SYNTHETIC ESTERS

IN THE FORMULATION OF FLUIDS AND LUBRICANTS

FOR ELECTRIC VEHICLES

NYCO

INDUSTRY & AUTOMOTIVE

a. Powerful drivers make the movement unstoppable

E-mobility, or electro-mobility, refers to the use of electricity to power any means of transportation, in an attempt to gradually walk away from fossil fuel powered vehicles and reduce emissions of greenhouse gases.

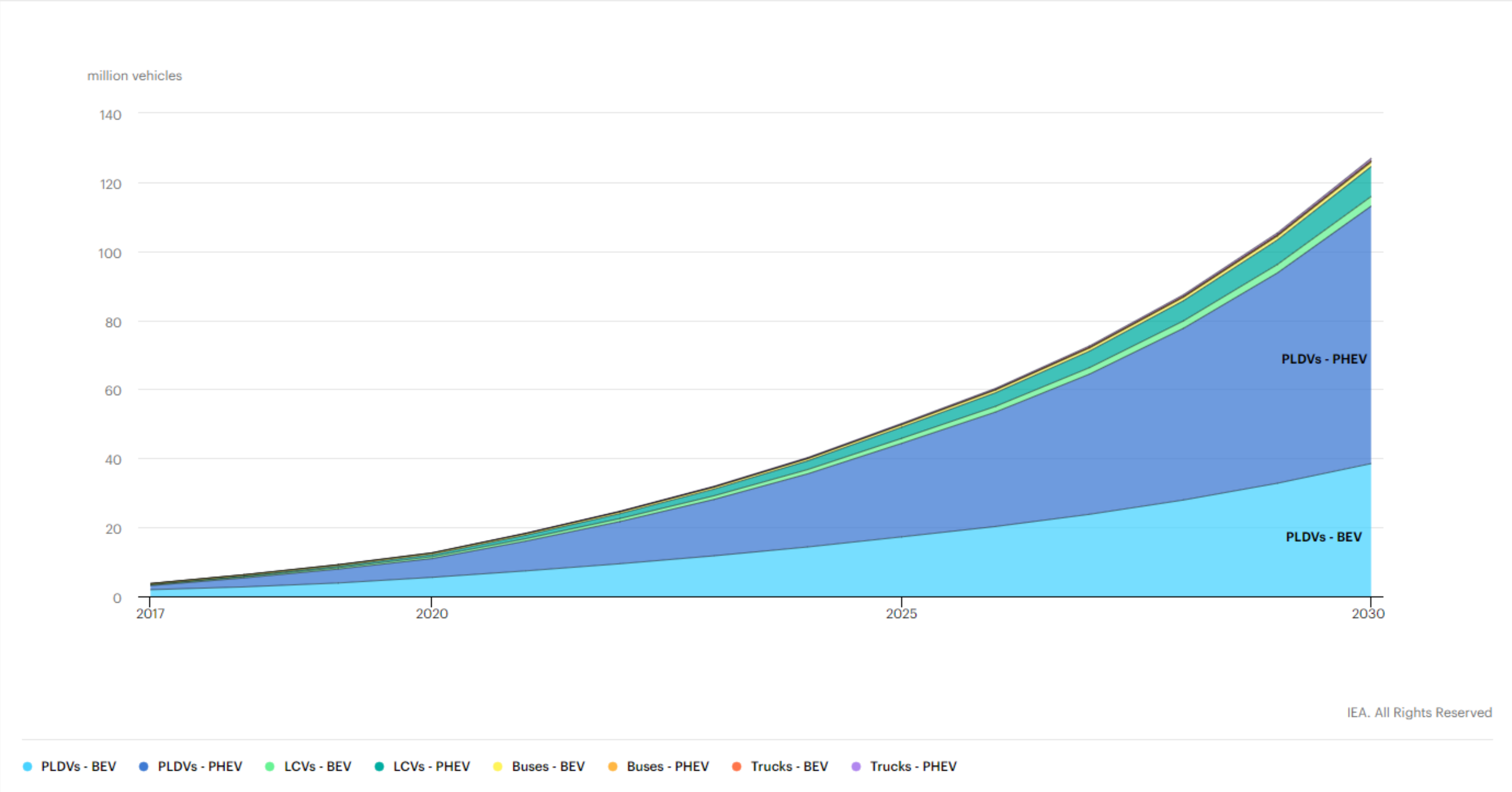
This technology therefore appears as an essential pathway towards achieving the goals of the fight against global warming, as targeted by various agreements, programmes, initiatives and coalitions (Paris agreement and the Race to Zero, EV100, EV30@30...), provided the energy used by electric vehicles is decarbonized. Even though the real benefit of e-mobility on CO2 emissions sometimes raises controversy and electric cars may only be one of the many leverages that will have to be used to reach the ambitious targets of carbon neutrality, it appears like the electrification movement is now unstoppable.

The growth of electric vehicles is largely fuelled by legislation banning internal combustion engines around the world, mostly between 2030 and 2040. Also, penalties on CO2 emissions exceeding targets in Europe, as well as industrial programs subsidizing the development of battery technologies further contribute to the rise of e-mobility. Even though the COVID-19 situation has had a negative impact on traditional car sales, it has not paused the development of e-mobility: it may even have reinforced the public's awareness of the need to reduce our carbon footprint, therefore facilitating market acceptance for electric vehicles.

The Clean Energy Ministerial, a forum involving energy ministers of various major economies, launched in 2010 the Electric Vehicle Initiative, dedicated to accelerating the introduction and adoption of electric vehicles. The resulting 2017 EV30@30 Campaign sets a target of 30% market share of BEV and PHEV by 2030.

