Material Compatibility of Cooling Oil and Winding Insulation System of Electrical Machines

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***Abstract*—Direct oil cooling of electrical machines is promising especially in the area of hybrid and electric traction drive trains, since it enables a high cooling efficiency and a large power density. Besides, a combined use of oils both as cooling fluid for the electrical machine and as lubricant for the transmission system helps to reduce the required installation space and subsequently increase the power density. For a proper application of oils in the electrical machine, the safety issues, especially the material compatibility of oils with the electrical machine, still need to be studied carefully. In the present work, the material compatibility between different types of cooling oils and machine components is studied. Results show that the traditional automatic transmission fluid has a poor material compatibility with the enamelled wire overall, and oil additives play a crucial role.**

***Index Terms*—automatic transmission fluid, direct oil cooling, electrical machine, material compatibility, oil additives**

I. Introduction

The modern design of electrical machines and electric drive train is usually focusing on reducing the volume requirement and increasing the power density. Typically for a high speed and high power density electrical machine, a traditional cooling method such as air cooling or water jacket cooling may not fulfil the high specified requirements. For this purpose, novel cooling concepts are developed to adapt to specific applications. As an example, direct oil cooling is getting popular in the recent decade, since it enables not only an effective cooling performance, but also an integration of lubricant and coolant for the transmission system and electrical machine. In the recent decade the concept of direct oil cooling has been widely studied [1]–[4]. On one hand, in some studies such as [5] the automatic transmission fluid (ATF) has been used as cooling fluid for the electrical motor and the inverter. On the other hand, oil manufacturers are working on the development of suitable oils for the cooling of electrical machines and a combined use in the entire electric drive train. Such oil categories are often called "E-Fluid". The main advantage of oil cooling is that the cooling oil itself is usually a good insulation fluid and therefore can be applied directly to the winding insulation of the electrical machine. In this way, the heat can be extracted and a higher cooling performance can be achieved.

In contrast to the benefit of direct oil cooling, however, problems raise from the fact, that the cooling fluid is in direct contact with the electrical insulation system. As a consequence, the requirements on the oil properties are becoming stricter. In the first place, the requirement of a good material compatibility between the applied oils and associated machine components must be fulfilled. State of the art is that the study on the direct oil cooling in the electrical machine is still in the infancy, the safety issues have not been fully studied. For example, in [3] conductive particles are found during the experimental study of direct oil cooling in the electrical machine, while the impact of particle contaminations on the performance of the insulation system of electrical machines have rarely been studied. In the past several years, the safety problem of such a cooling method is drawing more attention gradually. Specifically, [6] [7] have studied the material compatibility between the ATF and machine components. However, attention is mainly paid to the copper corrosion under the effect of ATF, while the compatibility issue between the insulation materials and the cooling oil is still not fully understood.

Particularly, for the evaluation of material compatibility, there is still no recognised standard providing instructions for the application of oils in the electrical machine and for the choice of materials during machine design. The oil manufacturers and users are prone to use internal standards regarding this research point. In the work of [8], besides the copper corrosion under the effect of E-fluid, the material compatibility of different polymer composite materials with different E-fluids is evaluated by means of tensile strength test of laminated materials. The question of whether these characterisations are sufficient and proper for the evaluation of material compatibility, however, still stays open within the author's knowledge.

In the present work, the material compatibility of different cooling oils and insulation materials are studied, what kind of roles the base oil and the oil-additives play on the material compatibility study are evaluated. Besides, methods of material characterization for the evaluation of material compatibility regarding the real machine conditions are discussed. Highlight of the present work lies in the fact that it provides the first information about the material compatibility of E-fluid with the insulation system, and the experimental results underline the importance of material compatibility study for oil application in the electrical machine.

