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Degradation Effects of Base Oils after Thermal and Electrical Aging for EV Thermal Fluid Applications

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Abstract: This study presents the experimental results of the effects on base oils after thermal and electrical aging to determine key parameters of next-generation fluids for thermal management in electric vehicles. The test fluids selected were a mineral base oil API G-III, an API G-IV Polyalphaolefin (PAO), a diester, and a polyolester, all of which had similar kinematic viscosity (KV100 = 4 cSt). All were initially characterized with measurements of density, viscosity, thermal conductivity, specific heat capacity, breakdown voltage, resistivity, and dissipation factor. They underwent two separate aging processes, one thermal, heating the test fluid at 150 ºC for 120 h with a copper strip as a catalyst; and the second one an electrical aging process, with the application of 1000 breakdown voltage discharges. The same properties were measured again after each aging process and compared to the initial ones. It was found that the thermal properties ranged with similar values and did not suffer major changes after the aging processes, unlike electrical properties, which vary between samples and after thermal and electrical stress. The insights gained from this study have implications for both the development of next-generation e-thermal fluids and the future standardization of these fluids for EV thermal management applications. The findings of this study underscore the significance of formulating and selecting a suitable dielectric fluid for EV thermal management. By leveraging the insights provided, researchers and engineers can advance in the development of efficient and reliable e-thermal fluids while working towards future standardization to enhance the performance and safety of EV battery systems.

Keywords: battery thermal management; immersion cooling; e-thermal fluid; resistivity; dissipation factor; thermal conductivity; specific heat capacity; thermal aging; electrical aging

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1. Introduction

The global transition towards decarbonization and sustainability has seen a significant shift towards the electrification of the transport sector. This shift is driven by concerns over climate change and the need to reduce greenhouse gas emissions. Projections show that electric vehicle (EV) sales are growing faster than expected, with forecasts indicating that by 2030, over 30% of new cars sold worldwide will be electric [1]. This rapid growth in EVs presents challenges that need to be addressed, particularly in terms of battery thermal management (BTM).

BTM is critical for the performance, safety, and lifespan of EV batteries. The efficient management of heat generated during battery charging and discharging cycles is vital to prevent damage to battery cells and ensure optimal battery performance. Therefore, researchers and engineers are exploring various methods to manage battery temperature, including passive and active cooling systems [2–4].

Passive cooling systems are a good energy-efficient approach for BTM, since they help to reduce noise and power consumption given the lack of pumps or fans; however, concerning the thermal loads that can be produced during fast charging or during EV operation, this type of system might not be enough to ensure the adequate temperature

range of the battery pack [5]. Active cooling systems might offer an enhanced cooling capacity and faster heat dissipation over passive cooling [6].

One promising approach to active cooling is immersion cooling, where battery cells are submerged in a dielectric fluid that extracts heat from the cells. Immersion cooling offers several advantages over traditional passive cooling systems, including higher cooling capacity, improved battery lifespan, and reduced risk of thermal runaway. Furthermore, it allows for faster charging rates and longer driving distances [7,8].

To fully realize the potential of immersion cooling, the selection of the right dielectric fluid is crucial. The fluid must have high thermal conductivity, low viscosity, and good dielectric properties. Researchers are exploring various e-thermal fluid properties, including resistivity, heat transfer, and lubrication [9,10]. For instance, Jonathan Hägerbrand conducted measurements of resistivity in transformer insulation liquids [11], while Z. Mu, Z.D. Wang, and Q. Liu measured the DC resistivity of insulating oils [12]. Both studies provide insights into the electrical properties of dielectric fluids and their potential for use in EV battery thermal management. Additional studies, such as those by Sharin Ab Ghani et. al [13] and L. Safiddine Oumert [14], investigate the effect of repeated electrical breakdown voltage discharges on dielectric fluids.

Other authors have discussed the importance of BTM in fast-charging EVs [15,16]. They highlighted the need for immersion cooling to manage battery temperature during fast charging, and noted that the selection of the fluid is essential in determining the cooling efficiency and battery lifespan.

Overall, the implementation of immersion cooling with the right fluid selection can greatly benefit the performance and longevity of EV battery packs, and since this is an emerging technology (in the EV transport sector), there are currently no standards that can be followed to develop, study, and select the proper e-thermal fluid. In this sense, this study uses available standards to measure important properties of candidate fluids in order to determine an approach for e-thermal fluid characterization and selection, attending to their advantages and drawbacks.

2. Materials and Methods

There were four base oils selected as the candidate fluids: API Group III mineral (GIII), API Group IV polyalphaolefin (PAO), diester, and polyolester. These are fluids with different molecular structures but with similar kinematic viscosity at 100 ºC (between 3 to 5 cSt), as low-viscosity oils present better thermal properties [17]. Selecting four different base oils with similar kinematic viscosity broadens the scope of the analysis, as base oils from the same group might show similar results since the base structure is the same. The mineral GIII was taken into account due to its major use as dielectric fluid in transformer oils, and the synthetic PAO and esters have shown enhanced thermal performance in recent studies [18,19].

All the fresh fluids were fully characterized with measurements of their physical, thermal, and electrical properties following international standards shown in Table 1.

Table 1. Equipment and standard used for measurements.

