Aging of dielectric fluids used for direct contact immersion cooling of batteries

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1 Abstract

Batteries of electric vehicles require appropriate cooling to allow for increased performances such as high energy density and fast charging capabilities. Immersion of the cells in a dielectric fluid provides substantial benefits in terms of safety and performance, but the selection of a relevant coolant remains a complex task. This paper reviews the fluid properties which are considered most significant for this application, and provides an experimental comparison of the key properties of one fluid candidate under various aging conditions devised to reproduce several years of operation in a vehicle.

2 Introduction

In recent years, as the demand for electric vehicles (EVs) continues to grow, the extension of driving range of EVs implies to develop batteries with higher energy density and propose fast charging options. As a result, heat generation of batteries and safety issues increase. Thus, the need for efficient battery cooling solutions, and more generally thermal management solutions, is becoming increasingly important.

A promising approach is battery immersion cooling, in which a dielectric fluid used as a coolant is in direct contact with the cells, the terminals and busbar. The dielectric fluid helps reduce the risk of thermal runaway, can mitigate its propagation, and improve the overall safety and performance of the battery system.

In the last decade, developments of dielectric fluids with enhanced thermal properties and low carbon footprint have been carried out. However, selection of the optimal dielectric fluid is a complex task that requires a complete understanding of the fluid properties enabling its effectiveness (J-W Han, 2022). Therefore, in this article, we outline some key properties required for dielectric fluids to excel as EVs battery immersion cooling fluids. Measurement methods and analysis are detailed, and experimental results of key properties after aging of the fluid are presented.

3 Materials and methods

3.1 Key properties of fluid for immersion cooling of EV batteries

Oils' chemical inertness makes them good insulators in electrical applications, notably in transformers, circuit breakers, cables, and capacitors. In addition to electrical properties, good thermal properties such as conductivity and stability are also sought after for electro-technical applications. Indeed, the phenomenon of electrical dissipation causes the oil to heat up, which is particularly the case in transformers.

Exoes has developed a full list of specifications for fluids used as coolant in immersion cooling of batteries. More than 50 quantified properties make up this list, along with qualitative requirements. Values or ranges are proposed based on Exoes' extensive experience, and relevant standards have been identified. Some of the key properties are presented and commented below.

3.1.1 Key fluid thermo-physical properties

3.1.1.1 Thermal conductivity and Volumetric heat capacity

A coolant exhibiting a high thermal conductivity is desired for it allows for a more effective heat removal from the cells, which can help reduce the cooling load and energy consumption. It indicates how much heat can be transferred from the surface of the cells into the fluid, before considering the fluid will itself be moved away due to natural or forced convection. A thermal conductivity above 0.14 W/m/K at 40°C is recommended for acceptable performance and can be assessed using the standard ASTM D7882. This property can vary substantially between oils, with typical mineral oils having a thermal conductivity of about 0.13 W/m/K at 40°C, while ester oils reach 0.16 W/m/K and specific transformer oil could exhibit thermal conductivities above 0.35 W/m/K.

Volumetric heat capacity is an important thermal property of dielectric fluids when used in immersion cooling. This thermal property refers to the amount of heat that a specific volume of a material can absorb, and it is calculated as the heat capacity of a sample of the substance divided by the volume of the sample. The standards ASTM7896 and ASTMD4052 offer guidance on the measuring method.

Common dielectric fluids used for immersion cooling have a volumetric heat capacity more than 1000 times higher than that of air. One liter of dielectric fluid will therefore carry more heat than 1m3 of air. At any given time, the power supplied to the dielectric fluid can be viewed as the product between the mean temperature, the fluid's volumetric heat capacity and flow rate. At a given flow rate, the average battery temperature depends on the volumetric heat capacity of the dielectric fluid, making it one of the key characteristics for efficient dielectric fluids for immersion cooling.

To achieve high thermal efficiency, dielectric fluids should have volumetric heat capacity values greater than 1.5 kJ/L/K at 40°C (preferably above 1.9 kJ/L/K).

