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Electric Mobility: A New Era for Thermal Fluids

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Introduction

Automobile manufacturers are in the process of mass-developing the electrification of their models; a technological revolution that stems from the anti-pollution legislation the industry has had to take into account in recent decades. In their ongoing quest for lower fuel consumption and fewer emissions, carmakers have benefited from the constant support of the lubricants industry [1] which has naturally stepped up to the mark to propose a variety of innovations for electric vehicles. The introduction of a specific range of fluids for electrified vehicles by TotalEnergies [2] in 2019 has been followed by the release of products made by other players in the segment.

The technical characteristics of fluids for electric vehicles differ from those of conventional lubricants. Battery fluids, for example, are new to the market and respond to the expansion of zero-emissions vehicles. Over and beyond their characteristics, however, it is important to understand how these brand-new products required a different, particularly agile approach to their development.

Electric vehicle fluids: a new range in response to specific constraints

The thermal properties of fluids for electric vehicles are of capital importance. For decades, the lubricants industry has long sought to optimise friction and fuel economy, but today its focus is on improving the thermal properties of the fluids it proposes, with thermal management having superseded fuel economy as the new primary focus.

The drivetrains of Battery Electric Vehicles (BEV) comprise four main assemblies [3], as described in Figure 1.

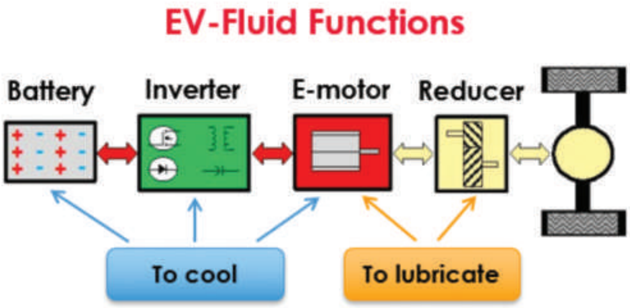


Figure 1: *The four principal assemblies of Battery Electric Vehicle (BEV) drivetrains and EV fluid functions.*

While different, and sometimes more compact architectures exist, notably with regard to the electronic peripherals of the e-motor [4], each of these assemblies is subjected to different constraints which directly influence the type of fluid needed for them.

For example, certain fluids have to deliver flawless lubrication, while others don't, but efficient cooling is always crucial and dictates the formulation of the different fluids employed.

Fluids for Electric Drive Units

The architecture of next-generation electric vehicles will call for the development of a single type of fluid for their Electric Drive Units (EDU) [5], combining high-performance lubrication of the transmission and efficient motor cooling.

Early-generation electric motors were entirely air-cooled [6], but air's low specific heat capacity in relation to its volume necessitated a different approach. Water cooling systems [6] began to appear as a potential solution, but these were soon superseded by the use of dielectric cooling fluids, a switch explained by the findings of digital simulation work illustrated in Figure 2 [5].