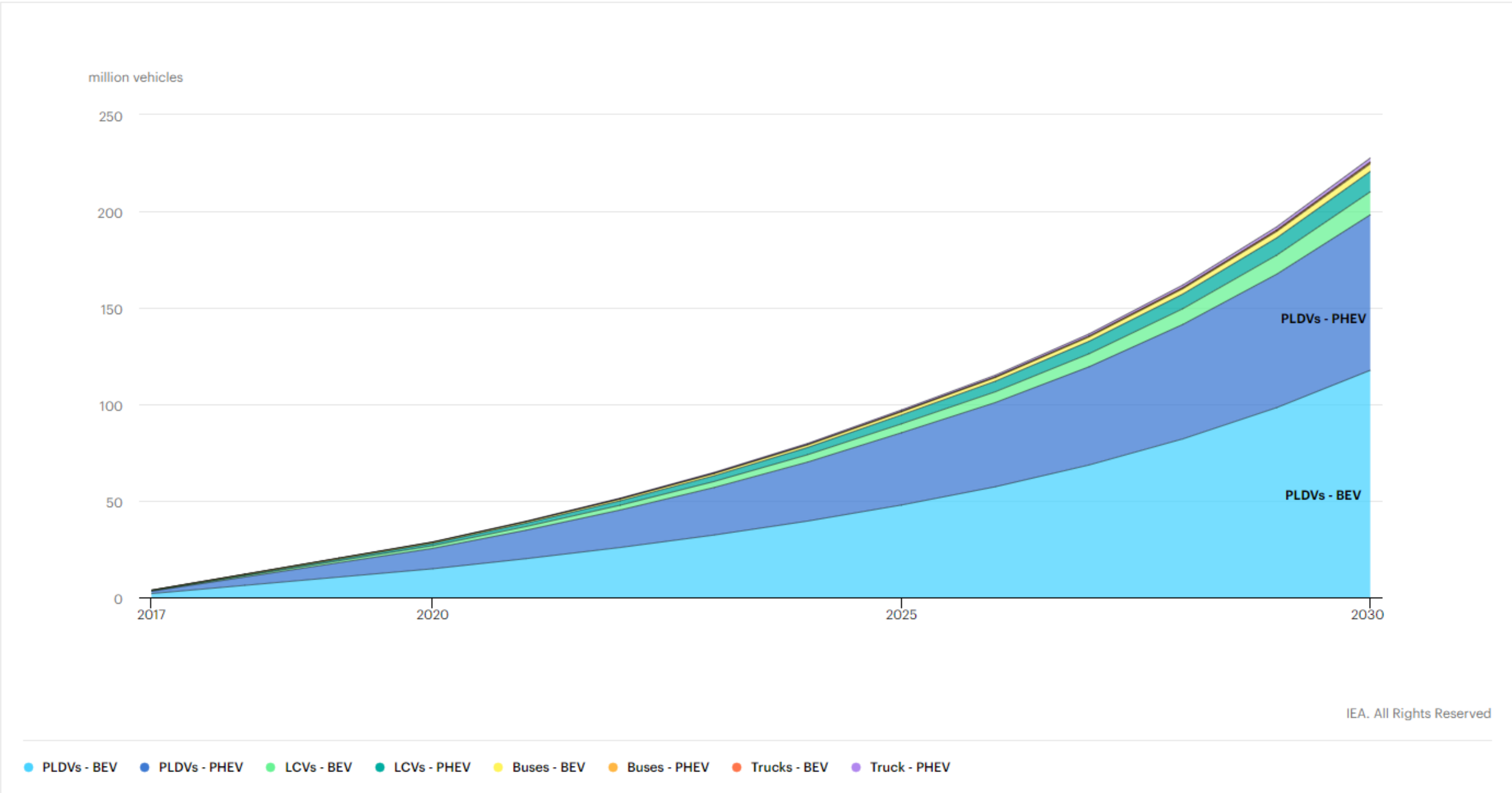
According to latest projections [1], sales of BEV and PHEV will jump from 2.1 million cars in 2019 to 23 million and up to 43 million in 2030 depending on the scenario, representing nearly 1 out of 2 new car sales in the world. The electric car fleet would then increase from 7 million units in 2019 to 140 million and up to 245 million in 2030, worldwide.

The annual battery production capacity is predicted to raise from roughly 110 GWh in 2017 to 440 GWh in 2023 and 1.5 TWh in 2030. Even though some analysts say projected figures on the production of electrified cars may be overestimated, there is no doubt the revolution is on the march.



Projected increase of electrified car fleet – New Policies Scenario from IEA
PLDV = Passenger Light Duty Vehicle – LCV = Light Commercial Vehicle

IEA, Global EV deployment in the New Policies Scenario, 2017-2030, IEA, Paris
https://www.iea.org/data-and-statistics/charts/global-ev-deployment-in-the-new-policies-scenario-2017-2030