Properties	Equipment	Standard
Viscosity and density	SVM 3001 Viscometer, Anton Paar	ASTM D7042, D4052, D287, D1298
Water content	Coulometric Karl Fischer titration, Metrohm	ASTM D6304
Breakdown voltage	HZJQ-X1, Huazheng	ASTM D1816
Resistivity, dissipation factor	Oil Tan Delta & Resistivity DF9010 system, APT Power Technology Co	IEC 60247
Thermal conductivity and specific heat capacity	THW-L1, Thermtest Instruments	ASTMD7896

The sections below describe the experimental methodologies used to degrade the base oils and to measure their thermal, electrical, and physical properties to characterize the effects of the degradation. Regulations and testing for e-thermal fluids are yet to be fully standardized, and therefore, where possible, the methodologies follow relevant standards for conventional oils and lubricants.

2.1. Thermal Aging

To simulate the potential degradation of e-thermal fluid throughout its operating lifetime, accelerated thermal aging was performed on the test fluids. A large conical flask was filled with approximately 500 mL of fresh oil samples, and a pure copper strip was added to the flask. The copper acted as a catalyst to accelerate the thermal aging process, promoting oxidation of the oil sample [20,21]. The conical flask, containing the oil sample and copper strip, was then placed in a thermal bath set at 150 °C for 120 h. This thermal aging method was adapted from the ASTM D130 standard [22], which evaluates the corrosiveness of petroleum products to oil. Once removed from the thermal bath, the samples were allowed to cool to room temperature before being transferred to air-tight containers to prevent water absorption from humidity in the air.

2.2. Electrical Aging

The 'Huazheng HZJQ-X1 Transformer Oil BDV Tester' was used to perform electrical aging on the base oils. This equipment comprises a small oil cup with hemispherical electrodes submerged in the oil sample and operates at room temperature. The electrodes were separated by a conventional gap width of 2 mm, consistent with the ASTM D1816 [23] standard for breakdown voltage (BDV) testing. The voltage applied through the electrodes was gradually increased at a rate of 5 kV/s until charge was carried through the oil between the electrodes, resulting in a breakdown discharge. To achieve electrical aging of the base oils, 1000 breakdown discharges were performed [14]. The electrical discharges were performed at room temperature, where the mean relative humidity was 65% RH. Oil temperature was monitored during the entire process.

2.3. Breakdown Voltage

The 'Huazheng HZJQ-X1 Transformer Oil BDV Tester' was also used to measure the breakdown voltage of the base oil samples in accordance with the ASTM D1816 standard. This equipment had an accuracy of ±3%. Each of the base oils was tested for their BDV in fresh, electrically aged, and thermally aged states. Each sample underwent five measurements, with a 2 min wait time between each breakdown test, while being maintained at room temperature between 15–25 °C, as required by the ASTM D1816 standard.

2.4. Resistivity and Dissipation Factor

Following the IEC 60247 [24] standard, oil resistivity (volume resistivity) and dissipation factor were measured using the DF9010 system manufactured by APT Power Technology Co. The oil sample cup was filled with 90 mL of the oil, which filled a small test cell. The small test cell was filled and drained three times with the sample to clean the equipment by displacement of any previous residual oil. The test procedure was then initiated, with the sample heated to 90 °C and measurements taken automatically by the equipment. The equipment generated a DC voltage and measured the current through the test circuit to calculate the resistance and resistivity of the sample. Up to eight readings were taken for each oil sample. The accuracy for resistivity measurements was ±10% and for dissipation factor was ±1%.

2.5. Thermal Properties

Measurements of thermal conductivity and heat capacity were performed using the Thermtest THW-L1 system with an accuracy of ±2%. This equipment used the transient hot wire (THW) method to directly measure thermal properties of liquids, following the

ASTM D7896 [25] standard. The measuring instrument utilized a thin platinum wire that was submerged in a measuring cell containing approximately 20 mL of the oil sample. Before testing, the instrument was calibrated using distilled water at 20 °C to ensure accuracy of the results. The sample cell was then prepared with the oil for testing and inserted into the temperature controller, and a schedule of measurements was set up in the Thermtest software. For each sample, the schedule was set to take measurements at 10 °C intervals from 20 to 120 °C. At each temperature step three readings were recorded, with a 10 min delay between tests to ensure isothermal conditions were maintained.

2.6. Viscosity and Density

Viscosity and density of the samples were measured using the Anton Paar SVM 3001 Viscometer, with an accuracy of ±1%, which conforms to the ASTM D7042 [26] standard. Readings of kinematic viscosity, dynamic viscosity, and density were recorded at 10 °C intervals from 20 to 120 °C. The sample to be tested was prepared in a 20 mL syringe. To begin testing, the temperature was set to 20 °C, and approximately 1.5 mL of the sample was injected into the inlet nozzle to fill the sample cell. When prompted by the equipment, a further 1 mL of the sample was injected prior to the reading at each temperature step to refill the sample cell. Between the testing of different oil samples, the equipment was cleaned by injection of 10 mL of toluene and 10 mL of methanol, then dried using compressed air to ensure there was no cross-contamination that could interfere with the measurements.

2.7. Water Content

The water content of the oil samples was measured to parts per million (ppm) by implementing the Karl Fischer Coulometric (KFC) titration method [27] using the Metrohm 917 Coulometer equipment with an accuracy of ±3 ppm. The KFC method involves the consumption of water contained in the sample by reaction with iodine. Pure iodine reagent is produced electrochemically by the equipment for high-precision dosing. The endpoint of the titration is detected voltametrically by applying a current between two platinum electrodes. When a trace amount of unreacted iodine is present in the solution, the voltage difference between the platinum wires drops significantly and signals that all of the water has been consumed by the reaction.