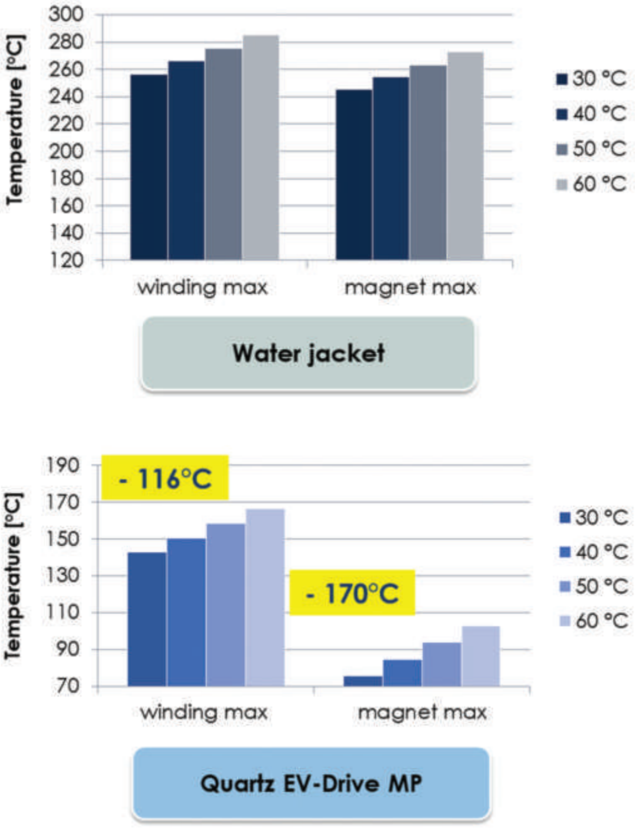


Figure 2: *The peak winding and magnet temperatures recorded for the two types of cooling system tested. The difference achieved using Quartz EV-Drive MP compared with the water-jacket system is highlighted in yellow.*

The uppermost graph in Figure 2 shows the maximum temperatures reached by an electric motor cooled indirectly by glycolated water. Temperatures in excess of 200°C can lead to component deterioration. In the case of the electric motor cooled directly using the fluid developed by TotalEnergies, the temperatures recorded were more than 100°C lower, which means the motor is able to run in more extreme environments than permitted by glycolated water. A high number of tests was carried out before this conclusion was reached [7, 8] and the level of performance obtained thanks to this technology is today recognised by automobile manufacturers, many of whom now plan to use it for their upcoming vehicles.

Fluid performance has led to a step forward being taken in terms of heat flux-related research and the rules established following the analysis of the motor's architecture can be expressed by the following equation:

$$FOM = \frac{\rho^{\alpha}\lambda^{\beta}c_p^{\gamma}}{\mu^{\delta}}$$

ρ= Density [kg/m^3]
k = Thermal conductivity [W/(m K)]
Cp = Specific heat capacity [kJ/kg K]
μ = Dynamic viscosity [cP]

Although the coefficients can vary depending on the configuration in question, an initial approach suggests that the three chief levers capable of optimising heat flow are low viscosity, a high specific heat capacity and high thermal conductivity. As is frequently the case in formulation work, however, the difficulty resides in striking the ideal compromise between opposing properties. For example, while low viscosity may favour thermal performance, a high-viscosity fluid can prevent wear and extend component life. Solutions are already available for OEMs, but research into fluid optimisation continues.

Fluids for power electronics

Power electronics enable the transfer of energy from the battery to the motor. Recent developments suggest that this technology will enable higher quantities of energy to be handled in the future. This will heighten the importance of the phenomenon of local heating, especially given the thermal losses associated with these conditions. The probability of electronic components suffering damage at higher temperatures makes enhancing thermal management and efficient heat extraction from these components essential for the longevity of the whole.

Today, these components are frequently cooled by specific water-cooling plates. This system risks reaching its limits very quickly, however, so it is possible to combine it with direct cooling of those components that generate the most heat [9], although this raises the same problems described above in relation to electric motors. Here again, performance is a function of the fluid's thermal properties, the aforementioned optimisation of which and the attention that has been paid to them in recent years are in this case quite significant. Some manufacturers tend to incorporate their power electronics in the motor-reducer unit which is a solution that calls for a specific fluid that covers several components. This pooling of different functions is a further pointer to the value of the research that has been undertaken in recent years.

Given that power electronics were previously of limited interest to the lubricants industry, new tools needed to be invented in order to make progress and guarantee the pertinence and sustainability of the different solutions proposed. The same observations apply to battery thermal management fluids which are a potential source of innovation for the automobile industry.

Battery thermal management fluids

All the techno-economic analyses conducted with regard to electric vehicles emphasise the essential role played by their batteries. Figure 3 (below) draws its inspiration from the data contained in a paper by Kampfer et al [10] to show relative costs of the different elements that make up battery electric vehicles.