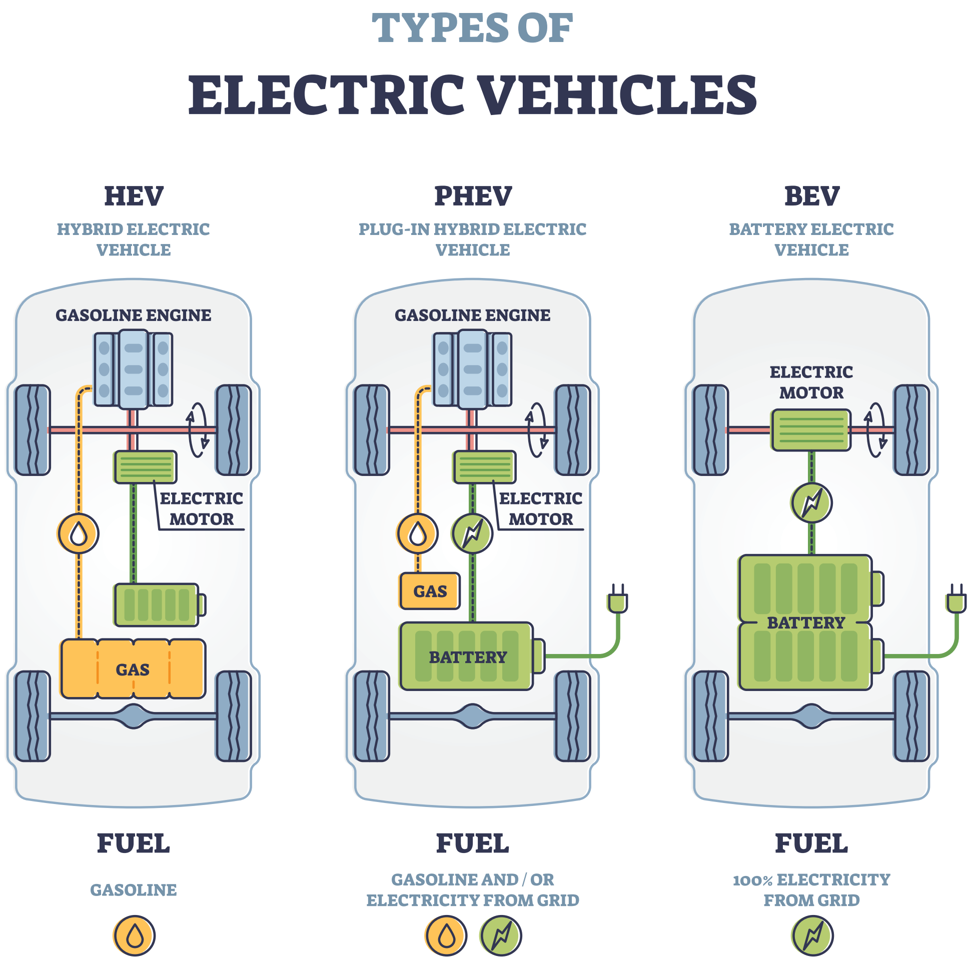
Projected increase of electrified car fleet – EV30@30 Scenario from IEA
PLDV = Passenger Light Duty Vehicle – LCV = Light Commercial Vehicle

IEA, Global EV deployment to 2030 in the EV30@30 Scenario, 2017-2030, IEA, Paris
https://www.iea.org/data-and-statistics/charts/global-ev-deployment-to-2030-in-the-ev3030-scenario-2017-2030

b. Clear dynamics but undefined, evolving fluid technology

Electric vehicles may be distinguished between:

- Full electric vehicles, including Battery Electric Vehicles and Range Extended Electric Vehicles (REEV) where the battery may be refuelled by a combustion engine to increase autonomy
- Hybrid vehicles, where both electric and combustion engines power the wheels; they include Plug-In Hybrid Vehicles that may be recharged from the grid.



Various types of electrified vehicles

Market acceptance relies on 3 essential notions: autonomy (sometimes described as "range anxiety" for consumers), charging time, and cost. These parameters will be major drivers for the choice of the right technologies in the design of electrified vehicles, and in turn, for the formulation of their fluids.

The components in electric vehicles that need fluids and lubricants include the electric motor, the battery, the transmission organs, and the power electronics – let alone the conventional, possibly adjusted, lubricants for the combustion engine in hybrid vehicles, as well as bearing greases.

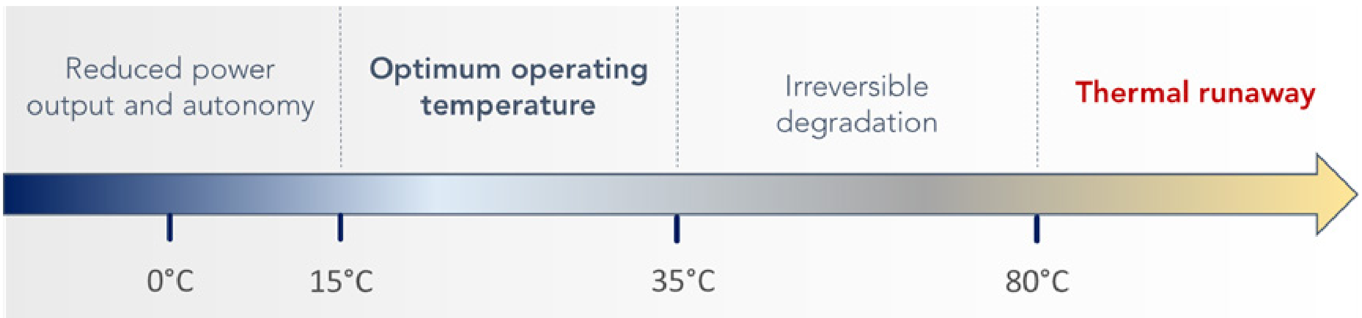
Whilst conventional fluids and lubricants from existing technologies have been widely used so far in electrified vehicles, and no dedicated products have been designed until recently, this time is now over, and specific products need to be developed. However, there is no industrial consensus or clear technical requirements for EV fluids, as equipment design is still evolving.

a. Tight control over temperature is key

Lithium-ion batteries produce electrical power through electro-chemical reactions. Like any other chemical reaction, they are very sensitive to temperature. In addition, the flow of electricity through the battery generates heat due to the Joule effect, the conversion of electrical power into calories.

