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Recent trends in batteries and lubricants for electric vehicles

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Abstract

Future progress in hybrid and battery vehicles heavily relies on the optimization of involved battery components and lubricants. Attention must specifically be given to the material composition and surface coatings of the electrodes as well as the electrolyte used to maximize energy output, while also ensuring safety. Additionally, prioritizing the effective utilization of specific lubricants for electric motors and various tribological contacts, such as wheel bearings and the steering system, is the prospective goal of lubrication research. The energy output of the most promising battery, the Li-ion battery (LIB), must result in driving ranges, which can compete with the 600 km driving range of combustion engine (ICE) vehicles. Consequently, ongoing research activities in cell chemistry, electrode surface engineering, electrolyte engineering, and engine lubrication offer the greatest opportunity in achieving these goals.

Keywords

Electric vehicle, battery, lubricants, energy conservation, internal combustion engine

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Introduction

According to the Environmental Protection Agency (EPA), traditional internal combustion engine (ICE) vehicles cause 75% of carbon monoxide emissions, while the transportation sector is the largest contributor to greenhouse gases, accounting for 28% of total US emissions.[1] Pollutant by-products are mainly produced by the burning of fossil fuels, but can also stem from non-exhaust related sources including tire and brake wear.[2] These emissions, which include lead, ozone, and nitrogen oxides, have noteworthy adverse effects on human health, crops, buildings, and roads.[3,4] As the world becomes further aware of global warming and rapid degradation of air quality, electric vehicles (EVs) present a vital solution in the advent of renewable energy. The electric motor and battery of EVs do not produce nearly as much exhaust-related emissions as compared to traditional ICEs. Although, non-exhaust emissions are still present in the form of battery manufacturing, production of grid electrical energy, as well as braking wear. Qiao et al.[5] discovered that the manufacturing of EV parts, namely the battery, led to an approximately 50% higher level of greenhouse gas emissions as compared to ICE vehicles, prompting further efforts toward more eco-friendly battery manufacturing processes. Additionally, vehicle-to-grid (V2G) connection results in the utilization of electrical energy,

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which most likely came from the burning of fossil fuels.[6] As such, technologies such as regenerative braking,[7] which transform the kinetic energy of the vehicle back into electrical energy, as well as the integration of solar-powered charging stations[8] help to limit the overall emissions.

Nonetheless, EVs certainly provide a paramount step toward a greener future. However, their widespread integration into the automobile industry is primarily crippled by low driving range, battery efficiency and energy output, as well as high costs. EVs are expectedly higher in cost than ICE vehicles due to the relatively new and sophisticated technologies being developed. However, operating costs for EVs are much lower, at an average of 2 cents/mile as compared to 12 cents/mile operating ICE vehicles.[9] Reasoning for the large principle and low operating cost of EVs lies in the used battery technology. Most lithium-ion batteries, being the most promising and commercially available, contain cobalt, a relatively scarce metal contributing to high costs.[10]

In order to compete with ICE vehicles, EVs must reach a driving range of 600 km. Extending this range can be accomplished by the optimization of the involved battery technology, as well as minimizing frictional energy losses through proper lubrication. Regarding the first aspect, battery engineering and technology consists primarily of determining optimal electrode–electrolyte compositions, as well as necessary surface coatings to maximize energy output and efficiency. Battery research has also focused on preventing problems such as mechanical fracture of the electrode during (de)lithiation,[11] the formation of residual lithium compounds at the electrode–electrolyte interface,[12] limited electrode density,[13] and the gradual decrease in capacity retention and safety characteristics.[14] In this regard, the current challenge is to develop advanced battery systems that overcome these shortcomings, reduce the involved costs, and offer maximal driving range.

According to Holmberg and Erdemir,[15] 57% of the electrical energy in EVs is utilized to overcome friction losses. Minimizing the loss of energy due to friction enables substantially bolstered energy efficiency and thus extending the respective driving range. The energy losses by air drag, rolling resistance, and braking dissipation are directly reduced by mechanical design, while lubrication remains vital in reducing frictional losses in the electric motor and transmission, which account for about 1% and 3% of losses, respectively.[15] Lubricants applicable to traditional ICE vehicles can be translated to EVs, however, attention must be paid on the lubricant's electrochemical properties, corrosion resistance from copper, and interaction with elastomers/polymers found in EVs. Nano-additives, such as TiO_2 and CuO,[16] offer an interesting approach to alter the oil properties thus becoming more applicable in EVs.

This article primarily seeks to compile recent advancements, notably after 2019, in battery engineering, lubricants, and lubrication techniques for EVs. Special attention has been put on the electrodes composition, the electrodes surface coating technology, and the electrolytes to offer the greatest opportunities toward further commercializing EVs.