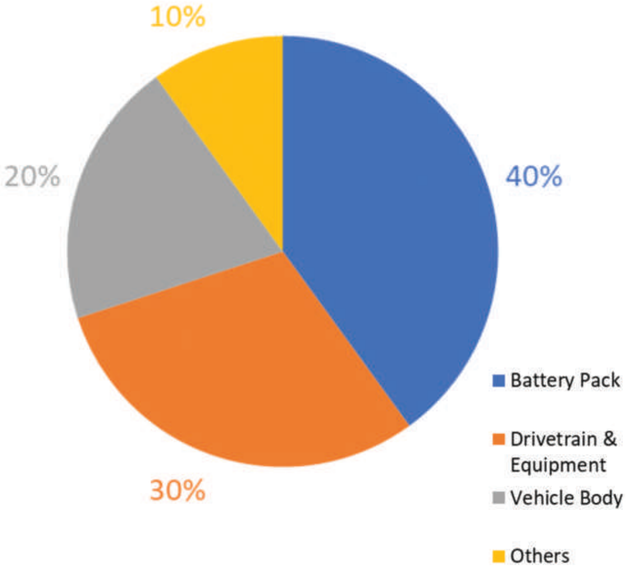
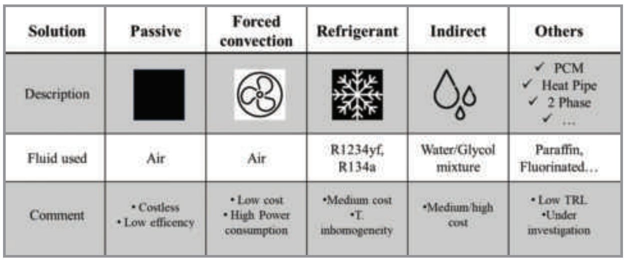


Figure 3: *Proportion of the costs represented by each family of assemblies, according to Kampfer et al [10].*

Any innovation that extends battery life plays a part in lowering TCO (Total Cost of Ownership), but the duration of a battery's life is directly influenced by its temperature history. Batteries that heat excessively or frequently reach very high temperatures can suffer damaged or have their working life shortened. It is for this reason that charging rates are capped, especially in the case of high-power charging stations. Battery thermal management is consequently of the utmost importance for automobile manufacturers who, on the one hand, want to extend battery life, but are looking to shorten charging times on the other. This was one of the main topics raised at events like Tesla's Battery Day and Volkswagen's Energy Day.

Working actively on this issue, the first step was to undertake a detailed review of existing solutions. Table 1 below indicates the different existing battery thermal management systems and solutions currently being developed (for further information about these technologies, please refer to reference [11]). A brief analysis makes it clear that these systems are unable to handle very high loads.



Solution	Passive	Forced convection	Refrigerant	Indirect	Others
Description	■		❄	💧	✓ PCM ✓ Heat Pipe ✓ 2 Phase ✓ …
Fluid used	Air	Air	R1234yf, R134a	Water/Glycol mixture	Paraffin, Fluorinated…
Comment	• Costless • Low efficency	• Low cost • High Power consumption	•Medium cost •T. inhomogeneity	•Medium/high cost	• Low TRL •Under investigation

Table 1: *Electric vehicle battery thermal management solutions.*

That said, a promising solution that is being explored is direct battery cooling using dielectric fluids, the insulating properties of which allow them to be in direct contact with the electrochemical cells. The larger heat-exchange surface area makes it an inherently effective solution. However, its TRL (Technology Readines Level) was very low (<3) during the research process's early days. It was consequently necessary to work not only on the fluid's optimisation but also on its application in order to increase its TRL. TotalEnergies also broadened its skill set by working on the battery's thermal management in its entirety in order to be able to evaluate its performance with great accuracy.

Initial development work was founded on the four areas of focus described in Figure 4 below:

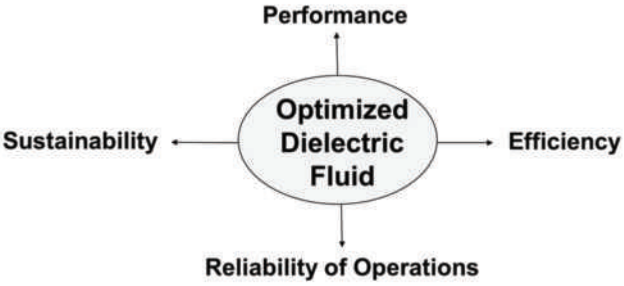


Figure 4: *Areas of focus for the development of battery thermal management fluids.*