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II. METHODOLOGY

A. Choice of Materials

The insulation system of the electrical machine is one of the main concern regarding the issue of material compatibility with the cooling oil. As important parts of the electrical insulation system, the enamelled wire and the insulation paper are used for the material compatibility study with oils. For the choice of material, the basic principle is that the insulation materials are targeted at an application area of electrical traction machines with a thermal class between $180\,^{\circ}\mathrm{C}$ and $220\,^{\circ}\mathrm{C}$. In terms of enamelled wire, the *Damid 200*, grade 2 with a nominal diameter of $1\,\mathrm{mm}$ is applied. *Damid 200* has a thermal class of $200\,^{\circ}\mathrm{C}$ and a dual-coating system, Polyester-imide (PEI) and Polyamide-imide (PAI) as the base and over coat, respectively. In fact, such a dual-coating system is widely used as a standard combination for the enamelled wires applied in the area of automotive drives with the mentioned range of thermal class. For the insulation paper, the product *Myoflex AHA* is used for the study. The *Myoflex AHA* insulation paper is composed of three layers (Aramid-Polyimide-Aramid), with a thickness of $0.3\,\mathrm{mm}$ and a thermal class of $180\,^{\circ}\mathrm{C}$. It is usually used in electrical motors with high performance ratio as slot and phase insulation or wedge. In the author's knowledge, there is still no widely recognised standards or guidelines for the choice of appropriate insulation materials, which are typically used in electric traction machines with direct oil cooling. The current study with the aforementioned traditional insulation materials will show qualitatively, that how the material should be improved when they are applied in the direct oil cooling.

E-fluid is generally composed of base oil and oil additives, and the latter ranges normally from $5\,\%$ to $15\,\%$. There are mainly two categories of base oils for the lubricant industry, namely mineral and synthetic oil. In terms of the additives, different additive packages can be added to the base oil to fulfil the specific requirements of customers. Considering the fact that the main difference between different technical oils lies in either the base oil or the additives, one commercial ATF composed of classic ATF-additives and mineral base oil, is selected for the study. For comparison, one type of E-fluid made of mineral base oil and e-motor dedicated additives (E-fluid M), and another type of E-fluid also with e-motor dedicated additives but synthetic base oil (E-fluid S), are chosen for this study. In this way, the influence of oil additives and base oils on the material compatibility with the insulation materials can be studied. Parameters of the aforementioned three oils are summarized in TABLE I.

B. Approaches of Material Characterization

The basic function of the insulation materials in the electrical machine is to separate the conductors from each other and avoid short circuit. The primary requirement on the material is that it should possess sufficient dielectric and electrical properties. Besides, considering the rotation and vibration of a rotating electrical machine, the insulation material should also be able to withstand a certain mechanical stress. Therefore, following properties and related parameters are studied, and the material compatibility is evaluated qualitatively and comparatively, combining all the following properties:

- *Dielectric properties.*
  The capacitance C_{p} is measured at $10\,\mathrm{kHz}$ for both the enamelled wire and the insulation paper.
- *Electrical properties.*
  As the representative parameter of electrical properties, the partial discharge inception voltage (PDIV) of the insulation paper is measured under a unipolar and a sinusoidal voltage, respectively. The PDIV of the enamelled wire is measured under a bipolar-shaped voltage with a switching frequency of $10\,\mathrm{kHz}$. The employed PDIV measurement methods are introduced in details in [9].
- *Mechanical properties.*
  Peel test is conducted with the enamelled wires at different ageing stages. During the test, one end of the wire is fixed, a constant stretch force of $25\,\mathrm{N}$ and a rotational speed of $100\,\mathrm{rpm}$ is added to the other end of the wire. For the insulation paper, tensile test is conducted in the rolling direction (RD) of the paper under a constant strain rate of $5\,\mathrm{mm}/\min$ until fracture, the applied strain rate is adjusted from the standard [10].

