Performance Characterization of Automotive Lubricant Used in Electrical Vehicles and Hybrid Electrical Vehicles

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Abstract

Global automotive industries have recently switched their developments trends from powertrain mechanical components into digital electrification components in advanced propulsion vehicles thus creating an innovative technology for propulsion systems such as electric vehicles (EVs) and hybrid electric vehicles (HEVs) [1]. These advanced propulsion systems have significantly improved vehicle fuel efficiency thus minimizing pollution emissions from transportation vehicles. Many EVs and HEVs still have automotive lubricants, such as drivetrain fluids or coolants, which have been integrated with electrification components operating in a wide temperature range and under various operating conditions.

This article aims at summarizing the state-of- the art and future trends in electrification and the required lubricants for advanced Hybrid/EV vehicles. Moreover, different failures modes caused by the electromagnetic and electrostatic effects are addressed. To further understand these phenomena, shaft voltages (the main source of electrical failures) must be studied and evaluated upon. In this paper, the main causes of shaft voltages are divided into 3 parts: the magnetic flux asymmetry, electrostatic effects, and inverter-induced voltage effects.

In an EV/hybrid systems, the automotive driveline fluid or coolant is not in contact with the e-motor, but it still needs to maintain all the traditional driveline fluid properties such as aeration, oxidation, frictional properties and gear/bearing pump wear durability. In order to meet these new requirements for electrification components in hybrid vehicles, fluid formulations must be carefully balanced with the need to optimize driveline performance and protection, particularly in a lower viscosity environment, all of which introduces new requirements for the driveline fluid or coolants considerations for these applications.

The authors have reviewed all current bench tests developed for characterization of electrical and thermal heat transfer properties for automotive lubricants or coolants used in EVs and HEVs. Among those bench tests, several ASTM Test Standard Tests for lubricant properties have been reviewed including the following basic lubricant properties: viscosity, density, thermal conductivity, electrical conductivity**,** and heat capacity / specific heat. All bench test methods have been summarized in this review paper. In addition, the other industrial standard tests for evaluation of tribological properties of automotive lubricants will be described to supplement their required performance characterization.

At the end of this paper the authors provide an overview of relative compatibility between various interface materials and the required coolant options. The polymer or metal materials interfaced with cooling fluids under the extreme operating conditions must be managing carefully to assess fluid and material interactions at specific temperatures, pressures, and other environmental conditions. Those fluid-material compatibility studies in this review paper can definitely provide helpful solution that is optimized for your requirements in EV/Hybrid thermal management systems.

Introduction

On a global scale, gas emissions originating from automotive and transportation industry continuously rise, which creates an enormous impact on global warming and climate changes. Responding this global impact on mitigation of climate changes for reducing greenhouse emission, electrical vehicles (EVs), and hybrid electrical vehicles (HEVs) have been developed and manufactured along with advancements in electric, thermal, and lubrication systems for electrification components [1]. New developments in the electrified vehicles have been made to decrease CO_2 emissions and increase the overall energy efficiency. These advanced propulsion systems have significantly improved vehicle fuel efficiency thus minimizing pollution emissions from transportation vehicles. Many EVs and HEVs still have automotive lubricants, such as drivetrain fluids or coolants, which have been integrated with electrification components operating in a wide temperature range and under various operating conditions. Advanced automotive lubricants used for those electrification components have led to the addition of thermal and electrical components along with conventional lubricant properties [1]. These electrification components require for higher energy efficiency and extended durability. Recent automotive and energy industry R&D activities have been focused on minimizing frictional loss and maximizing components' durability.

In hybrid systems, the automotive driveline fluid is not in contact with the e-motor, but it still needs to maintain all the traditional driveline fluid properties such as aeration, oxidation, frictional properties, and gear/bearing pump wear durability. However, in HEVs that contain an oil cooled motor, new fluids must focus on motor cooling, materials compatibility, and electrical properties. To meet these new requirements for electrification components in HEVs, fluid formulations must be carefully balanced with the need to optimize driveline performance and protection, which introduces new requirements for driveline fluids or thermal coolants.

In this regard, all current bench tests developed for the characterization of electrical and thermal heat transfer properties for automotive lubricants or coolants used in EVs and HEVs have been reviewed. Among those bench tests, several ASTM Test Standard Tests for lubricant properties are capable to evaluate the following basic lubricant properties: viscosity, density, thermal conductivity, electrical conductivity**,** and heat capacity / specific heat. Additionally, the other industrial standard tests for evaluation of tribological properties of automotive lubricants will be described to supplement their performance characterization.

Additionally, new developments and technologies in thermal management fluids have been reviewed [3]. Those thermal management fluids or coolants have been applied to promote high efficiency cooling systems for driveline motors, power electronics, and electric batteries. Finally, the advanced thermal cooling fluids have been demonstrated to create high potential applications in EVs and HEVs compared with the traditional coolants used in the IC engine vehicles in this paper. The driving range, thermal stability, and durability can be extended with the high-performance cooling system designs and applications of thermal management fluids.