The four areas of focus in detail:

- The question of **Performance** is directly linked to the thermal properties as described above, thereby necessitating the optimisation of the fluid's different parameters as specified in the Figure of Merit (FOM) equation.
- The question of **Efficiency** is a new aspect of the brief for fluid developers. Increasing a system's efficiency effectively calls for a thorough understanding not only of the fluid and the assembly to be cooled, but also of the entire thermal loop. It is necessary to compare direct cooling systems with existing systems across a variety of criteria (thermal performance, consumption of auxiliaries, onboard mass and volume). Additional thermal management skills were therefore required, and this has been beneficial to the development of all EDU fluids.
- The question of **Reliability** entails proposing fluids that have a longer life expectancy compared with that of the battery pack itself. The specificity of this development has been the necessity to work on the compatibility of new materials, since the battery packs are not made of elements that are widely used in lubricated circuits. Careful attention was also paid to repelling dampness and achieving stable insulation properties with time.
- The question of **Sustainability** is always factored in, the aim being to develop high-performance products that have the smallest possible impact on the environment, a consideration that could become a norm in the future.

The objectives listed included numerous new considerations, so it was necessary to acquire new skills and conceive new testing procedures. In order to speed up its work and be more agile, TotalEnergies quickly developed its own test method using rapid prototyping, as described in Figure 5. The rig takes the form of a battery module with dummy PHEV2 cells that incorporate heated cartridges to reproduce the temperature rises encountered when fast charging.

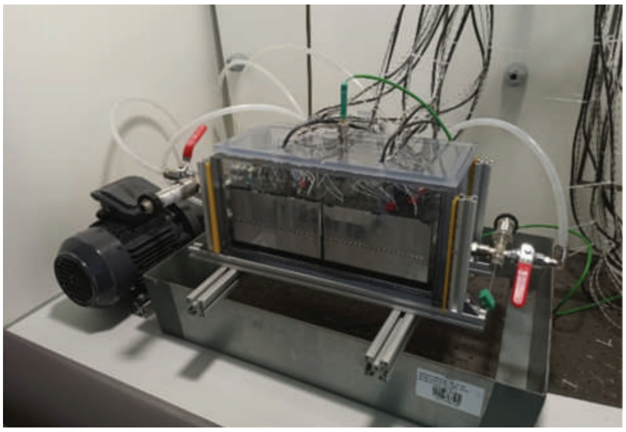


Figure 5: *A battery test rig incorporating dummy battery cells immersed in dielectric fluid.*

This test bench was conceived to demonstrate the performance of this type of solution and the results have been published in an SAE paper [12]. The solution's potential is confirmed by Figure 6 which extrapolates the temperature of the electrochemical cells during a rapid charge of a 50kWh battery pack.

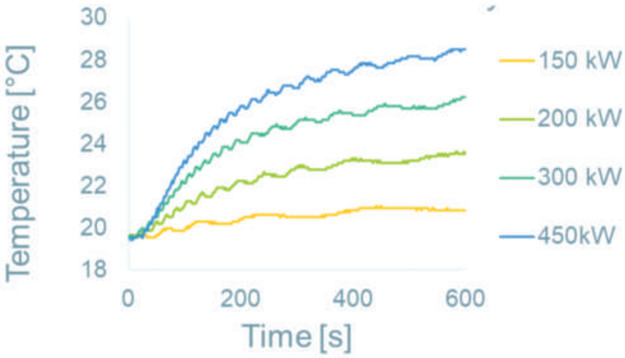


Figure 6: *Cell temperature during the rapid charge of a 50kWh battery pack. The colours represent different levels of charging power.*

The results show how this technology makes it possible to achieve particularly efficient cooling performance (target temperature: <30°C), even in the case of chargers not yet available on the market (>300kW). The flow and quantity of fluid required to achieve this level of performance is important. Above all, it is necessary to understand the solution's potential as revealed by this graph. The work of the automobile manufacturers is to optimise it and integrate it in their vehicles in a technically and economically viable way, while the work of TotalEnergies is to enhance the solution's techno-economic trade-off.