Twisted pairs and paper samples are used for the measurements of dielectric and electrical properties. Specifically, Fig. 1a shows the specimen of twisted pair produced according to the standard [11]. Fig. 1b displays the specimen of the insulation paper, in which two bare copper strips are separated by one layer of the insulation paper, and the entire setup is wounded with glass-fibre band. It should be noted that the design of the paper insulation specimen is modified from the model introduced in [12], in which one bare copper strip is wrapped with the insulation paper and wounded with the enamelled wire. Table II summarizes the test strategy for the present work.

The geometry of the specimen for the tensile test is shown in Fig. 2. During the tensile test, the loaded force F is recorded with respect to the elongation of the specimen Δl. The corresponding stress-strain ($\sigma - \varepsilon$) curve can be calculated with the following equations:

$$\varepsilon = \frac{\Delta l}{l_0} \cdot 100, \tag{1}$$

$$\sigma = \frac{F}{A} = \frac{F}{w \cdot t}. \tag{2}$$

Where l_0 is the initial distance between jaws in the tensile test, F indicates the force recorded by the tensile machine, A represents the cross-sectional area of the paper strip, which is the product of the width w by the thickness t.

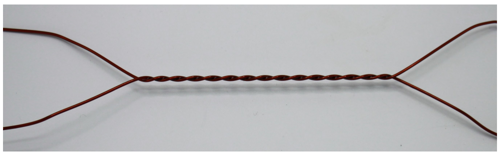
The ultimate tensile strength σ_{U} describes the maximum stress that a material can withstand while being stretched or pulled before breaking, corresponding to the peak point of the $\sigma - \varepsilon$ curve. In the present work, ten samples were tested

TABLE I: PARAMETERS OF OILS

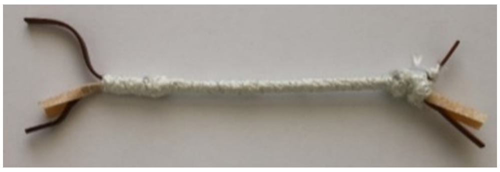
Oil type	*E-fluid S*	*E-Fluid M*	*ATF*
Viscosity at 40 °C / 100 °C in $\mathrm{mm^2/s}$	7.814 / 2.402	15.020 / 3.618	31.290 / 6.242
Thermal conductivity at 40 °C / 100 °C in $\mathrm{W/(m \cdot K)}$	0.1358 / 0.1235	0.1372 / 0.1270	0.1398 / 0.1342
Specific heat capacity at 40 °C / 100 °C in $\mathrm{J/(kg \cdot K)}$	2130 / 2410	2090 / 2320	2110 / 2340
Base oil	Synthetic	Mineral	Mineral
Additives	Dedicated e-motor, without sulphur	Dedicated e-motor, without sulphur	Classic ATF-additives
Application	E-motor	E-motor	Automatic transmission, e-motor

TABLE II: Overview of the test strategy of different materials for the present work.

Property	**Test parameter**	
	Enamelled wire	**Insulation paper**
Dielectric	Capacitance at 10 kHz	Capacitance at 10 kHz
Electrical	PDIV under bipolar-voltage	PDIV under unipolar- and sinusoidal-voltage
Mechanical	Peel strength	Tensile strength

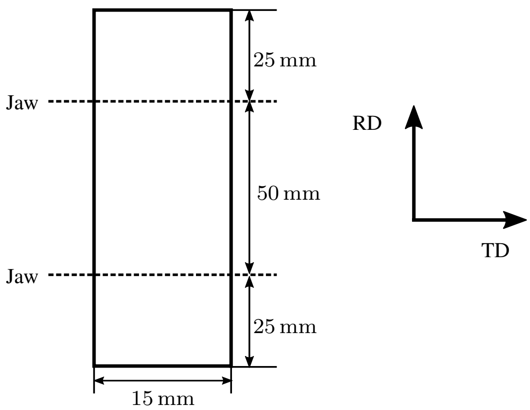


(a)



(b)

Fig. 1: Specimens of (a) enamelled wire (twisted pair) and (b) insulation paper.



Note: the drawing is not to scale.