3. Scope and Limitations

This study focuses on investigating the effects of thermal and electrical aging on different types of base oils with similar kinematic viscosity. The selected fluids included an API G-III mineral base oil, an API G-IV Polyalphaolefin (PAO), a diester, and a polyolester. Various properties such as density, viscosity, thermal conductivity, specific heat capacity, breakdown voltage, resistivity, and dissipation factor were initially measured and compared. The fluids then underwent separate aging processes: thermal aging at 150 °C for 120 h with a copper strip catalyst, and electrical aging with 1000 breakdown voltage discharges. Subsequent measurements of the properties were taken after each aging process.

The limitations of this study should be considered. First, the study focuses on a specific set of base oils with similar kinematic viscosity, and the results may not be directly applicable to other types of fluids or lubricants used in battery thermal management systems. Additionally, the study does not provide an in-depth analysis of the performance or long-term effects of the fluids on battery temperature management. It primarily focuses on the changes in properties before and after aging processes, without exploring the impact on battery performance or thermal management efficiency. Furthermore, the study does not compare the selected fluids to standards or benchmarks against other potential e-thermal fluids.

4. Results and Discussion

From the physical point of view (viscosity and density), the fluids did not suffer any significant changes after thermal and electrical aging, as shown in Figures 1 and 2. These effects, as well as their impact on their thermal performance are discussed in the next section.

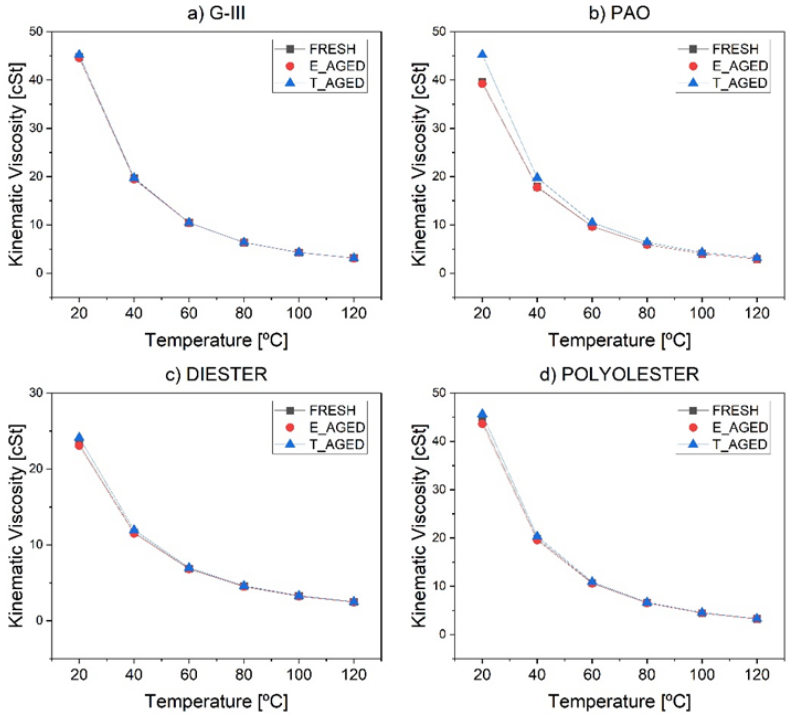

Figure 1. Kinematic viscosity of fresh, thermally aged, and electrically aged samples: (**a**) G-III, (**b**) PAO, (**c**) diester, (**d**) polyolester.

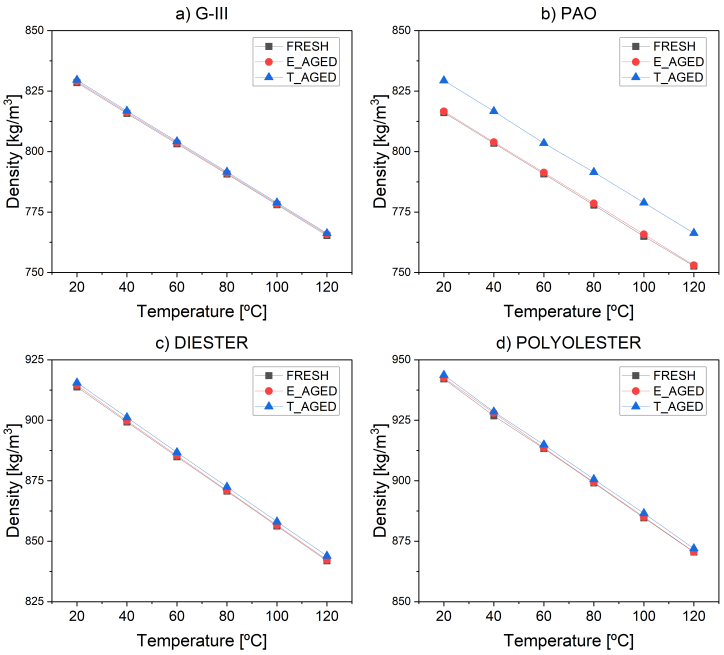

Figure 2. Density of fresh, thermally aged, and electrically aged samples: (**a**) G-III, (**b**) PAO, (**c**) diester, (**d**) polyolester.