Lithium-ion batteries (LIBs)

In recent years, significant research in LIBs has been dedicated toward the development of improved cathode and anode materials to match with the demands of increased charge capacity and durability for EVs applications. Regarding the cathode, nickel-based layered oxides – primarily NCM ($Li[Ni_xCo_yMn_z]O_2$) and NCA ($Li[Ni_{1-x-y}Co_xAl_y]O_2$) – have become a prominent focus of study due to their higher energy output (up to $300\,Wh{\cdot}kg^{-1}{}_{cell}$) compared to the state-of-art lithium-iron phosphate (LFP) cathodes (energy output between 180 and $190\,Wh{\cdot}kg^{-1}{}_{cell}$), in despite of the lower price of the latter (US\$80–135 $kWh^{-1}{}_{cell}$) compared to the first system (US\$100–175 $kWh^{-1}{}_{cell}$).[10] Additionally, although LFP cathodes exhibit superior safety characteristics and cycling performances, they are related to lower cell voltages (average voltage of 3.22 V) in comparison to NCM and NCA cathodes (average cell voltage: 3.6 V), which makes the latter more suitable for long-range EVs applications.[17–20]

Zhang et al.[17] recently stated that next-generation LIBs with nickel-based layered oxides cathodes are expected to storage an energy density of $800\,Wh{\cdot}kg^{-1}{}_{cell}$ for long-range EVs applications. In this respect, different approaches have been proposed to increase the specific and volumetric capacity of LIBs. One of the most promising options seems to be the re-engineering of the cathode by modifying the Ni (and/or Li) content, which indicates not only an improvement of the cell performance but also a reduction or removal of cobalt in the cathode.[21] This is attractive considering the scarcity of the global cobalt reserves and the socio-environmental concerns associated with its exploitation, which, in addition, makes it a costly material in the international market (average price of ca. US$16 per pound in 2020).[22] Even though this high-nickel approach seems promising in terms of rate capability and energy efficiency, a number of disadvantages to be tackled have been reported in the literature such as complex synthesis and conditioning processes,[10] mechanical fracture of the electrode during (de)lithiation,[11] formation of residual lithium compounds at the electrode–electrolyte interface,[12] limited electrode density,[13] and the gradual decrease in the LIBs capacity retention and safety characteristics.[14]

Many of the challenges outlined for the high-nickel approach can be faced by inserting dopants in the

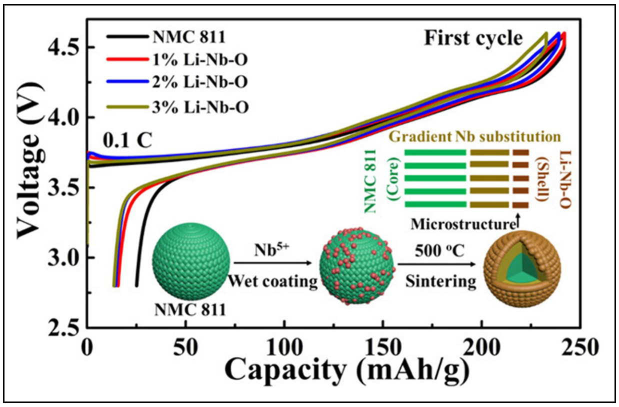

Figure 1. Performance of a LIB with a NCM 811 cathode having a Li-Nb-O coating/substitution.
Reproduced with permission Xin et al.[24]

cathode microstructure, with aluminum and manganese being some of the most promising elements.[10] The incorporation of Al/Mn intends to enhance the thermal stability of the electrode by side-stepping multi-step reaction processes, increases the reaction kinetics, and decreases the surface residual lithium compounds. However, certain disadvantages are still present, namely particle cracking and transition metal dissolution as well as the formation of dendrites. The usage of surface coatings may help to overcome the structural instability and high surface reactivity of Ni-based layered cathodes, as well as improve the material conductivity.[23] Electrochemical tests conducted by Xin et al.[24] resulted in a 45% reduction of the first cycle capacity loss in LIBs using $Li[Ni_{0.8}Co_{0.1}Mn_{0.1}]O_2$ (NCM 811) cathodes through the incorporation of Nb^{5+} into the electrode bulk structure in addition to a protective Li-Nb-O surface coating. Figure 1 shows the results obtained by these authors and an schematic of the modified cathode material. Similarly, a Li_2SiO_3 coating for the $Li[Ni_{0.90}Co_{0.05}Mn_{0.05}]O_2$ (NCM90) cathode has been considered, which increased the capacity retention of the electrode to 88.2% after 100 cycles in comparison to the 79.4% capacity reported for the bare NCM90 cathode. Additionally, the Li_2SiO_3-coated NCM90 electrode experienced a decrease in the voltage decay as well as greater rate performance and cycle stability than the uncoated material. The notably improved electrochemical performance of the high-nickel cathode was a result of the strong interaction between the NCM material and the Li_2SiO_3 coating.[25]