Fig. 2: Geometry of paper samples for tensile test.

at each ageing stage, the average σ_{U} is calculated for the evaluation of the tensile strength at each ageing stage.

III. Experimental Setup

In the present work, the raw materials including enamelled copper wire and insulation paper are immersed in three different oils, respectively. Besides, one group of materials, which is stored in air without oil bath, is also prepared as the reference group. A comparison between the reference group and other oil groups indicates the influence of oils on the insulation materials. As a convenience, the aforementioned four groups are named as group *E-fluid S*, *E-fluid M*, *ATF* and *Reference*, respectively. Afterwards, different combinations are subjected to thermal conditioning in the dry kiln at 180 °C for 1008 h in total. Sampling is carried out regularly within the entire ageing period, namely after 24 h, 336 h, 772 h and 1008 h, respectively. After that the enamelled wire and the insulation paper are carefully cleaned with the n-Heptane solvent and afterwards dried with tissues to remove the oil residuals on the material surface, before these raw materials are produced into specimens accordingly for the electrical, dielectric, mechanical and chemical tests.

IV. Result analysis and discussion

A. Material Compatibility of Oils and Enamelled Wire

During the preparation of twisted pairs, it is observed that the wire coatings gradually become fragile and come off with increasing ageing time for the wires aged in different oils. In summary, in the group *ATF* the aforementioned phenomenon is observed by sampling at 772 h, while in the groups *E-fluid S* and *E-fluid M* it happens by sampling at 1008 h. The group *Reference* is still in good condition at the end of the ageing period. Accordingly, material characterizations are terminated, when the wire coating is mechanically failed during sample preparation. As an example, Fig. 3 shows the cracking of the wire coating of group *ATF* after 772 h ageing during preparation of twisted pairs.

Fig. 4 and Fig. 5 show the test results of dielectric and electrical properties of enamelled wires aged in different oils with respect to increasing ageing hours. Specifically, with increasing ageing time the capacitance of the enamelled wire increases slightly in all the groups, including the *Reference*. For the PDIV measurement, the PDIV decreases slightly and continuously in all the groups. The same with the results of capacitance measurement, the PDIVs of the three oil groups are not significantly changed until mechanical cracking. Combining the results of capacitance and PDIV measurements, it can be concluded that the phenomenon of material ageing occurs gradually at this temperature, there is no obvious difference between the oil groups and the *Reference*, and the effect of different oil components such as the base oil and oil additives on the dielectric and electrical properties of the enamelled wires cannot be easily defined from this viewpoint. The result of peel test in Fig. 6 shows that, the peel strength of all the four groups decreases significantly with the increasing ageing time. Particularly, a faster degradation of the peel strength of group *ATF* is also observed. The different behaviour of the mechanical properties and the dielectric/electrical properties indicates that the mechanical properties are more crucial for the application of oils in the electrical machine.

Besides, it is noticed that the electrical and dielectric properties of group *Reference* stay almost the same, while the mechanical properties degrade significantly with increasing ageing time. On one side, it is in good agreement with the thermal class of the materials (200 °C) from the viewpoint of dielectric and electrical properties. On the other side, the material becomes gradually fragile within the allowed long-term operation temperature, though the dielectric and electrical properties are not largely influenced. The conflict of different methods of characterization requires further analysis of materials. Besides, it should be pointed out here, that the peel test is usually performed by the wire manufacturers to examine the adhesion strength of the new wire. Apparently, it is not suitable for the study of material compatibility in the electrical machine. Taking the group *Reference* for an example, though the peel strength decreases drastically after 336 h of thermal ageing at 180 °C, the material should still be able to withstand the real mechanical stress condition in the electrical machine for a long time within the allowed operation area, since its thermal class is higher than the ageing temperature.