4.1. Thermal Performance

Although thermal conductivity and specific heat capacity are important in determining the rate at which heat is transferred through the fluid, there are additional properties that also play a key role in thermal performance, such as density and viscosity, which dominate the heat transfer in a turbulent flow of a system [28]. To include these additional properties, a figure of merit (FOM) known as the Mouromtseff number (Mo) is used [29]:

$$Mo = \frac{k^a \rho^b c_p^d}{\mu^e} \quad (1)$$

where k is the thermal conductivity, ρ is density, c_p is specific heat capacity, and μ the dynamic viscosity. The exponents vary depending on the type of flow, as shown in Table 2.

Table 2. Mouromtseff number exponents.

Exponent	Laminar Flow	Turbulent Flow
a	0.33	0.80
b	0.67	0.67
d	0.33	0.33
e	0.17	0.47

Figure 3 compares the thermal properties of the BO vs. temperature, and Figure 4 shows the Mo in a laminar and a turbulent flow in the same temperature points.

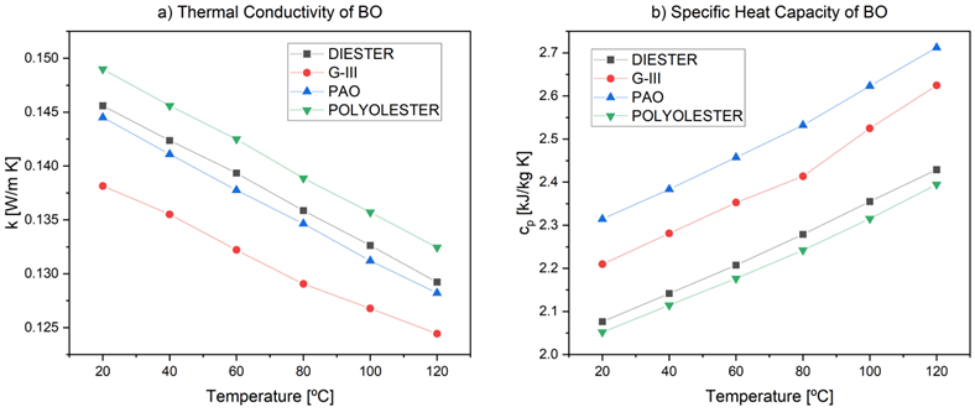

Figure 3. Thermal properties of fresh samples. (**a**) Thermal conductivity; (**b**) specific heat capacity.

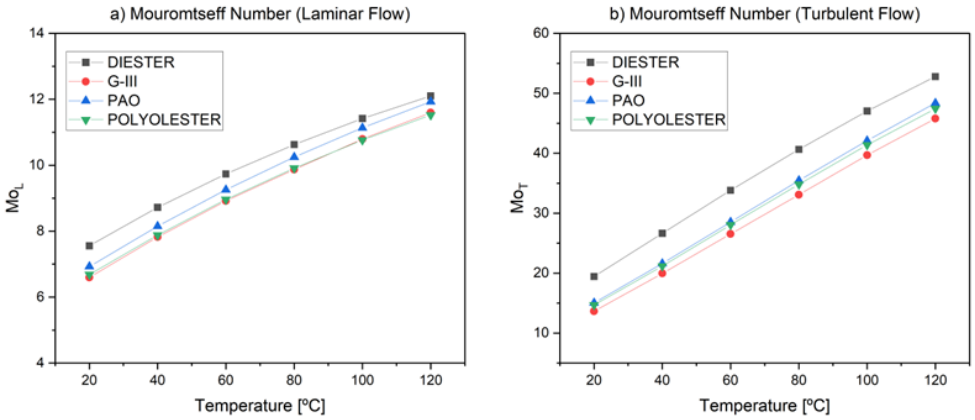

Figure 4. Mouromtseff number of fresh samples in (**a**) laminar flow; (**b**) turbulent Flow.

It can be inferred that although the polyolester has higher thermal conductivity and the PAO has higher specific heat capacity, the diester has better thermal performance in both laminar and turbulent flow.

After the thermal aging process, the most affected property, was viscosity as shown in Table 3, increasing to more than 1% and up to 9% on average for the PAO and to less than 3% for the others, which consequently caused the Mo to decrease down to 5.9% for the PAO and to less than 1% in the rest. The other properties remained relatively stable.

Following the electrical aging process, the same properties suffered negligible changes, with less than 1% variation.

Table 3. Average variation of thermal and physical properties after thermal and electrical stress (T_AGED and E_AGED respectively) in the temperature range of 20 °C to 120 °C.

Property	Status	G-III	PAO	Diester	Polyolester
Thermal conductivity	T_AGED	0.28%	−2.32%	0.61%	0.67%
	E_AGED	0.20%	−0.98%	−0.42%	−0.48%
Specific heat capacity	T_AGED	0.31%	−3.07%	0.31%	0.08%
	E_AGED	0.28%	−0.90%	−0.14%	−0.37%
Kinematic viscosity	T_AGED	0.65%	9.09%	2.20%	2.05%
	E_AGED	−0.25%	−0.43%	−0.65%	−0.89%
Density	T_AGED	0.12%	1.71%	0.21%	0.18%
	E_AGED	0.06%	0.07%	0.05%	0.05%
Mo	T_AGED	0.02%	−5.92%	−0.44%	−0.42%
	E_AGED	0.36%	−0.73%	0.01%	−0.01%

4.2. Electrical Performance

E-thermal fluids must have electrical properties that ensure the safety of passengers and the performance of the battery and electronic components and endure thermal and electrical loads that they might suffer. Figures 5–7 show the measurements of the most relevant electrical properties and their variation after thermal and electrical stress.