3.1.1.2 Viscosity

The dynamic viscosity is a measure of a fluid's internal friction, or, in other terms, a measure of a fluid's resistance to flow. In immersion cooling, dynamic viscosity is an important property because it affects the convection coefficient and the pumping requirement. A coolant with high viscosity will flow more slowly over a hot surface, resulting in a lower convection coefficient and a slower rate of heat transfer.

It's important to note that the relationship between viscosity and convection coefficient is not a simple one-to-one correlation. Other factors, such as the velocity and turbulence of the fluid, also affect the convection coefficient. However, in general, a coolant with lower viscosity will have a higher convection coefficient and will be able to transfer heat more effectively than a coolant with higher viscosity.

Kinematic viscosity is defined as the ratio of a fluid’s dynamic viscosity to its density.

In immersion cooling, the fluid needs to be able to flow around the cells, busbars and electric components in order to effectively remove heat away from them. In some configurations, the electronic control circuits supporting the Battery Management System (BMS) can also be immersed and is in contact with the fluid. If the kinematic viscosity of the liquid is too high, it will not flow easily and may not be able to effectively remove heat from the components.

In addition to its impact on heat transfer efficiency, the kinematic viscosity of immersion cooling liquid also has a significant effect on the performance and lifespan of the pumps used in the cooling system.

Indeed, for a given flow rate the pumping losses is given by the division of the dynamic viscosity by the square product of the density and the specific heat. Therefore, it is important to select an immersion cooling liquid with a kinematic viscosity that is suitable for the specific cooling application, as the pumping losses depend on it.

$$\dot{W}_{pump} = cst \cdot \frac{\mu}{\left(\rho \cdot C_p\right)^2}$$

Finally, the viscosity also impacts how easily the pump will be able to operate in cold start situations. Based on typical viscosity-temperature relationships, the following specifications can be considered relevant for this application, and can be evaluated using the standards ISO3104, ASTM D7042 or D445/446:

- $\nu_{25°C} < 5\ cSt$
- $\nu_{40°C} < 3.5\ cSt$

3.1.1.3 Mouromtseff number

Exoes has found that using the Mouromtseff number (Mouromtseff, 1942) is a valuable tool for ranking the performance of dielectric fluids in immersion cooling. With reference to a flow inside a fixed geometry at a given velocity, the highest heat transfer rate is achieved by the liquid coolant with the highest Mouromtseff number. This indicator encapsulates in one number most of the properties discussed previously.

For single phase forced convection, Mouromtseff found this figure of merit, Mo, to follow the form:

$$\boldsymbol{Mo} = \frac{\rho^{a} \cdot k^{b} \cdot C_p^{d}}{\mu^{e}}$$

where ρ, k, Cp, and μ represent the density, thermal conductivity, specific heat (at constant pressure) and dynamic viscosity of the fluid. The exponents a, b, d, and e take on values appropriate to the heat transfer mode of interest and the corresponding heat transfer correlation.

Exoes has developed a definition of the Mouromtseff number based on a Nusselt correlation built from experimental results conducted at their facilities on full immersion modules.

The standard shape correlation for the Nusselt number

$\boldsymbol{Nu = C \cdot Re^{\alpha} \cdot Pr^{0.33}}$, with Re the Reynold's number and Pr the Prandtl number

was used in a 50 nodes analytical GTsuite model of the module. The model was fitted to experimental results with one fluid on the following criteria:

- Module pressure drop,
- Module inertia,
- Heat generation of the cells and busbars,
- Average heat transfer coefficient between hot surfaces and fluid.

C and α parameters were chosen to minimize the average surface temperature error between the tests and the model. Five steady state tests at different flowrates and C-rates were taken into account.

The following fitted correlation is then proposed:

$$\boldsymbol{Nu = 0.175 \cdot Re^{0.65} \cdot Pr^{1/3}}$$

The following correlation is used by Exoes to define the Mouromtseff number:

$$\boldsymbol{Mo} = \frac{\rho^{0.65} \cdot k^{0.67} \cdot C_p^{0.33}}{\mu^{0.32}}$$

However, in addition to a fluid's heat transfer capability, the fluid's ability to store and move heat away from a heat source and the fluid's hydraulic performance should also be considered for optimum system performance. It is desirable to maximize the caloric and heat transfer capability while at the same time minimizing the hydraulic behavior, which is characterized by system pressure drop and required pumping power, as introduced in 2.1.2.