In the case of NCA cathodes, such as these utilized in the LIB stacks of the Tesla Model 3 which contain less than 50 g of cobalt, the removal of this metal increases the degree of Li/Ni off-stoichiometry resulting in a large compression of the transition metal layer that destabilizes the Ni^{2+} cations required to charge-compensate the excess Ni in the Li layer.[26] Therefore, as for NCM cathodes, the insertion of dopants in the NCA electrode microstructure and the use of protective coatings starts to be studied to enhance its performance. Ryu et al. proposed the incorporation of boron in the structure of Ni-rich NCA cathodes, which resulted in superior cycling stability with an 83% of the initial capacity preserved after 1000 cycles compared to only 49% of the initial capacity demonstrated for non-doped electrodes.[27] Correspondingly, a $LiAlO_2$-Al_2O_3 coating was tested on NCA cathodes operating under long-term stability conditions obtaining a capacity retention of ca. 89% after 100 cycles, while the bare NCA cathode only retained approximately 74% of the initial capacity.[28]

Regarding LIBs anodes, they are commonly made of graphitic carbon due to its low cost, stability, and cyclability, although graphite electrodes suffer from low-rate capabilities, dendrite formation due to overcharging, and limited theoretical specific capacity (ca. 372 $mAh{\cdot}g^{-1}$).[29] Different strategies have been employed to overcome these drawbacks, such as mild oxidation of graphite, the fabrication of composites with metal oxides, coatings with polymeric materials, and the use of alternative carbon structures. In the last decades, non-lithium-based anode materials have gained growing interest as substitutes for carbon-based electrodes, with silicon and tin as the most promising alternatives. Silicon-based anodes present a high theoretical specific capacity (4200 $mAh{\cdot}g^{-1}$), low cost and low toxicity.[30] One of the major concerns of using silicon in LIB anodes is the shrinkage associated with the lithium ions release, which considerably reduces its capacity. To solve this issue, several studies have reported the synthesis of nanostructured materials to reduce the stress on the structure during the charge-discharge process. Kim et al.[31] fabricated a three-dimensional silicon structure which exhibited a charging capacity of 2800 mAh g^{-1} over 100 cycles. In addition, silicon nanotubes have shown a great capacity retention (89%) after 200 cycles with a high reversible charge capacity of approximately 3200 $mAh{\cdot}g^{-1}$.[32] Sn-based anodes present a theoretical specific capacity of 993 $mAh{\cdot}g^{-1}$, high packing density, and safe working voltage.[29] Their practical use is limited by the high volume expansion (approximately 260%) experienced during the (de)lithiation process, along with a high surface reactivity with the electrolyte.[33] Issues associated with volumetric expansion can be reduced by decreasing the particle size of the anode materials and synthesizing alloys containing transition metals, which act as a matrix to accommodate the volume change during intercalation. Recently, Zhou et al. synthesized a Sn-based metal-organic framework (MOF) amalgamating with Si nanoclusters, which delivered a capacity of 1100 $mAh{\cdot}g^{-1}$ at 100 $mA{\cdot}g^{1}$ after 130 cycles with a high-rate capability.[34]

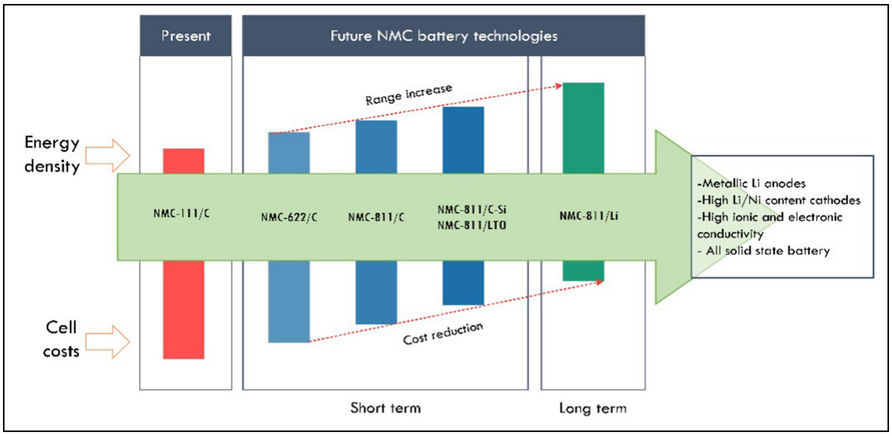

Figure 2. Future trends of electrode materials for LIBs
Adopted from Divakaran et al.[30] and reproduced with permission Divakaran et al.[30]

Finally, it is worth to summarize some recent advances regarding the stable operation of lithium metal anodes, which are centered in electrolyte and interface engineering, due to their ability to decrease the weight of LIBs and thus increase their capacity. Zhiao et al.[35] proposed electrolytes based on fluorinated 1,4-dimethoxylbutane as solvent and lithium bis(-fluorosulfonyl)imide (FDMB), which present excellent compatibility with both lithium metal anodes and conventional cathodes (NCM) and allow for the fabrication of batteries that retain 90% of their capacity up to 420 cycles at high coulombic efficiency (99.52%) and cell voltage (6 V). Yuan et al.[36] developed "spansules" made of $NaMg(Mn)F_3/C$ core-shell microstructures, which acted as a matrix for the lithium metal anode offering a long-lasting release of functional ions into the electrolyte that, in addition, formed a LiF bilayer at the electrode–electrolyte interface which suppress the growth of lithium dendrites.