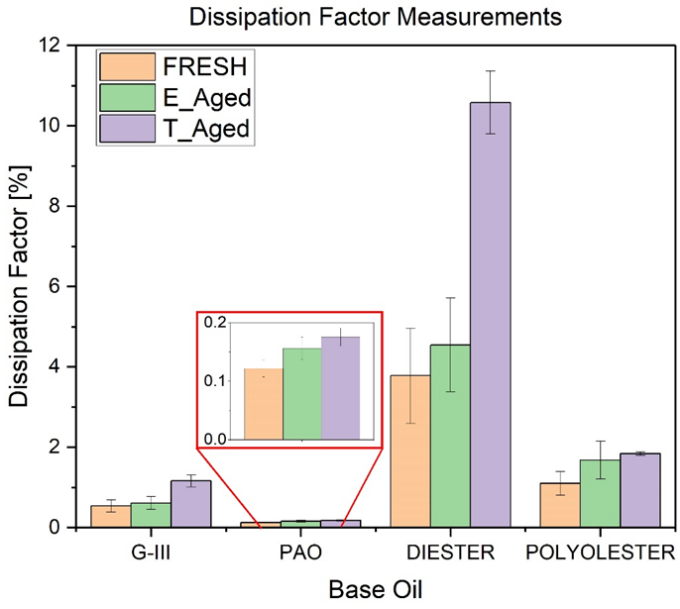

Figure 5. Dissipation factor of fresh, electrically aged (E_Aged), and thermally aged (T_Aged) base oils.

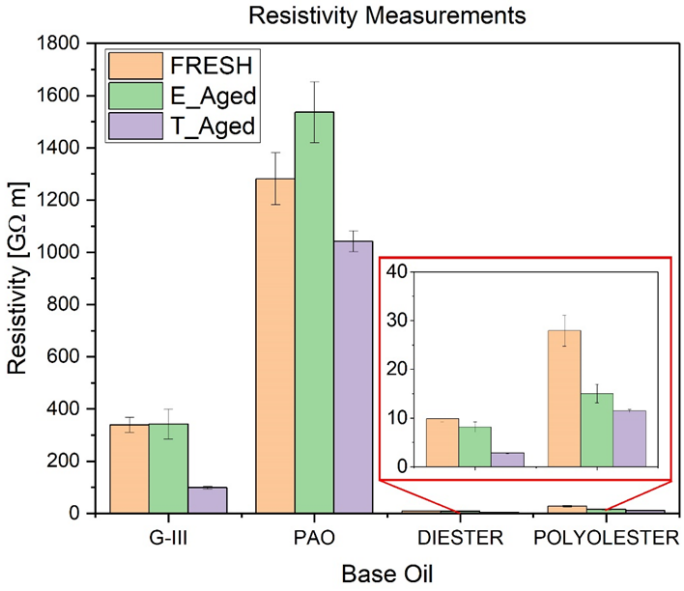

Figure 6. Resistivity of fresh, electrically aged (E_Aged), and thermally aged (T_Aged) base oils.

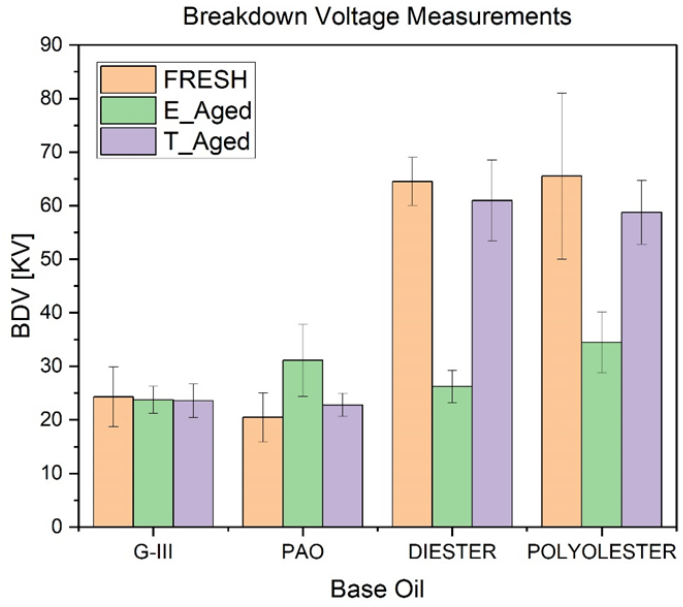

Figure 7. Breakdown voltage of fresh, electrically aged (E_Aged), and thermally aged (T_Aged) base oils.

The dielectric dissipation factor shown in Figure 5 indicates the effectiveness of a dielectric fluid's insulation properties by measuring the ratio of its resistive properties to its capacitive properties. An ideal dielectric fluid would have high capacitive properties and low resistive properties, resulting in zero conduction through the fluid and a dissipation factor that approaches zero. However, the degradation of the dielectric fluid can introduce impurities and oxidation products that allow current to flow through the fluid, leading to losses due to ohmic resistance. A higher dissipation factor is linked to greater dielectric losses, resulting in the loss of electrical energy to the insulating fluid.