A figure of merit (FoM) representing the relationship among key thermophysical properties for comparative purposes has been suggested by Yeh and Chu (L-T Yeh, 2002) for single phase forced convection cooling that captures this desire:

$\boldsymbol{FoM} = \frac{C_p \cdot h}{\dot{W}_{pump}}$, with h the heat transfer coefficient

3.1.1.4 Flash Point

The safety of electric vehicles is a critical concern for manufacturers, particularly with regards to the potential for battery thermal runaway. To minimize this risk, non-flammable fluids or high flash points fluids are used for safe operation. The flash point of a fluid is the lowest temperature at which its vapors will ignite when given an ignition source. While high flash point fluids could increase the safety of EVs, currently, there is no consensus among EV manufacturers on the requirements and limits for flash point, leaving a gap in both academic and industrial understanding.

Moreover, common dielectric fluids with viscosities in the ranges described in 2.1.2 have extremely low volatility and high flash points and more research is needed to understand their behavior under thermal runaway conditions. It is then worth noting that the flash point does not necessarily reflect a material's flammability behavior in the context of immersion cooling. To address this, companies such as Lanxess use a hot plate droplet ignition test to assess the risk of ignition.

3.1.2 Key dielectric properties

3.1.2.1 Volume electric resistivity

The volume electric resistivity, measured in Gohm.m, can be defined as the resistance of a cube with a unit length between two opposite faces on which metallic electrodes are applied. It indicates the ability of the fluid to conduct current. The electrical resistivity of insulating mineral oils, which can exceed 10^3Gohm.m, generally decreases during use due to chemical alteration. Indeed, the oxidation products of the oil, which are favored by the presence of metals, exposure to air, operation at high temperature, and the presence of polar pollutants such as water or solid particles, strongly increase conductivity. Water can indirectly contribute to the increase in oil conductivity by promoting the miscibility of contaminants in the oil.

The ISO-6469 regulation requires that for an 800V battery in electric vehicles, there must be a 500Ohm/V insulation resistance to the chassis, which results in a required electric insulation resistance greater of 400kOhm for a complete powertrain, including a 800V battery.

Assuming that:

- the typical distance between live parts and the chassis is 1mm,
- the surface area of the live parts is around 1m² with a voltage spread between 800V and 0V, half of the surface area (0.5m²) is taken into consideration.

A minimum fluid threshold resistivity of 0.2 Gohm.m would typically be required, with a polluted fluid or at its end-of-life.

3.1.2.2 Dissipation factor

The electrical dissipation factor of an insulating material is defined as the tangent of the loss angle (delta). The loss angle delta is the complementary angle of the phase shift between the applied voltage and the current. For dielectric materials, delta is often small and therefore can be approximated by its tangent. In the case of a perfect dielectric material, the phase shift between current and voltage is 90°. The electrical dissipation factor thus reflects energy losses due to Joule heating. The dissipation factor is an important consideration for transformer oils, but in the case of DC batteries, it is used as a sensitive indicator to assess the quality of the fluid with inexpensive and readily available testing methods.

3.1.2.3 Permittivity of the fluid

The electric permittivity is defined as the quotient of the electric induction by the electric field, and is expressed in farads per meter (F/m). It represents the ability of the fluid to form a capacitor under an electric field and tells how much the molecules oppose an external electric field. For mineral oils, the permittivity is typically between 2 and 2.5 F/m, but it strongly depends on the nature of the oil. For instance, the permittivity of aliphatic hydrocarbons is around 2 F/m, while that of aromatic hydrocarbons is around 2.3 F/m. The permittivity of oils increases with the presence of polar compounds such as impurities. This effect is even more pronounced in alternating current, where dielectric losses occur due to a phase shift between current and voltage. In insulating transformer oils, the permittivity is often considered complex. With the real part being related to the stored energy within the material. The imaginary part relates to the loss of energy in the material.