As a result, if temperature is too low, the reactions will be very slow and the ability of the battery to produce electricity will be severely impaired. In particular, autonomy may be strongly reduced.

If temperature is too high, the reaction rate will increase and generate more heat due to the Joule effect, potentially leading to a thermal runaway with possible catastrophic failures. In such an event, temperature in cells may reach several hundred °C, generating over pressure, leakage of flammable electrolyte, and propagation to neighbouring cells – making the whole phenomenon an uncontrolled, possibly explosive chain reaction.



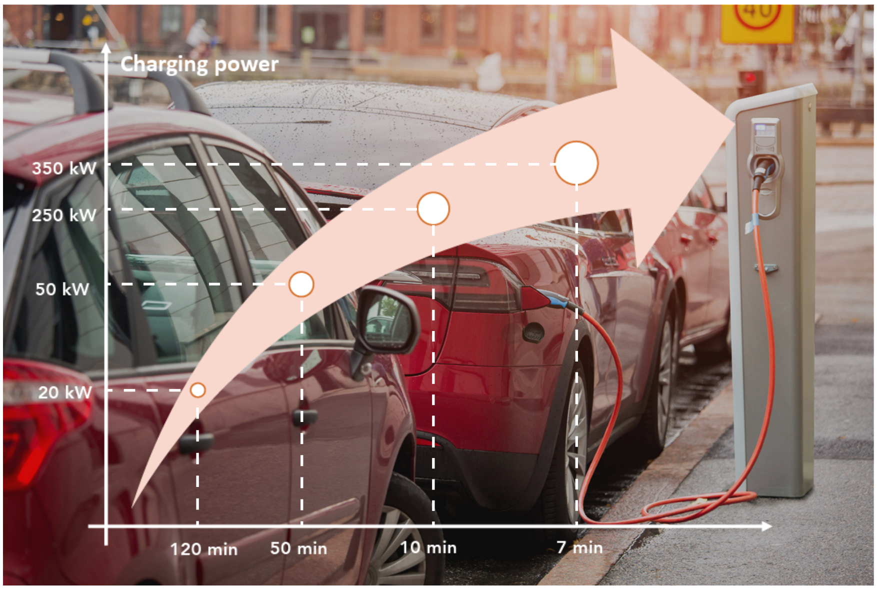
The effect of temperature on battery performance

Operating temperature also affects the useful life of the battery.

Therefore, operating temperatures for batteries must be tightly controlled and should ideally remain in a range of 15 to 35°C – which calls for a thermal management system, meaning batteries need to be cooled down, but also heated at low temperatures. This is not only a matter of battery efficiency – it is also a serious fire safety issue.

b. More power requires better cooling

Market acceptance will strongly depend upon the manufacturers' ability to design vehicles that can be charged quickly and show increased ranges – to compete with internal combustion engines. A few years ago, early electric vehicles used batteries showing capacities of less than 20 kWh, with a range of about 100 km. Latest models in preparation may show capacities of more than 100 kWh for a range exceeding 600 km. Besides, in order to cope with market demand on reduced charging times, the power of available charging stations has been increasing from a few kW to DC fast charge stations of 50, 150 and even 350 kW (dedicated to buses and trucks), allowing charging times of 20 min for a range of up to 600 km.



Reduced charging time means increased charging power

Whether we consider charging or discharging operations, such figures show that the heat generated by strong currents going through these systems and batteries will go increasing. This evolution comes at a price: more efficient cooling technologies for battery electric vehicles.

c. Immersion cooling, an efficient pathway for thermal management

Various cooling technologies are available for batteries:

- Vent (air)
- Forced air, the prevalent technology today
- Water/glycol coolant (jacketed design to avoid contact with electrical components)
- Immersion cooling (dielectric cooling fluid), not yet on the market
- Refrigeration fluid (direct or indirect) using evaporation to absorb heat
- Phase Change Materials

These technologies have their own drawbacks: air, even forced, because of its low density, will likely not be able to cope with the cooling needs of future powerful batteries. Phase change materials absorb heat but are not able to carry it away – unless used as an emulsion. Use of refrigerants poses questions about their high density and the Global Warming Potential of fluorinated fluids they may be composed of.

Amongst fluid cooling technologies, water/glycol cooling with indirect contact is the most prevalent on the current market. However, it remains a complex, heavy system, posing a risk of leakage of electrically conductive fluid on battery cells.

Immersion cooling with direct contact with a dielectric fluid appears to be the most effective technology, thanks to maximum direct surface contact enabling optimum heat exchange.

Immersion cooling will however pose some challenges too:

- Dielectric properties must be adapted to cell contact in order to avoid electrical losses or leaks. However, too much insulation may lead to charge build-ups possibly leading to arcing. A "dissipative conductivity" seems to be the right balance to find
- Compatibility with materials like copper, seals, coatings, and various plastics and elastomers must be ensured
- The fluid should demonstrate some level of resistance to ignition, as it is in direct contact with electrical parts

Obviously, thermal conductivity is a key contributor to liquid heat transfer. However, mathematical models show the most powerful leverage appears to be viscosity: the lower the better. Density and specific heat also contribute, to a lesser extent.

Therefore, the ideal battery immersion cooling fluid, at first glance, appears to be a low viscosity, high ignition temperature (and possibly flame retardant) dielectric fluid, with good material compatibility.

a. E-motor fluid requirements

The industry uses induction motors as well as permanent magnet motors, with a clear trend for the latter. Permanent magnets tend to lose their magnetization when exposed to high temperatures; heat may also damage insulation on the long run. Even though not as critical as for batteries, temperature control is here again very important to ensure good performance.