The PAO oil has the most effective insulating properties, with the lowest dissipation factor remaining relatively unaffected by degradation. The GIII mineral oil has the next lowest dissipation factor, but it increases slightly after thermal degradation due to the formation of oxidation products. The diester and polyolester, on the other hand, have a higher dissipation factor than the GIII, which can be attributed to their higher polarity and water content.

For e-thermal fluid applications, high resistivity and a low dissipation factor are desirable to fully insulate the battery cells in immersion cooling systems. If the fluid's resistivity is too low, this increases the likelihood of electrical conduction through the fluid during high-voltage applications, which would lead to short-circuiting. Resistivity is also closely related to the dissipation factor, shown in Figure 6, and generally, as the dissipation factor decreases, resistivity will increase.

Ester oils have lower resistivity compared to traditional hydrocarbon-based oils such as GIII mineral oil and polyalphaolefin, which have significantly higher resistivity. The chemical polarity of ester oils, attributed to the presence of C=O and C–O bonds in their structure, allows them to carry charge more efficiently, resulting in lower resistivity. While both PAO and GIII oils are nonpolar, the results indicate that PAO's resistivity is more than triple that of GIII mineral oil. This is due to PAO's synthetic nature, with its highly regular monomer units and absence of impurities contributing to its high resistivity.

The electrical discharges performed were not enough to cause a reaction on GIII, given its short duration and low power (compared to transformer discharges), and with no formation of byproducts, the impact on resistivity was minimal. Although PAO shows an increase in resistivity and dissipation factor after electrical degradation, this result is inconclusive, as it falls within the uncertainty range of the readings. This increase in resistivity could be attributed to the slight reduction in water content during electrical stress. After thermal degradation, GIII oil undergoes oxidation, resulting in a decreased resistivity due to the increased polarity of the molecules. A similar trend is observed in PAO, the diester, and the polyolester after thermal degradation, but the resistivity decreases to a lesser extent due to a lower degree of oxidation. The electrical properties of oils are highly influenced by the amount of water present, with even a minor increase in water concentration causing a significant decrease in resistivity. Thus, it is essential to take into account the alteration in water content during degradation, as it affects the ability of the oil to maintain high resistivity levels that are crucial for immersion cooling applications. Figure 8 shows the variation of the water content of each base oil after each aging process.

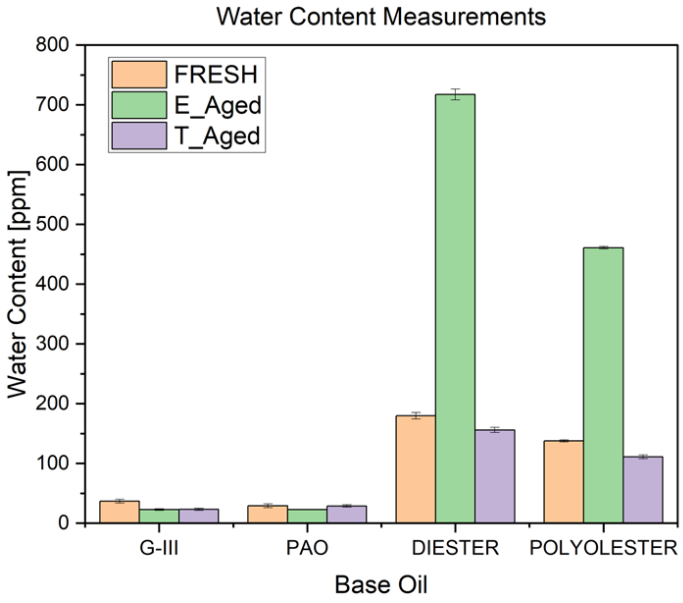

Figure 8. Water concentration of fresh, electrically aged (E_Aged), and thermally aged (T_Aged) base oils.

The analysis revealed that ester oils that have been electrically degraded exhibit a substantial rise in water content, most likely caused by absorbing moisture from the air during their two-day degradation period in the breakdown voltage sample cup. Ester oils have a polar nature, making them highly susceptible to absorbing water, particularly in high-humidity environments [30]. In contrast, thermally degraded ester oil samples demon-

strate a minor decrease in water content, as the high temperatures cause any absorbed moisture to evaporate.

The breakdown of oils under high voltages is a complex process that is affected by impurities, moisture, viscosity, and temperature. Gas dielectric breakdown is the most commonly observed mechanism, wherein high voltage energy causes the oil molecules to collide and generate free ions and electrons that form a conductive chain between electrodes. As current flows through the chain, the fluid heats up and eventually boils, creating a gas channel, through which an electric discharge occurs. Although it is very unlikely that a BDV occurs during battery charging or discharging in e-thermal fluid applications, a high breakdown voltage is preferred as a safety measure. Figure 7 shows the values of BDV of the base oils before and after the aging processes.

In general, the ester oils exhibit higher breakdown voltages than GIII and PAO oils. This can be explained by the gas dielectric breakdown theory, which suggests that the energy required to boil the fluid and form a gas channel for spark breakdown is partly responsible for the BDV. The polar nature of ester molecules results in stronger intermolecular forces and higher boiling points, requiring more energy to boil the fluid and form the gas channel, leading to a higher BDV. The BDV of GIII and PAO remain relatively constant after degradation, whereas the diester and polyolester exhibit a significant decrease in BDV after electrical degradation. This is possibly due to an increase in water content after degradation, which promotes the formation of conductive chains and breakdown discharge at lower applied voltage.