The growth of many sophisticated automotive technologies is encumbered by the demand for thermal cooling of electrical components. This review paper will highlight the high-tech thermal management technology in electric and hybrid vehicles, using novel nanofluids for thermal cooling. A nanofluid is a novel grade of thermal cooling liquids created by the dispersion of solid particles between 20 and 60 nm in size in traditional water- or oil-based fluid that is used as a coolant for heat transfer equipment such as heat exchangers, flat plates (for EVs and HEVs only), and (or) radiators [3]. The nano particles have a larger surface area and help to enhance the thermal cooling properties of the fluid. In addition, the suspended nanoparticles remarkably improve the thermal cooling process and the nanofluid has a significantly higher heat conductivity and heat transfer coefficient than conventional/outdated coolants used in traditional automotive cooling systems [4].

The major goal of this paper is to underline the future electrification development trends and the required lubricants for advanced Hybrid/EV vehicles [2]. In this review paper, the authors have described several failures modes caused by the electromagnetic and electrostatic effects. To further understand these phenomena, shaft voltages (the main source of electrical failures) must be studied and evaluated upon. In this paper, the main causes of shaft voltages are divided into 3 parts: the magnetic flux asymmetry, electrostatic effects, and inverter-induced voltage effects. At the end of this paper the authors provide an overview of relative compatibility between various interface materials and coolant options. The polymer or metal materials interfaced with cooling fluids under the extreme operating conditions must be managing carefully to assess fluid and material interactions at specific temperatures, pressures, and other environmental conditions. Those fluid-material compatibility studies in this review paper can definitely provide helpful solution that is optimized for your requirements in thermal management systems.

1. Failure Modes For EVs and HEVs due to Shaft Voltages and Bearing Currents

Different failures modes caused by electromagnetic and electrostatic effects will be distinguished. To further understand these aspects, shaft voltages (the main source of electrical failures) must be evaluated carefully. Therefore, the main causes of shaft voltages are divided into the magnetic flux asymmetry, electrostatic effects, and inverter-induced voltage effects.

1.1.1 Magnetic Flux Asymmetry

Magnetic asymmetry is a result of the changes of magnetic pole distribution which arise during designing, manufacturing, or installing, as shown in Figure 1 (a). The reasons include asymmetrical windings, rotor eccentricities, casting defects, and uneven permeability, among others [5-9]. Consequently, the flux present within the motor deviates from the standard symmetrical state as demonstrated in Figure 1 (b). The shaft thereafter forms a voltage during rotation due to unbalanced flux and cuts the magnetic induction line (Figure 1 (c)). Although the unbalanced flux may only induce sine waves with minimal frequencies [9], the implications on conducting paths and fluid behavior around the motor is of concern. The introduction of an electric field, as explained in the subsequent section, results in numerous changes in fluid properties and can incur drastic damage to vulnerable machinery parts, especially bearing balls. This can be avoided through insulation of certain ball bearings, and improvement of fluid properties in the presence of an external electric field, currents, or variable voltage sources [9, 10].

1.1.2 Triboelectric effects

The triboelectric effect causes an electrostatic charge to build up due to the gain or loss of an electron. During this reaction, one object gains electrons, while the other object loses electrons [11]. Electric motor engines, the source of tribological charges in electric vehicles, exert triboelectric forces on each other, which lead to charges accumulating and remaining for a while allowing for longer battery life [11]. A reduction in the overall weight of electric motors allows for less risk of excess charges accumulating on the electric motor engine and allows for a more stable engine. However, traditional EVs fail to balance the problem of accumulating charges on the electric motor with the triboelectric effect. Standard materials utilized for the vehicle body, cooling systems, and insulation such as carbon fiber reinforced plastics, thermal insulating polymers are also considerably dielectric materials. As a result, the accumulation of charge, and thus voltage, on these materials will continue until the electric field overcomes the dielectric breakdown of the air or fluid separating the surfaces. Thereafter, the surfaces will serve and act as a capacitor, and a burst of charge will occur leading to the formation of stray currents [9, 12, 13] (Figure 1(d)).