Rotational speeds of e-motors can reach 20,000 rpm, and up to 40,000 rpm in some cases. Working temperatures are expected to stay below 70°C, however bearings may reach 150 to 170°C, with peak temperatures of 200°C.

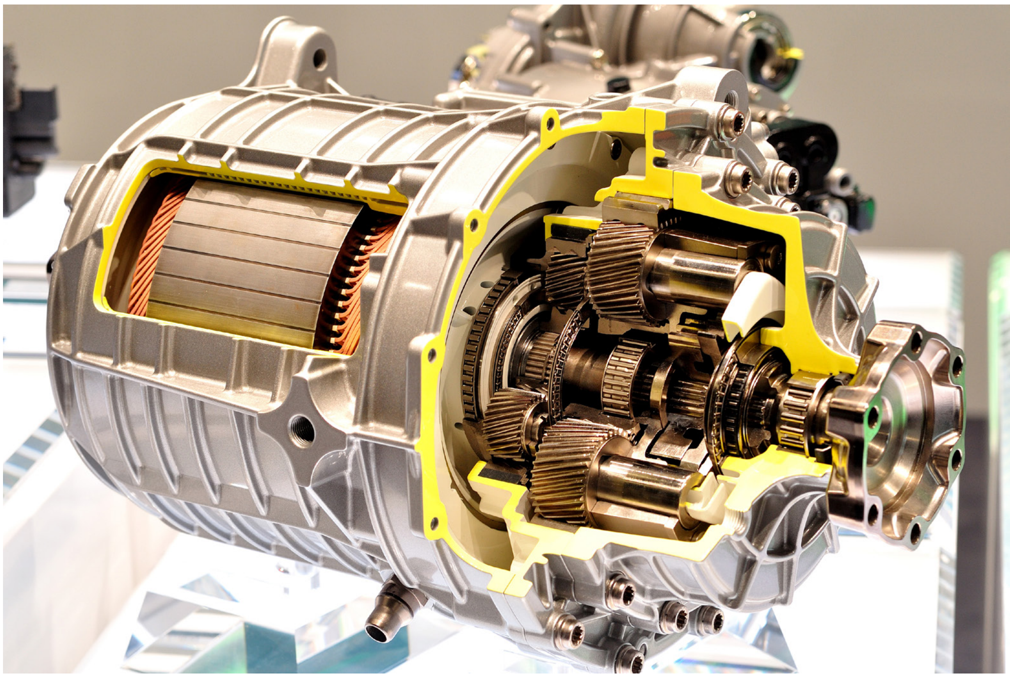
As with batteries, air-cooling is becoming insufficiently efficient to cope with increasing power, and water/glycol coolants passing through a jacket around the motor provide improved performance. Direct cooling with a dielectric fluid sprayed upon either the rotor or the stator delivers better heat exchange and is gaining popularity. However, such a direct cooling fluid will have to show satisfactory compatibility with various materials, coatings and lacquers – the first of which being copper.

Of course, integration could be considered with the battery cooling fluid loop, but in such a design temperature regulation would have to deal with 2 very different temperature levels.

b. Integration of e-motors in transmissions in BEV and REEV

Electrification should of course not add too much extra-weight and the quest for compact configurations is an important design factor. This explains why the industry is turning to the integration of the electric motor, the transmission, differential, and the power electronics (which essentially results in a geared motor, also called e-drive, e-transmission or e-axle). As a result, a common fluid loop must lubricate the gears and cool the electric motor.

Power electronics includes transformers (DC/DC), inverters (DC/AC), battery chargers, capacitors, printed circuit boards, as well as semi-conductors, diodes or transistors. Some of these components may show temperatures of up to 165°C and need to be cooled too. Integration in the e-transmission and cooling with the e-transmission fluid appears to be the preferred design route.



Integration of e-motor in transmission

E-transmission fluids must therefore combine the requirements of transmission lubricants and those of the electric motor cooling fluids. These requirements are based on 3 key notions:

1. Lubrication (in particular, extreme pressure properties and low traction coefficients)
2. Dielectric properties and compatibility with copper
3. Thermal management (ability to remove heat).

Whilst essentially conventional lubricants (Automatic Transmission Fluids in particular) have been used so far, adapted lubricants for dielectric properties have also been developed, and specific, dedicated fluid formulations are on their way to fill e-transmissions.

It is important to stress here the role of e-transmission fluids on the energy efficiency of the e-transmission. Whether that be through efficient heat transfer to ensure optimum operating temperatures of the motor or through low traction coefficients for minimum energy losses in gears, this fluid will contribute to optimize the "kilometres per kWh", thus potentially impacting battery design and cost.