5. Conclusions

The degradation processes tested had a minimal effect on the thermal and physical properties of the base oils. According to the analysis of the Mouromtseff number, the diester had slightly better heat transfer capabilities compared to the other base oils.

In terms of resistivity, the PAO outperformed the other base oils by a significant margin and remained relatively constant, even after degradation. Alternatively, the resistivity of the GIII, diester, and polyolester decreased after electrical aging. The ester oils had significantly lower resistivity compared to the hydrocarbon-based oils. A similar trend was observed for the dissipation factor, with the PAO showing the lowest value and the ester oils showing significantly higher values, which could be attributed to the presence of moisture in the fresh samples and then increasing after electrical aging due to the water absorption and the oxidation suffered after thermal aging.

It can be inferred, from the increasing pattern of the Mo with temperature, that the test fluids are more efficient at higher temperatures. Furthermore, for a BEV operating in extreme cold weather (−20 ºC), an idle time before operating the vehicle should be considered. However, further research and modeling is needed in order to determine proper idle times (if necessary).

From the thermal and electrical point of view, it can be concluded that the PAO is the most suitable base oil for e-thermal fluid applications, due to its high resistivity, low dissipation factor, and effective heat transfer properties, which make it better in comparison to the other base oils, as seen in Table 4. Nonetheless, it is important to note that this conclusion is drawn solely based on analysis of the thermal, physical, and electrical properties, and considering that the test fluids are base oils, it leaves room for additivation that can modify some of these properties. Other factors such as material compatibility, cost, biodegradability, and sustainability have yet to be considered in this study, and these aspects could greatly influence its suitability. The findings of this study not only contribute to the development of next-generation e-thermal fluids for electric vehicle thermal management applications, but also offer valuable insights for future standardization efforts in this field. Understanding the effects of thermal and electrical aging on different base oils provides crucial information for formulating requirements for e-thermal fluids. The stability of thermal properties suggests that future fluids should maintain consistent thermal performance even after aging processes, enabling efficient heat dissipation and temperature control in EV battery systems.

This highlights the need for e-thermal fluids with high thermal conductivity, specific heat capacity, and low thermal degradation rates. The variation observed in electrical properties after aging processes emphasizes the importance of electrical performance in e-thermal fluids for EV thermal management. Developing fluids with enhanced electrical insulation properties will contribute to improved electrical safety and reliability in EV applications.

Table 4. Decision matrix for the base oils suitability as an e-thermal fluid.

Property	G-III	PAO	Diester	Polyolester
High thermal conductivity	+	++	+++	++++
High specific heat capacity	+++	++++	++	+
High Mouromtseff Number	+	+++	++++	++
High resistivity	+++	++++	+	++
Low dissipation factor	+++	++++	+	++
High breakdown voltage	++++	+++	+	++
Low moisture absorption	+++	++++	+	++

Furthermore, the results presented can serve as a basis for future standardization efforts in the field of e-thermal fluids. Establishing standardized testing methods and performance criteria based on the measured properties, both before and after aging processes, will enable consistent evaluation and comparison of different fluids. This will facilitate the development of industry-wide standards for e-thermal fluids, ensuring compatibility, reliability, and optimal performance in EV thermal management systems.

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References

1. St.John, A. EV Sales Growing Faster Than Expected. 20321. Available online: https://www.autonews.com/mobility-report/ev-sales-growing-faster-expected (accessed on 31 December 2021).
2. Kim, J.; Oh, J.; Lee, H. Review on battery thermal management system for electric vehicles. *Appl. Therm. Eng.* **2019**, *149*, 192–212.
3. Huber, C.; Kuhn, R. 13—Thermal Mmanagement of Batteries for Electric Vehicles. In *Advances in Battery Technologies for Electric Vehicles*; Scrosati, B., Garche, J., Tillmetz, W., Eds.; Woodhead Publishing Series in Energy; Woodhead Publishing: Sawston, UK, 2015; pp. 327–358. [CrossRef]
4. Mali, V.; Saxena, R.; Kumar, K.; Kalam, A.; Tripathi, B. Review on battery thermal management systems for energy-efficient electric vehicles. *Renew. Sustain. Energy Rev.* **2021**, *151*, 111611.
5. Mallick, S.; Neog, S.; Mahanta, D.; Rafi, M. A Review on Passive Cooling Techniques for Lithium-Ion Battery Thermal Management System of Electric Vehicle. In Proceedings of the IOP Conference Series: Materials Science and Engineering, Coimbatore, India, 25–26 March 2021; Volume 1145, p. 012046.
6. Pesaran, A.A. Battery thermal management in EV and HEVs: issues and solutions. *Battery Man* **2001**, *43*, 34–49.
7. Pambudi, N.A.; Sarifudin, A.; Firdaus, R.A.; Ulfa, D.K.; Gandidi, I.M.; Romadhon, R. The immersion cooling technology: Current and future development in energy saving. *Alex. Eng. J.* **2022**, *61*, 9509–9527.
8. Lubrizol360. Why Immersion Cooling Is the Future of Electric Vehicle Battery Thermal Management. 2022. Available online: https://360.lubrizol.com/2022/Why-Immersion-Cooling-Is-the-Future-of-EV-Battery-Thermal-Management (accessed on 31 December 2022)
9. Patil, M.S.; Seo, J.H.; Lee, M.Y. A novel dielectric fluid immersion cooling technology for Li-ion battery thermal management. *Energy Convers. Manag.* **2021**, *229*, 113715.
10. Roe, C.; Feng, X.; White, G.; Li, R.; Wang, H.; Rui, X.; Li, C.; Zhang, F.; Null, V.; Parkes, M.; et al. Immersion cooling for lithium-ion batteries—A review. *J. Power Sources* **2022**, *525*, 231094.
11. Hägerbrand, J. Measurements of Resistivity in Transformer Insulation Liquids. Master's Thesis, University of Uppsala, Uppsala, Sweden, 2020.