Figure 2 summarizes the trends in electrode materials for LIBs suitable for long-range EVs applications, highlighting important research aspects such as energy density and cell costs. The optimization of these parameters does not only depend on the cell materials but also in aspects such as ionic and electronic conductivity, stacks design, and connections, which must be studied as well.

Lubrication and additives

As EVs are further commercialized in a world striving toward renewable and clean energy, compatible lubricants must also be developed to keep up with the constantly evolving mechanical parts and batteries. As displayed in Figure 3, lubricants must be evaluated along their efficacy with various EV and HEV parts, including the suspension system, wheel bearings, and AC unit.

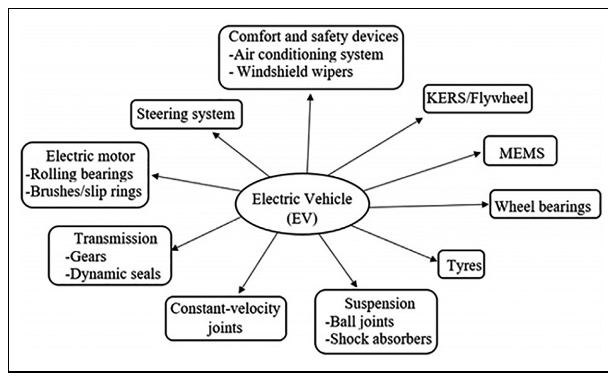

Figure 3. Components of EVs relevant to lubrication.
Reproduced with permission Farfan-Cabrera.[37]

The lubrication of the transmission and electric motor of EVs provides the greatest opportunity to reduce the energy required to overcome friction losses, which can be upwards of 57% of the total electric energy according to Holmberg et al.[15] Lubrication requirements and techniques for EVs considerably vary from ICE vehicles, since the conditions are fairly different. The electric parts and high temperatures present in EVs due to battery and electric motor operation prompts the need for novel EV lubrication. For instance, lubricants in contact with the electric motor, such as the electrical windings in the stator, must possess low electric conductivity to prevent a short-circuit.[39] Cu corrosion and the lubricants interaction with elastomers/polymers commonly found in EV batteries are also vital criteria. According to Yan et al.[38] "proper lubrication at above 25,000 rpm speeds will be important for friction and wear protection of seals, bearings, and gears." The driving range represents the paramount priority of modern EV research, which is mostly enhanced through battery efficiency and capacity. Therefore, novel greases must be developed alongside battery parts, such as surface coatings or cathode/anode materials, in order to avoid unwanted reactions and battery/lubricant degradation.[38] In this sense, tribological, electrochemical, and thermal properties of a lubricant must be studied extensively to determine greases with improved functionalities.

The base oil of EV lubricants must consist of strong molecular bonds as well as offer stable viscosity at varying temperatures, high specific heat capacity, thermal conductivity, and exceptional cooling performance. Aspects, which are not sufficiently fulfilled by the properties of the base oil, will be accounted for through the use of various additives. Early efforts in 2013 toward identifying prospective HEV lubricants centered around the utilization of dispersant/detergent additives. Low electrical conductivity, Cu reactivity, and property stability were primarily focused to prevent short circuits, rusting, or lubricant degradation. Tang et al.[39] analyzed the effect on base mineral oils of calcium detergents and dispersant additives produced from the reaction between a hydrocarbyl-dicarboxylic acid or anhydride and polyamine along electrical conductivity and anti-rust parameters. An optimal transmission fluid, HEVTF, was designed with a mineral oil base, which was characterized by low viscosity, exceptional anti-wear and pressure performance, low electrical conductivity (1700 pS/m), and satisfactory copper/rust protection. Importantly, these properties demonstrated far greater resiliency as compared to traditional lubricants upon varying temperature and aging.[39] The interaction of dispersants with other additives must be analyzed to prevent degradation of lubricant properties. Zhang et al.[40] studied the chemical interactions between bis-succinimide dispersant and borated bis-succinimide dispersant with four anti-wear and extreme pressure additives utilizing X-ray absorption near edge structure spectroscopy. The extreme-pressure additives were less reactive and led to fewer dispersion losses than the anti-wear additives. The addition of dispersants and metal detergents laid the fundamental framework in the alteration of conventional lubricants and greases for EV lubrication.