For a better understanding of the interactions between oils and enamelled wires, X-ray photoelectron spectroscopy (XPS) is used to measure the elemental compositions of the new and aged wires in air and different oils at 336 h, 772 h as well as 1008 h, respectively. Particularly, for the group E-fluid S, only the wires after 336 h of ageing is analysed. To prevent the interference of surface contaminations, the wire surface is etched for 150 s before the measurement. As shown in TABLE III, the analysed elements are mainly composed of two categories: polymer composition of the insulation coating, which is mainly composed of 81.5 % carbon (C), 8.3 % nitrogen (N) and 10.2 % oxygen (O) in the original state, as well as the main lubricant elements, particularly sulphur (S), phosphorus (P) as well as silicon (Si) as the representative elements. One obvious observation regarding the polymer composition is that, the oxygen content of group *Reference* is increased by 25.5 %, while in other oil groups, the oxygen content remains stable at the ageing stage of 336 h. The reason lies in the fact that the wire is prone to oxidise in air at high temperatures, while in other aged groups, the oil bath works as a protective medium, protecting the wire coating from oxidation. With a longer ageing period (ageing stages of 772 h and 1008 h), the oxygen content of all the groups increases continuously, which indicates a further oxidation process. Besides, sulphur is detected typically in the group *ATF*, which proves the penetration of ATF-additives into the coating layer. The negative effect of the sulphur penetration can be explained by comparison of the group *E-fluid M* and the group *ATF* at the ageing stage of 336 h. At this point, the oxidation process is generally suppressed for both groups, however, the sulphur penetration of the group *ATF* is remarkable. Correspondingly, the material degradation in the group *ATF* is much more significant than the other, as analysed at the beginning of this section. From this viewpoint it can be concluded that the sulphur penetration has a large negative effect on the material degradation. Additionally in the group *E-fluid M* at 336 h, where the oxidation is still suppressed and the polymer maintains almost the original composition, the phenomenon of silicon penetration makes it evident that the oil additives are responsible for the mechanical degradation of the insulation coating. The element is not detectable when the content is less than 0.1 %

For a quantitative overview of the changes of the polymer compositions and the corresponding degree of oxidation at different ageing stages, the C–O/C=O ratio is also measured with the XPS. During the oxidation process, the C–O loses and the C=O gains, the ratio decreases with increasing oxidation degree. As shown in Fig. 7, the wire of *Reference* are already oxidised significantly at 336 h. In comparison, the oxidation process of the *E-fluid M* and *ATF* are almost completely suppressed at the ageing stages of 336 h and 772 h. The measurement of the C–O/C=O ratio verifies the conclusion about the different mechanisms of mechanical degradation in the element analysis.

B. Material Compatibility of Oils and Insulation Paper

Similar to the case of enamelled wire, the evaluation of material compatibility of oils and the insulation paper is also conducted by means of dielectric, electrical and mechanical characterizations at different ageing stages. Fig. 8 and Fig. 9 show respectively the changes of dielectric and electrical properties of the insulation paper with respect to increasing ageing time under different ageing conditions. For the group *Reference*, the PDIV and capacitance remain stable.

TABLE III: COMPARISON OF ELEMENT ANALYSIS RESULTS OF NEW AND AGED ENAMELLED WIRES OF DIFFERENT AGEING STAGES.

Category	Element	New wire	Aged wire (336 h, 772 h, 1008 h)			
			Reference	*E-Fluid S*	*E-Fluid M*	*ATF*
Polymer composition in atom%	C	81.5	78.1, 78.9, 77.3	80.1, -, -	80.7, 79.8, 79.2	80.1, 78.9, 78.2
	N	8.3	8.4, 8.1, 8.5	8.6, -, -	8.5, 8.4, 7.1	8.7, 8.3, 8.2
	O	10.2	12.8, 12.6, 13.7	10.5, -, -	10.0, 11.4, 13.6	10.1, 12.0, 13.0
Lubricant element in atom%	S	<0.1	<0.1, <0.1, <0.1	<0.1, -, -	<0.1, <0.1, <0.1	0.4, 0.5, 0.4
	P	<0.1	<0.1, <0.1, <0.1	<0.1, -, -	<0.1, 0.2, 0.2	<0.1, <0.1, <0.1
	Si	<0.1	<0.1, <0.1, <0.1	<0.1, -, -	0.2, <0.1, 0.2	<0.1, <0.1, <0.1