Synthetic esters stand out: benefits and challenge

4

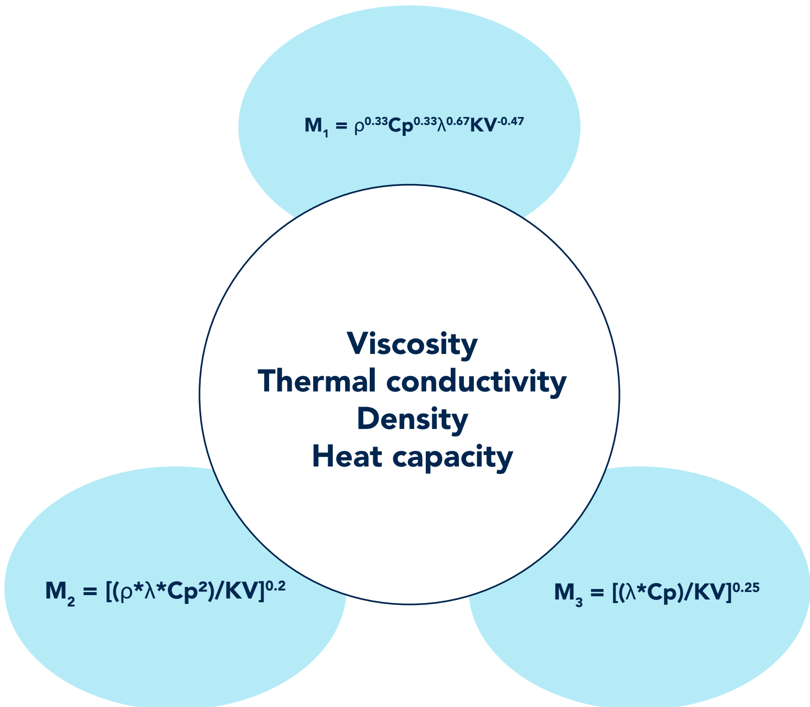
a. Heat transfer properties

The ability of a fluid to evacuate heat is dependent upon its viscosity, thermal conductivity, density and heat capacity. In particular, the Mouromtseff number, a commonly used figure of merit in heat transfer studies, evaluates the heat transfer capability of a fluid forced through a given geometry. [2]

$$\mathbf{M_o = (\rho^a\, \lambda^b\, C_p^{\,c})/V^d}$$

ρ : Density [kg/m³]
λ : Thermal conductivity [W/m.K]
$\mathbf{C_p}$: Heat capacity [J/kg.K]
V : Dynamic viscosity [kg/m.s]

The Mouromtseff number



Examples of Mouromtseff numbers adapted to various cases: turbulent flow (M1), constant power flow (M2), constant pressure loss flow (M3) from various studies

Depending on initial hypotheses and cooling system designs adopted by the industry, the exponents **a**, **b**, **c** and **d** of the Mouromtseff number may assume various values. Whatever the chosen mathematical model, the common feature of these figures of merit is their trends with regards to the importance of each parameter as a contributor in heat transfer.

Viscosity as a physical quantity may have highly variable values, which represents a significant variability for heat transfer coefficients. The other contributors such as density, thermal conductivity and heat capacity are much more limited in their value ranges. According to the Mouromtseff number, **viscosity appears like the most powerful factor to maximize heat transfer.**

	Low heat transfer base line	Improving heat transfer with KV	Improving heat transfer with density	Improving heat transfer with heat capacity	Improving heat transfer with thermal conductivity
KV25 (mm^2/s)	55	4.5	55	55	55
MV25 (kg/m^3)	858	858	992	858	858
Cp (J/Kg.K)	1821	1821	1821	1993	1821
k (W/m.K)	0.115	0.115	0.115	0.115	0.158
M1 (turbulent flow)	269	**412**	282	277	333
M2 (constant power)	359	**592**	369	372	382
M3 (constant pressure loss)	221	**413**	221	226	239

The relative impact of each variable of the Mouromtseff numbers

However, in the specific case of e-transmission fluids, viscosity will have to be adjusted so that lubricity requirements be met. Thermal conductivity will then appear to be a parameter of first order, because viscosity will offer a limited range of possible values.

Synthetic esters are available in a wide range of viscosities and may be designed to deliver ultra-low viscosity properties.

Thermal conductivity, as another contributor, is dependent, to some limited extent, upon chemical structures. Esters with optimized structures will normally display high thermal conductivities of up to 0.16 W/m.K @25°C, possibly exceeding that of PAO and group III base fluids at the same viscosity level.

Specific heat and density are other factors that may be played with, however there is not much space for optimization on esters with them.

b. Fire safety

Fire safety in electric vehicles embraces various aspects:

• Ease of ignition of the fluids, when in touch with electrical components, in case of a spark, arc, or breakdown of static charges. This parameter may be easily evaluated with standard tests like flash point or fire point

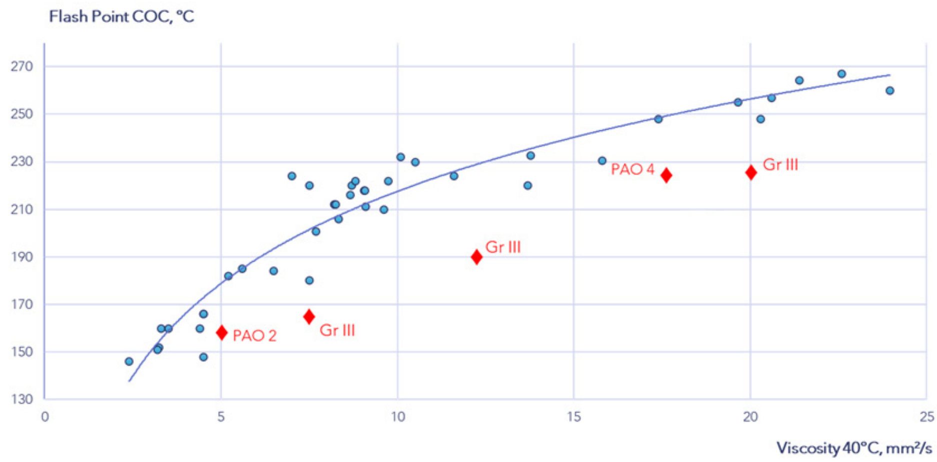
• Thermal runaway of battery: in such an event, flammable liquid electrolyte may leak out of cells. The ability of the battery cooling fluid to evacuate the heat efficiently is key to preventing thermal runaway or slow down propagation to neighbouring cells should it still take place. As discussed above, this ability is strongly related to the viscosity and thermal conductivity of the fluid.