3.1.2.4 Breakdown Voltage

The breakdown voltage, which measures the minimum voltage at which an arc appears between two electrodes, typically separated by 2.5mm (0.1 inch) according to the standards, is crucial for safety considerations in EV batteries. A minimum breakdown voltage of 2.5kV or 1000V/mm is typically required for 800V batteries. Impurities and moisture usually result in a decrease of the breakdown voltage in transformer oils (M.S.M. Abeyrathna, 2021).

These classic dielectric properties play a vital role in ensuring the optimal performance and safety of the immersion cooling fluids used in EV battery applications.

3.2 Fluid evaluated

As part of Exoes' investigations on immersion cooling, we here report the assessment of the fitness of a fluid for this application. The objective of the testing campaign we carried out was to evaluate the possibility of having a "filled-for-life" fluid, with a targeted life-expectancy of about 10 years in the car. The main properties of the fresh fluid, a mineral oil with additives, are reproduced in Table 1 below.

3.3 Test protocol

The fluid was submitted to aging conditions in a sealed chamber (autoclaves) at high temperature to achieve acceleration of the aging process. According to Arrhenius law, which generally relates the rate of thermal decomposition to temperature (Lansdown, 1994), the process simulated 2.5 years of service in 240h by setting the temperature at 80°C. About 25% of the real life expectancy was therefore simulated, which was considered sufficient to identify any onset of degradation. The experimental set-up is described in Figure 1(A) while Figure 1(B) shows a picture of a closed autoclave.

Two aging conditions were defined:

- First test: 240h at 80°C in presence of material samples and with water contamination.
- Second test: 240h at 80°C in presence of material samples and with renewal of dried air (no water contamination).

When material samples were added, the selected samples were based on structural materials found in battery modules (plastics such as PET, PPE, PA, elastomers such as NBR, and metals such as aluminum and copper). The wet surfaces and aspect ratios have been defined to match the typical conditions of a battery pack cooled by immersion.

Air renewal flow rate has been calculated based on a severe daily air ingress due to the thermal expansion and contraction of the fluid during charging, and scaled according to the volume of fluid in the autoclave relative to a typical battery, i.e. 1L/h.

Water contamination was simulated by mixing ~1.000 ppm of water to the fluid, which far above its saturation limit. Droplets of water are littering the floor of the autoclave.

The aging process as defined above, allowed us to perform comparisons of key properties of the fluid under 3 conditions: fresh, aged, and aged with moisture.

The influence of the condition of the fluid on its thermo-physical properties (specific heat, thermal conductivity, viscosity and density) as well as on its dielectric properties (resistivity, breakdown voltage, permittivity and dissipation factor) was then evaluated and the results are presented in the next sections.

4 Results

4.1 Experimental results: thermo-physical properties

The kinematic viscosity, density, thermal conductivity and specific heat of the fluid, between the fresh condition and the aged condition wherein water contamination was present, were measured and compared. No change at all in those properties could be detected.

4.2 Experimental results: dielectric properties

The resistivity in all 3 conditions was assessed according to IEC60247 and the results are shown in Table 2 for two temperature levels, 23°C and 90°C. The presence of water in the fresh sample decreased the resistivity, and the aging process including air renewal had a similar, though reduced, effect which might be attributed to oxidation processes taking place. While both outcomes were expected (cf. 2.2.1), we can observe that the aging condition in the presence of water actually improved the resistivity substantially. No explanation for this observation could be proposed. In any case, fresh or aged, the fluid remains above the threshold we consider acceptable in the relevant temperature range.

The breakdown voltage according to IEC60156 (2.5mm) in the 3 conditions is shown in Table 3. Surprisingly, this property was most of the time higher for aged fluids compared to fresh ones, regardless of the chemistry. This tends to indicate that aging, especially involving aeration, improves the insulating property of the fluids. Conversely, the presence of moisture in the fresh fluid always decreases the breakdown voltage, which is expected.

The permittivity in all conditions was measured according to IEC60247 for two temperature levels, 23°C and 90°C. Contrary to what is often reported in the literature, moisture nor aging seem to be altering this property for the tested chemistry.