A consideration of both advanced thermal management systems and cooling fluids with improved thermal cooling properties enabled enhancements regarding the resulting energy efficiency of the power electronics, battery, and electric motor in EVs.[41] Regarding the cooling fluids, Pettersson[42] emphasized that properties such as thermal conductivity and heat capacity of lubricants are primarily determined by the molecular structure of the base oil. As such, early efforts in enhancing the thermal properties of lubricants were based on synthetic oils, such as polyalphaolefin (PAO), which offered good thermal cooling properties. However, advances regarding the technology of EVs induced an increase in the operating temperatures of the power electronics, electric motor, and battery. Consequently, the usage of additives is necessary to counterbalance these changes thus allowing for an enhanced thermal conductivity and stability. For instance, an earlier work by Yang et al.[43] evaluated the tribological properties of triazine derivatives to be used as additives in PAO. The anti-wear and extreme pressure properties of the triazine derivatives were exceptional, and the additives only began decomposing at temperatures above 200°C.[43] These promising results were directly applicable to the demanding conditions in EVs.

Bio-lubricants have also witnessed a steadily rising research focus in the hopes to develop better lubricants with characteristic biodegradability and renewability. However, the application of bio-lubricants is challenging due to the structural nature of triglycerides, or vegetable oils, which leads to a low thermal stability and a poor low temperature lubrication.[44] Despite these hurdles, continued research efforts have been made to synergize bio-lubricants with certain additives. Reeves et al.[45] compared the friction and wear properties of base fatty acids in various oils, including avocado, rapeseed, and vegetable (soybean) oils. They discovered that oxidative stability and fluid viscosity heavily varied on the fatty acid differences between the tested natural oils.[45] Recent research focusing on the advancement of bio-lubricant properties is centered around the utilization of nano-additives.[46]

More recent fluid engineering efforts employ the utilization of nano-materials, including TiO_2 and CuO,[47] which withhold promising advantages toward manipulating the characteristics of standard base oils. According to Rajaganapathy et al.,[16] the coefficient of friction (COF) was greatly reduced by the addition of 0.5 wt.% CuO to palm oil. Ali et al.[48] analyzed the frictional performance of copper/graphene additives in automobile engines. This study achieved similar results with COF reduction up to 32.6% for the Cu/graphene nano-lubricants. Evidently, a variety of nano-additives can improve the tribological performance of standard ICE lubricants, which can be translated for use in the field of EVs. Similar results are obtained when measuring the impact on thermal stability and conductivity. Sridhara and Satapathy[49] confirmed that the thermal properties of oils can be directly enhanced as the number of solid suspended particles increases since these nano-materials are far greater heat conductors than fluids. Choi et al.[50] particularly measured the effect of adding suspended carbon nanotubes and discovered a 160% increase in the thermal conductivity of PAO.

The prominent challenge in utilizing these nano-additives is the sufficient suspension and stability of the solids within the medium. Nonetheless, proper selection

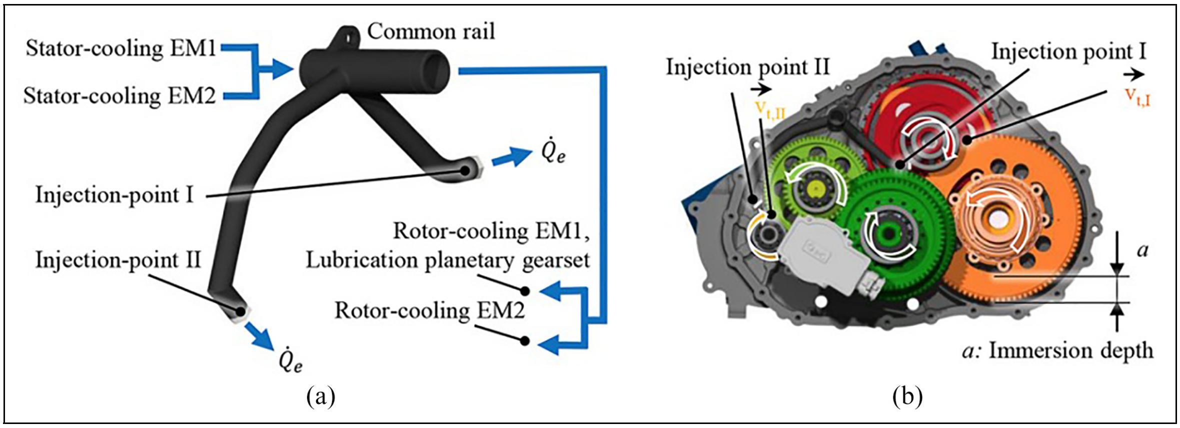

Figure 4. Oil distribution after 0.3 s for (a) B1 (Injection and No Dip), (b) B2 (Injection and Dip, $a = 20$ mm), and, (c) B3 (Injection and Dip, $a = 40$ mm).
Reproduced with permission Morhard et al.[56]