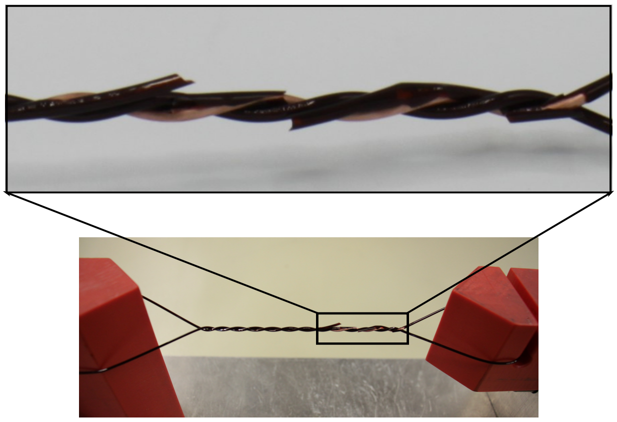


Fig. 3: Cracking of the wire coating during twisted pair preparation after ageing of 772 h in the ATF.

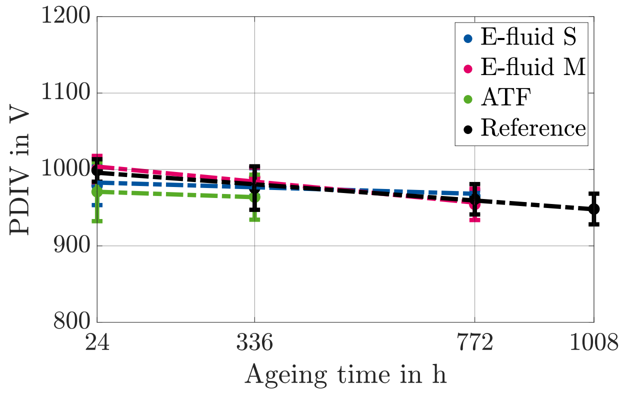


Fig. 5: Influence of oils on the PDIV of the twisted pairs at 10 kHz with respect to increasing ageing time.

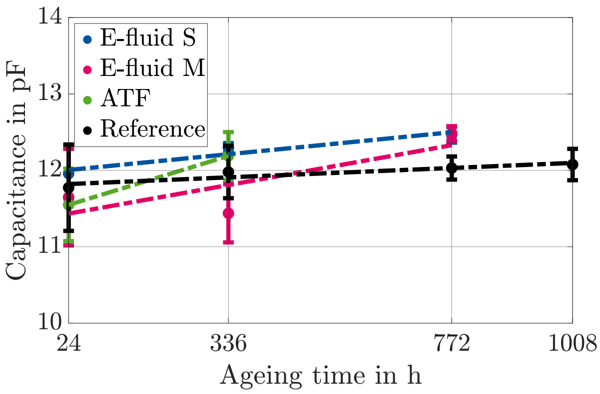


Fig. 4: Influence of oils on the capacitance of the twisted pairs at 10 kHz with respect to increasing ageing time.

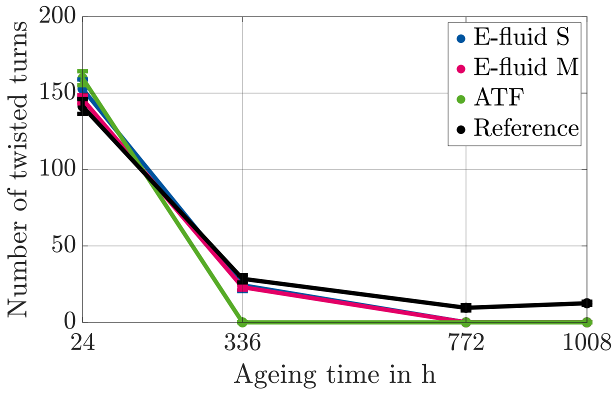


Fig. 6: Influence of oils on the peel strength of the enamelled wires with respect to increasing ageing time.