• Possible ignition of battery cooling fluid in case of thermal runaway: an additional, obviously undesirable possible side effect of a thermal runaway. In this case the temperature of the electrolyte may be such that ignition of the cooling fluid could be inevitable. This is where slowing down the fire propagation and having self-extinguishing properties make sense.

The ability of a fluid to self-ignite is dependent upon a variety of parameters, volatility being one of the most important. Fire safety appears like a conflicting parameter with viscosity which should be minimized to maximize heat transfer coefficients. The solution therefore lies in the trade-off that will be achieved between viscosity and flammability.

Esters do show excellent viscosity-volatility ratios, and consequently excellent viscosity-flash point ratios. Such features translate into improved fire safety, as illustrated in transformer oils where synthetic esters are used, amongst other reasons, for their fire points exceeding 300°C [3] and are considered self-extinguishing fluids. Esters are also used as fire resistant HFDU hydraulic fluids [4].

No pool fire has been reported on transformers using ester based dielectric fluids in over 30 years



The outstanding viscosity-flash point ratios of synthetic esters

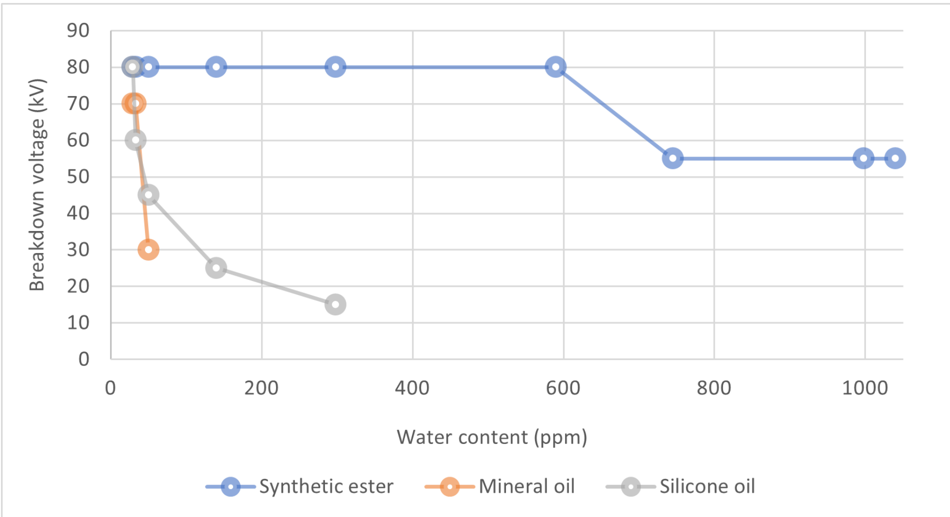
c. Dielectric properties

Esters, like many other base fluids, are essentially insulating fluids: they demonstrate very low electrical conductivity – to the extent that they are properly manufactured and purified. Breakdown voltages are also very high on such fluids. The use of synthetic esters as high fire-point, non-flammable dielectric fluids is well established in traction, distribution or power transformers.

Breakdown voltage	kV	80	IEC 60156
Dielectric dissipation factor 90°C and 50Hz	-	0.006	IEC 60247
DC Resisivity @ 20°C	GΩ.m	500	IEC 60247
Conductivity 20°C	pS/m	10 to 20	ASTM D2624
Relative permittivity 20°C	-	3.0	IEC 60247

The typical dielectric properties of IEC 61099, ester based dielectric fluids

Another interesting feature of esters is their ability to absorb water and dissolve it up to a much higher level (about 600 ppm typically) than hydrocarbons do (about 30 ppm) without degrading electrical insulation properties, since water is linked to ester molecules.



Impact of water content on breakdown voltage

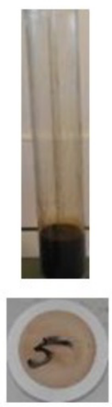
As a matter of fact, the typical electrical conductivity of pure, clean esters may be so low that the possible generation of static charges build-ups and possible sudden discharges (arcing) causing damages may have to be considered. However, many additives will increase conductivity to a dissipative level, and specific additives may even be considered to increase, stabilize and control it. In addition, degradation products forming over time and ageing will also contribute to increasing, to acceptable levels, electrical conductivity.

d. Aging

Synthetic esters, when properly formulated, show excellent resistance to oxidation and provide superior cleanliness features in operation. Such properties are precious, especially for e-transmission fluids that may be exposed to peak temperatures reaching 200°C, a temperature that pushes PAOs to their limits. Stability to high temperatures also makes for stable dielectric properties.

It should be noted that synthetic esters may also be used as components of a full formulation, blended with other base fluids to improve thermo-oxidative and cleanliness performance.

Several features in synthetic esters explain their behaviour when exposed to high temperatures. Of course, the purity and cleanliness of esters strongly contribute to their performance. Additionally, these compounds are intrinsically resistant to oxidation and, in the case of neopolyol esters, to thermal degradation. Their degradation pathways are quite different from those of hydrocarbons: saturated synthetic esters do not tend to polymerize or generate carbonaceous deposits. Moreover, as polar species, they contribute to some detergency and dispersency action and they act as good solvents for degradation by-products, therefore providing a high level of cleanliness.