Finally, the dissipation factor of all samples was measured according to IEC60247 and the results are shown in Table 4. Here too, no major differences between the values measured on fresh and aged samples can be identified.

5 Discussion

The tests performed tend to demonstrate that the fluid would actually behave very well as an immersion cooling fluid for batteries, over many years. Polluted and aged samples exhibit sufficient properties after the tests, which should guarantee that the properties would remain satisfactory for at least 2.5 years of use, given the severity of the conditions tested. Many of the results seem to be at odds with what the literature on insulating oils typically reported. One explanation could be that previous investigations mostly focused on transformer oils, operating in AC, which could exacerbate deviations of properties. In any case, more research, particularly involving chemical analysis, would be necessary to understand the mechanistic processes at stake behind some of the observations reported here.

6 References

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7 Funding and Conflict of Interest

This study has been ordered and financed by an automotive OEM as part of a work package to assess the relevance of battery immersion cooling for passenger cars. The manufacturers of the fluid tested is also a customer of EXOES on other projects.

8 Author Contributions

R.D. designed and directed the study, worked out the technical details and supervised the experiments. He defined the list of properties to be considered and investigated. A.B. and T.K. wrote the manuscript in consultation with R.D.. All authors provided critical feedback and put the results of the analysis into perspective.

Table 1: Main properties of the tested fluid

Flash point [°C]	ν(40°C) [cSt]	ν(20°C) [cSt]	Thermal conductivity at 20°C [W/m/K]	Density at 20°C [kg/m3]	Specific heat capacity at 20°C [kJ/kg/K]
150	5	60	0.14	0.8	2.2

Table 2: Evolution of the fluid resistivity under various conditions

	Fresh Fluid	Fresh Fluid + 1,000ppm water	Aged Fluid + 1,000ppm water	Aged Fluid + air renewal

Fluid resistivity at 23°C [GOhm.m]	6,900	3,700	13,000	5,300
Fluid resistivity at 90°C [GOhm.m]	1,200	400	1,500	800

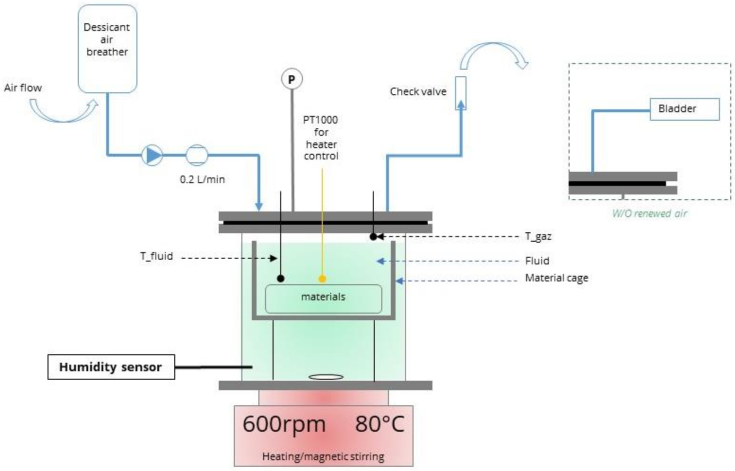
Table 3: Breakdown voltage of the fluid under various conditions

	Fresh Fluid	Fresh Fluid + 1,000ppm water	Aged Fluid + 1,000ppm water	Aged Fluid + air renewal
Breakdown voltage [kV]	46	20	46	80

Table 4: Dissipation factor of the fluid under various conditions

	Fresh Fluid	Fresh Fluid + 1,000ppm water	Aged Fluid + 1,000ppm water	Aged Fluid + air renewal
Dissipation factor (60Hz) 23°C	0.0011	0.0014	0.0002	0.0015
Dissipation factor (60Hz) 90°C	0.0046	0.0074	0.0021	0.0102

Figure 1(A): Setup used for the aging process - Figure 1(B): Picture of the sealed and insulated autoclave


Dessicant air breather
Air flow
0.2 L/min
P
PT1000 for heater control
Check valve
Bladder
W/O renewed air
T_gaz
T_fluid
Fluid
Material cage
materials
Humidity sensor
600rpm
80°C
Heating/magnetic stirring