The stable behaviour of the group *Reference* over the entire ageing period is in good agreement with the given thermal class (180 °C). For the group *E-fluid S* and *E-fluid M*, the capacitances decrease continuously with increasing ageing hours while the PDIVs remain stable. In Fig. 10 it shows that there is a slight decrease of the tensile strength of all groups within in the given ageing period. Through the multiple characterizations, it can be concluded that, the AHA paper generally has a good material compatibility with all the three types of oils within the given ageing period, though a slight material degradation is already observed.

V. Conclusions and Outlook

In the present work, the material compatibility between different insulation materials and different technical oils used

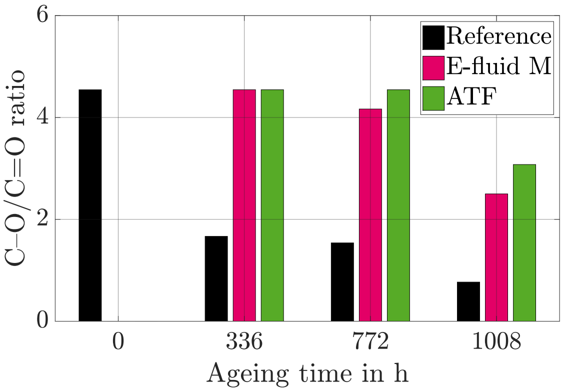


Fig. 7: C–O/C=O ratio of the polymer with respect to increasing ageing time.

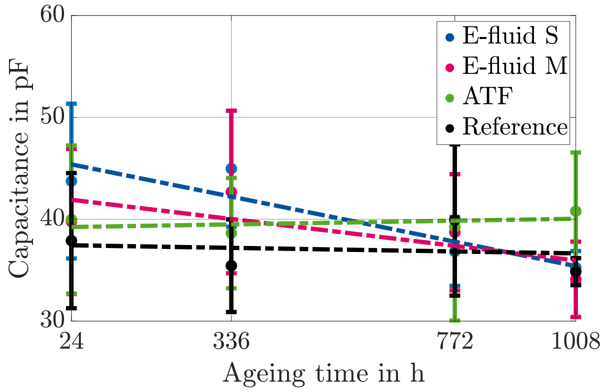


Fig. 8: Influence of oils on the capacitance of the AHA insulation paper at 10 kHz with respect to increasing ageing time.