of nano-particles/nano-sheets, and extensive evaluation of particle concentration, size distribution, and zeta potential offer vital tools toward stability.[51] Recently, the advent of multi-wall carbon nanotubes (MW-CNT) and graphene have gained traction. Ahammed et al.[52] studied the changes in viscosity and surface tension of a graphene-water nanofluid as a function of volume concentration (0.05%, 0.1%, and 0.15%) and temperature (10°C–90°C). They discovered that the volume concentration of graphene was a major determining factor in viscosity and surface tension as compared to the smaller effect of temperature. A rising research focus has further extended the application of hybrid nanofluids, which synergize multiple nano-additives with proper dispersion and stability.[53] Moradi et al.[54] measured the change in thermal conductivity of TiO_2-MWCNT/ethylene glycol (EG)-water hybrid nano-fluids as a result of varying temperature (20°C–60°C) and volume concentration (0.0625%, 0.125%, 0.25%, 0.5%, 0.75%, and 1%). This study found that the thermal conductivity increased with the increase of both temperature and volume concentration, which has been shown as a general trend for hybrid nanofluids.[53] Namely, the largest increase of the thermal conductivity was 34.3% at a temperature of 60°C and a concentration of 1 vol.%. However, the direct application of these additives in the field of EVs remains hesitant, as for instance, the addition of carbon nanotubes in greases also bolsters electrical conductivity.[55] As a consequence, a set of different nano-additives, which adhere to high thermal cooling, low electrical conductivity, exceptional lubrication, and low Cu reactivity, must be further developed.

Improved oil distribution involving electromechanical powertrain engine

A joint research project involving seven industrial and five university partners, termed Speed4e, currently develops and researches an electromechanical powertrain engine with speeds upwards of 30,000 rpm for a test vehicle and 50,000 rpm for a test-rig. This study conducted by Morhard et al.[56] focused on the lubrication techniques, namely injection, dip, and hybrid lubrication, as well as their respective oil distribution and power loss. The injection technique is for high-speed bearings of circumferential speeds up to $250\,m \cdot s^{-1}$, which require direct lubrication only, as injection to all bearings is not preferable due to "high constructive effort and pump power needed."[56] Contrarily, dip lubrication is most reasonably utilized at circumferential speeds $< 20\,m \cdot s^{-1}$, whereby oil distribution is believed to scale exceptionally with immersion depth.[56] Another promising method of application not thoroughly explored by the study is spray lubrication. According to Liu et al.,[57] spray lubrication is characterized by an increased gearbox efficiency than dip lubrication. This increased efficiency may also be applicable as a hybrid technique with injection lubrication concerning the powertrain engine. Nonetheless, computational fluid dynamics approaches, such as the particle-based smooth particle hydrodynamics (SPH) outlined by Kurth et al.,[58] was utilized to simulate the resulting oil distribution.

The Speed4e powertrain consists of a holistic thermal management and lubrication structure (Figure 4(a)), which simultaneously coats the gears during stator-cooling for electric-machines 1 and 2 (EM1 and EM2). Morhard et al.[56] utilized a water-containing polyalkylene glycol lubricant, which was injected at Injection Point I and II (Figure 4(b)) at volume flow rates of Q_e during simulation. Additionally, power loss calculations and oil distribution simulations were conducted over a series of three performance classes split into two groups, A and B. Group A had lower gear speeds, where the sun gear speed was 10,000 rpm and the oil injection speed was $0.13\,m \cdot s^{-1}$. Group B had

Table 1. Total power loss, no-load gear power loss, and efficiency calculations for various performances.

Operating point	A1	A2	A3	B1	B2	B3
Total power loss P_L	0.23 kW	0.26 kW	0.3 kW	5.04 kW	5.18 kW	5.63 kW
No-load gear power loss P_{LG0}	0.02 kW	0.04 kW	0.09 kW	0.48 kW	0.62 kW	1.1 kW
Efficiency η	94.2%	93.6%	92.5%	97.5%	97.4%	97.2%

Reproduced with the permission Morhard et al.[56]