In parallel to these tests, the development process also included a significant amount of simulation with a view to obtaining a correlation between the digital and experimental data so as to be able to extrapolate the results of the simulations and apply them to real cases, using the automobile manufactures' CAD systems. Figure 7, for example, shows the digital simulation of the experimental test rig described in Figure 5.

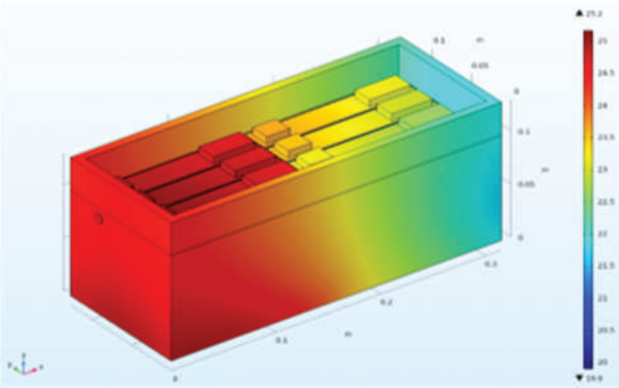


Figure 7: *Digital simulation of the experimental test rig described in Figure 5.*

Thanks to the global results of this test work, it was possible to optimise the fluids employed for battery thermal management. Work was also carried out on the fluids' environmental impact thanks to an eco-design taking into account their life cycle as presented in Table 2.

Property	Measure (@25°C)	Value
Thermal	Viscosity	4.3 cSt
	Thermal conductivity	135 mW/m.K
	Calorific capacity	2130 J(kg/K)
	Density	774 kg/m3
Environment	Biodegradability	Readily biodegradable
	Origin	>95% bio-sourced
Reliability	Drain interval	>Battery pack lifetime
	Compatibility	Done

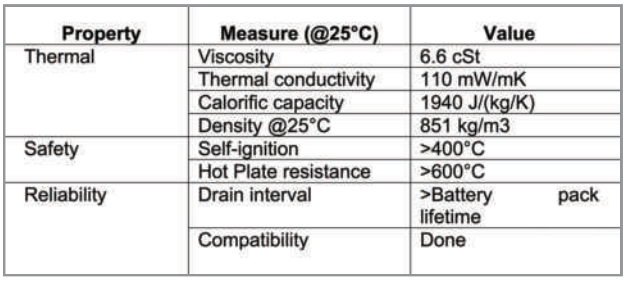
Table 2: *Characteristics of Quartz EV Battery Fluid – Eco-Friendly.*

A major innovation in terms of battery safety

There was frequent dialogue with automobile manufacturers during the development of this fluid. This dialogue also highlighted the research into enhanced safety, another key factor when it comes to the design of battery packs where the biggest fear is the propagation of thermal runaway (a sharp increase in the temperature of the electrochemical cell temperature (>400°C) that can start a battery pack fire) [13].

Significant attention was paid to securing a thorough grasp of the issue of thermal runaway in battery packs and the extent to which the use of a dielectric fluid can help. Again, specific test procedures were conceived to improve the ability of TotalEnergies fluids to resist temperature leaps of the kind that are observed in this sort of situation. The engineers in charge of the project focused on the fluid's resistance to high temperatures aimed at preventing secondary accidents resulting from inflammation and the propagation of thermal runaway to neighbouring cells (a description of the scientific approach taken to this work is described in an SAE paper [11].