12. Mu, Z.; Wang, Z.; Liu, Q. Measurements of DC Resistivity of Insulating Oils. In Proceedings of the 2016 IEEE International Conference on High Voltage Engineering and Application (ICHVE), Chengdu, China, 19–22 September 2016; pp. 1–4.
13. Ab Ghani, S.; Khiar, M.S.A.; Chairul, I.S.; Zamir, M.I. Effect of repeated electrical breakdowns on mineral and natural ester insulating oils. *Bull. Electr. Eng. Inform.* **2021**, *10*, 2989–2996.
14. Oumert, L.S.; Boucherit, A.; Zafour, A.H.Z.; Fofana, I. Comparative study of the degradation rate of new and regenerated mineral oils following electrical stress. *IET Gener. Transm. Distrib.* **2018**, *12*, 5891–5897.
15. Keyser, M.; Pesaran, A.; Li, Q.; Santhanagopalan, S.; Smith, K.; Wood, E.; Ahmed, S.; Bloom, I.; Dufek, E.; Shirk, M.; et al. Enabling fast charging—Battery thermal considerations. *J. Power Sources* **2017**, *367*, 228–236.
16. Ahmed, S.; Bloom, I.; Jansen, A.N.; Tanim, T.; Dufek, E.J.; Pesaran, A.; Burnham, A.; Carlson, R.B.; Dias, F.; Hardy, K.; et al. Enabling fast charging—A battery technology gap assessment. *J. Power Sources* **2017**, *367*, 250–262.
17. Clarke, D. *Understanding Lubricant Requirements of Hybrid-Electric Vehicles*; No. 2014-01-1476; SAE Technical Paper; SAE: Warrendale, PA, USA, 2014.
18. Narvaez, J.A. Thermal Conductivity of Poly-alpha-olefin (pao)-Based Nanofluids. Ph.D Thesis, University of Dayton, Dayton, OH, USA, 2010.
19. Szewczyk, R.; Wicks, R.; Martin, R. Comparison of Synthetic and Natural Esters With Focus on Thermal Aspects of Insulation Systems. In Proceedings of the CIRED 2021—The 26th International Conference and Exhibition on Electricity Distribution, Online, 20–23 September 2021; Volume 2021, pp. 142–146. [CrossRef]
20. Fenske, M.; Stevenson, C.; Lawson, N.; Herbolsheimer, G.; Koch, E. Oxidation of lubricating oils. Factors controlling oxidation stability. *Ind. Eng. Chem.* **1941**, *33*, 516–524.
21. Yao, T.; Zhang, N.; Zhang, M.; She, X.; Liao, X.; Shen, Y.; Gan, Z. Effect of iron and copper on the thermal oxidation stability of synthetic hydrocarbon aviation lubricating oil. *Catal. Commun.* **2021**, *161*, 106363.
22. *ASTMD130*; Standard Test Method for Corrosiveness to Copper from Petroleum Products by Copper Strip Test. ASTM International: West Conshohocken, PA, USA, 2019.
23. *ASTMD1816*; Standard Test Method for Dielectric Breakdown Voltage of Insulating Oils of Petroleum Origin Using VDE Electrodes. ASTM International: West Conshohocken, PA, USA, 2012.
24. *IEC60247*; Insulating Liquids—Measurement of Relative Permittivity, Dielectric Dissipation Factor (tan d) and d.c. Resistivity. International Electrotechnical Commission: Geneva, Switzerland, 2004.
25. *ASTMD7896*; Standard Test Method for Thermal Conductivity, Thermal Diffusivity, and Volumetric Heat Capacity of Engine Coolants and Related Fluids by Transient Hot Wire Liquid Thermal Conductivity Method. ASTM International: West Conshohocken, PA, USA, 2019.
26. *ASTMD7042*; Standard Test Method for Dynamic Viscosity and Density of Liquids by Stabinger Viscometer (and the Calculation of Kinematic Viscosity). ASTM International: West Conshohocken, PA, USA, 2021.
27. *ASTMD6304*; Standard Test Method for Determination of Water in Petroleum Products, Lubricating Oils, and Additives by Coulometric Karl Fischer Titration. ASTM International: West Conshohocken, PA, USA, 2021.
28. Richenderfer, A. Heat Transfer Performance of Fluids for EVs. In Proceedings of the Inaugural STLE Tribology & Lubrication for E-Mobility Conference, San Antonio, TX, USA, 3–5 November 2021.
29. Simons, R.E. Calculation corner: Comparing heat transfer rates of liquid coolants using the Mouromtseff number. *Electron. Cool.* **2006**, *12*, 10.
30. Villarroel, R.; de Burgos, B.G.; García, D.F. Moisture dynamics in natural-ester filled transformers. *Int. J. Electr. Power Energy Syst.* **2021**, *124*, 106172. [CrossRef]