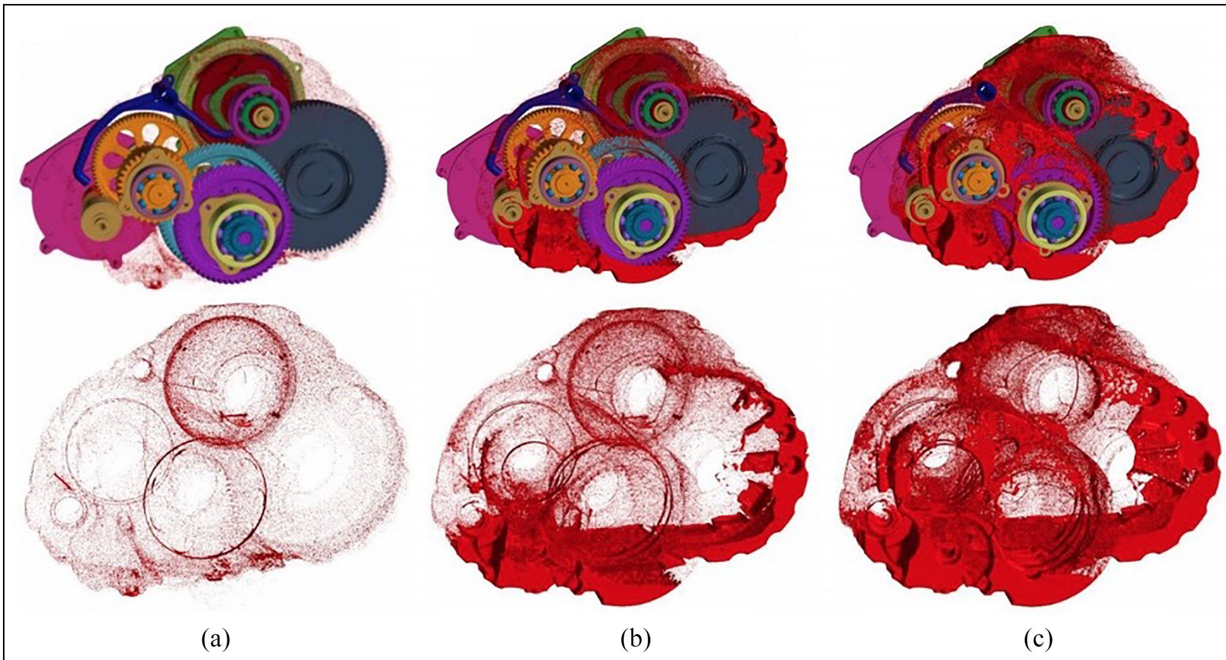

Figure 5. Oil distribution after 0.3 s for (a) B1 (Injection and No Dip), (b) B2 (Injection and Dip, $a = 20$ mm), and, (c) B3 (Injection and Dip, $a = 40$ mm).
Reproduced with permission Morhard et al.[56]

higher speeds, with a sun gear speed of 30,000 rpm and an oil injection speed of 6.70 m·s^{-1}. In each group, the simulation consisted of three different techniques: injection with no dip lubrication (A/B 1), hybrid lubrication (Injection and Dip) with an immersion depth, $a = 20$ mm (A/B 2), and hybrid lubrication with an immersion depth, $a = 40$ mm (A/B 3).

In order to determine the optimal technique of lubrication, both the oil distribution and the power loss for each method must be considered. Table 1 summarizes the calculated values of P_L, total power loss, P_{LG0}, or the No-Load gear power loss, and η, the efficiency. Clearly, when comparing power losses between Groups A and B, P_L and P_{LG0} increased with greater input speeds. More importantly, the efficiency values calculated for Group A are less than those calculated in Group B and experienced a greater decline with increased immersion depth. Morhard et al.[56] concluded that No-load gear power losses have a greater effect on efficiency at lower input speeds and power. Furthermore, Table 1 displays the effect of introducing dip lubrication and increased immersion depth on efficiency. Among Groups A1–A3 and B1–B3, the greatest efficiency was calculated utilizing solely injection lubrication, as introducing dip lubrication and increasing the immersion depth decreased efficiency. Although this greater efficiency is ideal, further research is required to ensure that a sufficient oil distribution can be achieved throughout all tribological contacts using only injection lubrication.

CFD simulation results using SHP methods are depicted in Figure 5. The oil distribution is shown after 0.3 s of 30,000 rpm, which was reached in 0.15 s by applying a sinusoidal acceleration ramp with an average of 3333.3 rev·s^{-2}/it can be seen that as dip lubrication is introduced and immersion depth increases (Figure 5(b) and (c)), the oil distribution is much greater than solely injection lubrication (Figure 5(a)). This homogenous distribution is further proven quantitatively by the calculation of the relative particle coverage, $V_{\text{rel,sensor,i}}$, using virtual sensors at various gear stages, where i denotes the specific sensor. The average $V_{\text{rel,sensor,i}}$ for groups B1–3 were 1.74%, 5.18%, and 9.12%, respectively. The simulations and calculations represent that hybrid lubrication and greater immersion depth leads to a more homogenous distribution of oil.

