lubricating fluids," *Lubrication Science*, vol. 29, no. 4, pp. 279–290, 2017.

[6] M. Beyer, G. Brown, M. Gahagan, T. Higuchi, G. Hunt, M. Huston, D. Jayne, C. McFadden, T. Newcomb, S. Patterson *et al.*, "Lubricant concepts for electrified vehicle transmissions and axles," *Tribology Online*, vol. 14, no. 5, pp. 428–437, 2019.

[7] L. Yang, Y. Cao, S. Zhang, H. E. Bahi, and K. Hameyer, "Preliminary study on the applicability of water-based lubricant as a direct cooling medium in rotating electrical machines," in *2023 IEEE International Electric Machines & Drives Conference (IEMDC)*, 2023, pp. 1–7.

[8] R. Lehmann, A. Petuchow, M. Moullion, M. Künzler, C. Windel, and F. Gauterin, "Fluid choice based on thermal model and performance testing for direct cooled electric drive," *Energies*, vol. 13, no. 22, p. 5867, 2020.

[9] C. McFadden, K. Hughes, L. Raser, and T. Newcomb, "Electrical conductivity of new and used automatic transmission fluids," *SAE International Journal of Fuels and Lubricants*, vol. 9, no. 3, pp. 519–526, 2016. [Online]. Available: http://www.jstor.org/stable/26273483

[10] L. Yang, S. Zhang, F. Pauli, C. Charrin, and K. Hameyer, "Material compatibility of cooling oil and winding insulation system of electrical machines," in *2022 International Conference on Electrical Machines (ICEM)*, 2022, pp. 1334–1340.

[11] *IEC 60317-0-1: Specifications for particular types of winding wires – Part 0-1: General requirements – Enameled round copper wire*, International Electrotechnical Commission Standard, 2013, accessed: October 2024.

[12] F. Pauli, L. Yang, M. Schröder, and K. Hameyer, "Life time estimation of winding insulation systems in sic operated low voltage electrical machines," *e & i Elektrotechnik und Informationstechnik*, vol. 136, pp. 175–183, 2019.

[13] *IEC 60034-1:2022 - Rotating Electrical Machines - Part 1: Rating and Performance*, International Electrotechnical Commission Standard, 2022, accessed: October 2024.

[14] *IEC 60112:2020 - Method for the determination of the proof and the comparative tracking indices of solid insulating materials*, International Electrotechnical Commission Standard, 2020, accessed: October 2024.