ASTM D4636 - 175°C	**ISO VG 32 - gr II - formulated**	**ISO VG 32 gr II + 20% neopyol ester - formulated**	**ISO VG 32 - Full neopolyol ester formulation**
KV change (%)	30	9	3.6
TAN change (mg KOH/g)	6	3	0.3
Sludge (mg/100 ml)	52	9	2.3
			

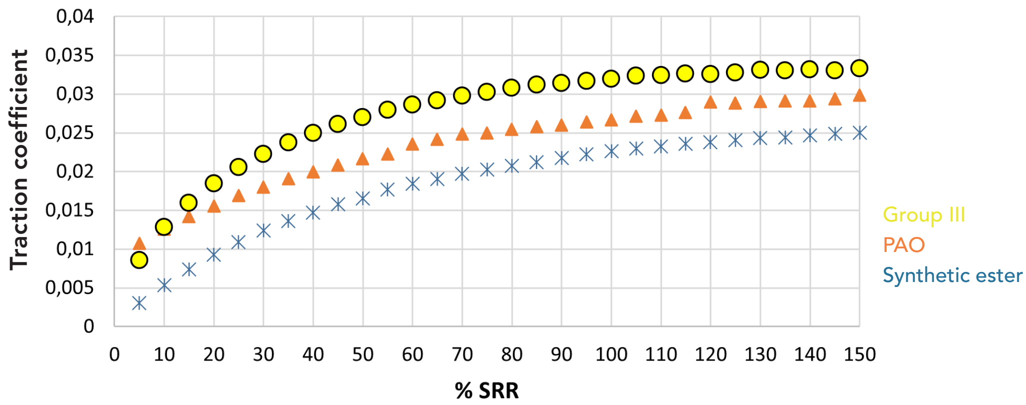
ASTM D4636 oxidation and corrosion test – 175°C

e. Friction modification

Synthetic esters are essentially pure and clean products. Their chemical structure may be designed to generate linear molecular shapes. Such molecular assemblies will have the ability to sustain high pressure, high shear movement without becoming too viscous.

Traction coefficients, measured as a friction parameter in the specific elasto-hydrodynamic lubrication regime, are an indication of the resistance of a fluid to shear under high pressure, hence the ability of carefully chosen synthetic esters to reduce traction coefficients.

Low traction coefficients correlate to improved energy efficiency in gears and transmission oils, a precious feature in the formulation of e-transmission fluids. Of course, attention must also be given to the protection of surfaces against wear and fatigue.



Traction curve on 4 mm²/s @100°C synthetic ester, gr III and PAO, using MTM2 equipment – 100°C, 1 m/s, 1 GPa (38 N)

f. Material compatibility

Esters, as polar species, interact with elastomers and with some plastics. A property like the aniline point illustrates this behaviour, with values revolving around 10°C for esters. A polarity index may also be calculated for a given ester base fluid, as a useful indicator or prediction of interactions between esters and usual elastomers. This matter is of specific relevance since we are considering here low viscosity products, prone to stronger interactions.

Many interactions are known and understood to some level, which allows for the design of optimized structures for specific compatibility requirements with a given material. However, this may have to be done at the expense of other useful properties: here again, the notion of trade-off is key.

Interactions on usual elastomers used in lubrication are well known, and show that preference should be given, if possible, to elastomers like H-NBR or FKM. Polypropylene and PA 6 may also be considered, as plastic materials.

The use of esters as insulating fluids in transformers is well established and also tells us that a number of other types of materials (insulating polymers, coatings, adhesives…) may be considered.

Finally, blending esters with low interaction base fluids is effective at mitigating the impact on materials, if necessary.

The technology of synthetic esters as base fluids demonstrates the following precious features: design flexibility, purity and cleanliness. These features not only bring a high level of performance, but they also allow for some level of adjustments to meet application-specific requirements.
Formulations based on synthetic esters are able to deliver:

- Superior heat transfer performance, thanks to the availability of ultra-low viscosities and high thermal conductivities
- An excellent compromise between viscosity and fire safety
- High stability and cleanliness in elevated temperature operations
- Low traction coefficients for optimised energy efficiency in transmissions.

The lack of industrial consensus or standards for the design of thermal management systems for batteries and electric motors makes it difficult to identify one ester technology that suits all equipment. Ester manufacturers, thanks to their fine knowledge of esters, will be able to adapt their product recommendation to a great variety of requirements. Synthetic esters therefore provide precious tools for the optimization of fluids for e-mobility applications. They are compatible, for the most part, with other base fluids, allowing possible blends.

Additionally, they may display biodegradability and renewable carbon contents should such features become requirements in the near future – a likely scenario.

Sources

[1] IEA (2019), Global EV Outlook 2019, IEA, Paris
IEA, Global EV deployment in the New Policies Scenario, 2017-2030, IEA, Paris
https://www.iea.org/reports/global-ev-outlook-2019
https://www.iea.org/data-and-statistics/charts/global-ev-deployment-in-the-new-policies-scenario-2017-2030

[2] Simons R, Comparing Heat Transfer Rates of Liquid Coolants Using the Mouromtseff Number, Electronics Cooling Magazine 2006
Bergles, A.E., and Bar-Cohen, A., "Direct Liquid Cooling of Microelectronic Components," Advances in Thermal Modeling of Electronic Components and Systems, Vol. 2, Bar-Cohen, A., and Kraus, A.D., eds., ASME Press, New York, NY, 1990.
https://tel.archives-ouvertes.fr/file/index/docid/492962/filename/These_KARIM-Opt.pdf
dspace cover page (mit.edu)

[3] IEC 61099:2010 - Insulating liquids – Specifications for unused synthetic organic esters for electrical purposes

[4] ISO 12922-2020 – Fire resistant hydraulic fluids – Specifications for HFDU category

NYCO

Solutions ahead