The effect of incorporating dip lubrication and increasing immersion depth on both no-load power loss and oil distribution is a vital consideration to utilize an optimal lubrication technique. Morhard et al.[56] showed that although a greater power loss is obtained when utilizing hybrid lubrication, oil distribution is improved and covers a majority of important tribological contacts. In order to find the optimal method of lubrication, these trade-offs must be weighed against the apparent advantages. The study suggests that hybrid lubrication using an immersion depth of $a = 20\,\text{mm}$ is most effective at minimizing no-load power loss, while simultaneously increasing lubricant distribution for the Speed4e electromechanical powertrain. This technical analysis of lubrication methods serves as an example in optimizing the electric motor performance of EV engines, and further reaching prospective goals.

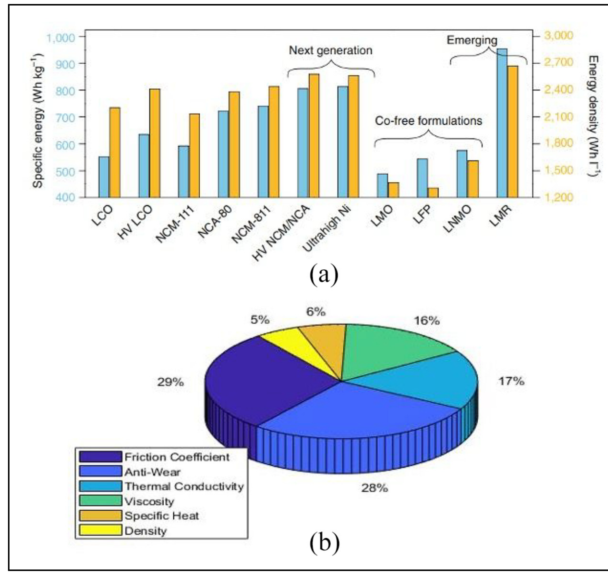

Figure 6. (a) Specific energy and density of standard, next generation, and emerging LIB cathodes: $LiCoO_2$ (LCO) High Voltage (HV) LCO, NCM-xyz ($Li[Ni_xCo_yMn_z]O_2$), NCA ($Li[Ni_{1-x-y}Co_xAl_y]O_2$), Ultrahigh Ni, LMO ($LiMn_2O_4$), LFP ($LiFePO_4$), LNMO ($LiNi_{0.5}Mn_{1.5}O_4$), LMR ($Li_{1+n}Mn_{1-n}O_2$) (Reproduced with permission from Li et al.[10]). (b) Proportion of nano-additives enhancing respective lubricant properties (Adopted and reproduced with permission from Kotia et al.[61]).

Prospective outlooks

The world begins to dawn on a new age of clean transportation and energy, as greater concern is placed on the environmental effects of fossil fuels withhold. A gradual shift toward this new age of green energy occurs as renewable energy sources, including wind and solar energy, continue to rise in usage. A key sign of this developing "green conscience" is the exponential commercialization of HEVs, PHEVs, and BEVs in the past couple of years, which has now reached 2.3 million sales in 2020.

As green energy and the commercialization of EVs continue to grow in the future, battery and lubrication technologies must be developed alongside. Figure 6(a) represents a set of standard, next generation, emerging, and Co-free cathodes for LIBs. High-nickel cathodes appear as promising materials for future LIBs, although further research must be conducted on the complete elimination of cobalt to produce cobalt-free batteries. The absence of cobalt assures a decrease in both mass and cost, as well as improved LIBs performance and energy output. The emerging cathodes, LMNO and LMR, are not expected to enter the EV industry until the late 2020s. This is due to a number of research challenges in terms of unstable surface chemistry and metal dissolution, as well as the lack of key developments in electrolyte and separator technologies.[10] Nonetheless, prospective utilization of these cathodes remains promising, as recent research have demonstrated the benefits of Fe doping for LNMO[59] and PVP ($(C_6H_9NO)_n$) molecule bridging/coating for stability and cycle enhancements.[60]

The last few decades have witnessed a noticeable shift toward the determination of optimal additives, especially nano-additives. Figure 6(b) depicts the proportion of nano-additives, which enhance numerous lubricant properties including COF, anti-wear, thermal conductivity, viscosity, specific heat capacity, and density. Modern additive research aims to fix the problems of instability and lack of sufficient dispersion. Lubrication of EVs will hinge primarily on the electrochemical and thermal properties of greases, which have not been sufficiently explored during use in ICEVs. Although the structure of greases remains fundamentally intact, whereby a lubricant is composed of the BO and additives, characterization focused on desirable properties, such as viscosity index, electrical and thermal conductivity, and specific heat capacity, is the main focus of tribology in the EV industry. The likewise growing field of nanotechnology will surely give rise to vital additives for EV lubricants, TiO_2, and MoS_2 already being promising prospects.

A combination of optimal surface coating materials, battery compositions, and electrolyte salts will be the future focus of the EV industry as the industry begins to age. Additional technologies, including battery cooling systems and dynamic wireless power transfer, will also begin to obtain an increased focus as sufficient batteries begin to arise from development.

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