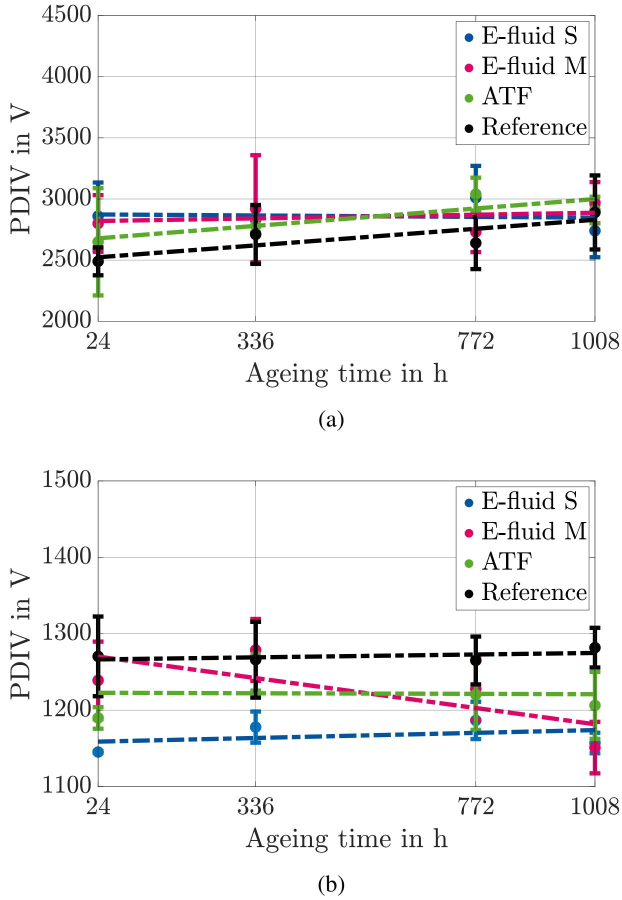


Fig. 9: Influence of oils on the PDIV of the AHA insulation paper under (a) surge voltage and (b) sinusoidal voltage with respect to increasing ageing time.

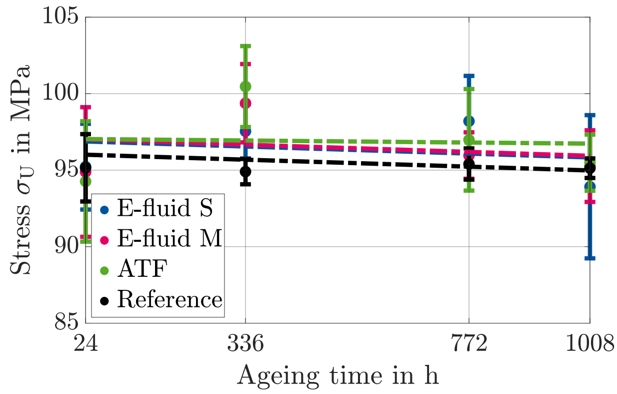


Fig. 10: Influence of oils on the tensile strength of the AHA insulation paper with respect to increasing ageing time.

in the electric drive train is studied. For the compatibility between oils and enamelled wire, the mechanical properties of the wire coatings are significantly degraded by all the three oils, which indicates that the oil is generally detrimental for the wire coating. Besides, it is noticed that the group *ATF* has a more significant side-effect on the mechanical property of the wire coating than the other groups, from which it can be concluded that oil additives are more crucial when compared to the base oil regarding the material compatibility with enamelled wires. Particularly, as mentioned at the beginning of the work, current state of the art is that the ATFs have been used in some integrated electric drive trains as both lubricant for the transmission system and cooling fluid for the electrical machine. While through this study, it should be learned that the existing commercial ATFs in the market are not necessarily suitable for a combined use in the electric drive system, otherwise, the lifetime of electrical machine can be threatened. It is observed that the e-motor dedicated oils have obviously better material compatibility with the enamelled wire in comparison with the commercial ATF. Surely, there are still much space of improvement for these E-fluids, for the seek of a healthy operation condition in the e-motor. Besides, the additive penetration into the coating layer is detected with element analysis, especially in the case of *ATF*, the sulphur penetration should take the responsibility for the early material degradation.

For insulation paper, a very slight trend of degradation of the tensile strength for all the groups is observed within the given ageing period, and there is no significant degradation of the dielectric and electrical properties of the insulation paper. In comparison with the case of enamelled wire, a better compatibility can be concluded.

In the future work, efforts will be made in aspects of both oils and electrical machine. From the viewpoint of E-fluid development, the chemical composition should be improved, particularly, The role of additive elements such as sulphur, phosphors and silicon in the material degradation process needs to be studied intensively. In aspect of machine diagnose and design, more importance should be paid to the mechanical behaviour of the insulation system, considering that in the traditional machine diagnose, focus is mainly on the dielectric and electrical properties. Considering the large difference of mechanical, dielectric and electrical behaviours of enamelled wires, the material compatibility may not be detected by individual approach of material characterization. Instead, a comprehensive evaluation is necessary to guide the application of oils in the electrical machine and the choice of materials during machine design. Besides, the material compatibility is only evaluated qualitatively and comparatively, instead of quantitatively. Therefore, a widely recognised end-of-life (EOL) criterion is still necessary for the material compatibility study.

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VI. Biographies

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