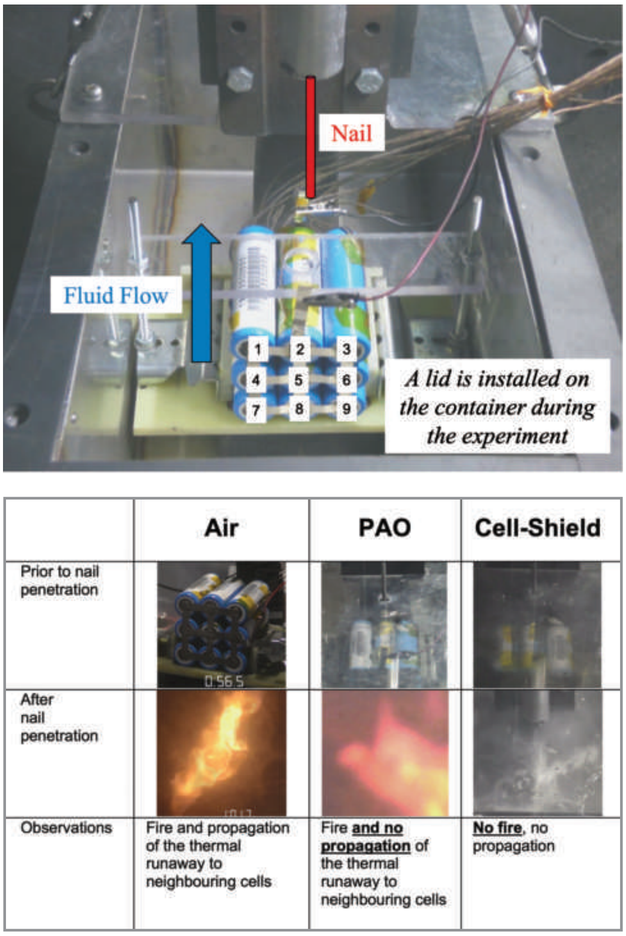
Furthermore, in-house tests permitted the development of a fluid with a particularly high resistance to high temperatures with no detriment to its outstanding thermal properties, as illustrated in Table 3 below.



Property	Measure (@25°C)	Value
Thermal	Viscosity	6.6 cSt
	Thermal conductivity	110 mW/mK
	Calorific capacity	1940 J/(kg/K)
	Density @25°C	851 kg/m3
Safety	Self-ignition	>400°C
	Hot Plate resistance	>600°C
Reliability	Drain interval	>Battery pack lifetime
	Compatibility	Done

Table 2: *Characteristics of Quartz (chk) EV Battery fluid– Cell Shield.*

In order to demonstrate the performance of this fluid, a module consisting of nine Samsung 21700 5A.h cells was subjected to a damage test, whereby a nail was driven through cell #2 (Figure 8) to ascertain whether the thermal runaway would spread, as well as the fluid's behaviour in this sort of situation.



	Air	PAO	Cell-Shield
Prior to nail penetration			
After nail penetration			
Observations	Fire and propagation of the thermal runaway to neighbouring cells	Fire **and no propagation** of the thermal runaway to neighbouring cells	**No fire**, no propagation

Figure 8: *Top: damage test rig involving driving a nail through cell #2. Bottom: results.*

The table in Figure 8 (right) presents the results. In the case where the cells were surrounded by air, there was propagation of thermal runaway. This was not the case when the cells were immersed in a dielectric fluid. A difference was observed between the use of a conventional hydrocarbon fluid (PAO2) and the specifically-developed fluid which did not catch fire. The use of this specific fluid consequently marks an improvement in terms of electric mobility safety. TotalEnergies used its physical chemistry expertise during this innovation's development to contribute to making electric mobility safer.

Conclusions and outlook

The path taken by mobility in favour of electricity has had a big impact on lubricants and their development. The different fluids for electric vehicles presented in this paper show the considerable role that thermal management is playing in the work of TotalEnergies.

Furthermore, in response to the shorter development times, new skills have been acquired, leading to the development of in-house testing procedures and in order to respond swiftly and flexibly to the potential problematics faced by automobile manufacturers. This experimental development combines with the development of digital simulation to enable results to be applied easily to different powertrain architectures and facilitate dialogue.

Last but not least, it has been demonstrated that a new fluid can permit the emergence of a new technology, and also that direct cooling enables faster battery-charging while at the same time improving safety. Special attention has been paid, as well, to the products' environmental impact, something that is going to become an industry norm in the years ahead.

The lubricant industry has long assisted its customers during such shifts and the boom enjoyed by electric mobility is a perfect illustration of this. The understanding of fluids is an asset for the emergence of new technologies and TotalEnergies is more than ever committed to working alongside automobile manufacturers in the drive towards electric mobility.

Further reading

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