1.1.3 Inverter-Induced Voltage Effects

In modern EVs, the pulse-width-modulation inverters with fast switching devices are commonly used in electric motors to achieve variable speed control [9]. Many problems can arise related to medium-voltage drive machinery which involves either the front-end grid or inverter technology [14]. Most notably is the presence of high switching frequencies present in the semiconductor devices in power electronic converters which is referred to as "dv/dt". An excessive rate of voltage change can lead to numerous inverter-induced voltage effects including common-mode (CM) voltages and currents, electromagnetic interference, shaft voltages, and bearing currents [15]. Figure 1 (e) depicts a three-phase induction motor driven by an adjustable speed drive that contains a three-phase inverter. If the voltage output from the inverter is a symmetrical sinusoidal signal, the CMV remains at zero (Figure 1 (f)) [9]. Contrarily, if asymmetrical pulse waveforms are utilized as a substitute for these ideal sinusoidal waves, then CM voltages and currents will be induced (Figure 1 (g)) [9]. Extending this phenomenon, Figure 1 (g) represents the CM effects of an unbalanced inverter or converter, whereby capacitive and magnetic coupling result in CM voltage waveforms [9]. A balance must be established in tuning the rate of voltage change (dv/dt) as to optimize inverter-induced voltage effects on lifting efficiency while also minimizing the amplitude of distortion which produced the unwanted CM voltage and current effects [9]. High amplitudes and frequency shaft voltages can be devastating for various machinery surface components and electrically susceptible fluids. Steps must be taken towards mitigating such stray external electrical effects through insulation efforts while simultaneously making EV components and fluids more compatible with these unexpected disturbances.

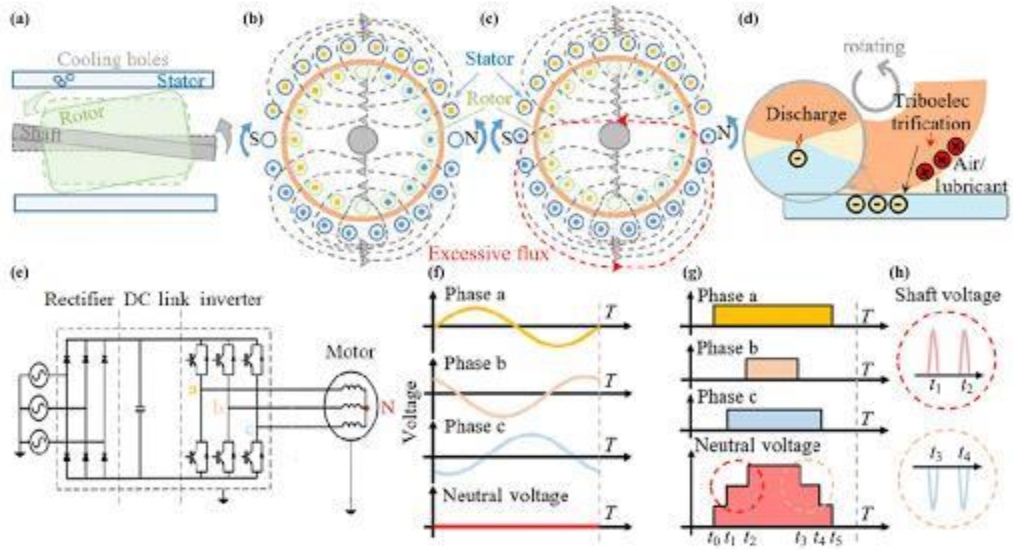

Figure 1: (a) the asymmetry of stator, rotor, and shaft upon operation, (b) standard induction motor, (c) induction motor with unbalanced flux present, (d) discharge induced by triboelectrification, (e) a circuit configuration of an induction motor driven by typical adjustable speed drive [14], (f) symmetrical three-phase sinusoidal wave forms, (g) pulse-width modulation forms of three-phase signals, (h) shaft voltages produced by magnetic and capacitive coupling at steps of CM voltage waveforms [9].

1.2 Bearing Currents

Clearly, numerous failure modes in EVs results in the production of bearing currents so it is thus vital in characterizing the precise impact such currents have on ball bearing performance. One type of bearing current is the "non-circulating" bearing current which moves unidirectionally from the rotor to the stator [9, 13]. On the other hand, currents produced from high dv/dt effects are conductive and capacitive, which primarily depends on engine conditions such as speed. However, these dv/dt-related currents are often minimal in magnitude and thus present little effect in bearing performance [9,13]. Electric discharge machining (EDM) breaking currents occur when the bearing voltage exceeds the threshold of an insulating lubricant film, and as the interfaces act as a capacitor a surge of arcing and destructive current. Contrarily, "circulating" currents are complex and are most commonly produced by magnetic flux asymmetry and changing shaft speed frequencies [9]. During operation, circulating current is also induced upon penetration of the thin oil film in ball bearings by stator shaft voltages. It is also important to note that the grounding properties of different components leads to different current paths and amplitudes [9, 19]. Thus, much research has been conducted to model the bearing currents under different electric parameters [19, 20].

It is therefore important to accurately characterize various lubricant properties which determine this maximum threshold value causing insulation of bearings. In actual working conditions, the lubricant film thickness is affected by speed, load, and lubricant viscosity. Lubricant kinematic viscosity is of primary importance in the selection of a wide range of petroleum products and is generally calibrated capillary viscometers. The kinematic viscosity bath developed by Koehler Instruments Co. (Figure 2) is an instrument that measures the kinematic viscosity in lubricants, fuels, and dissolved plastics in a flexible and versatile manner. This instrument can measure kinematic viscosity in Newtonian fluids like lubricants, fuels, or dissolved plastics and since there is currently no other viscometry meter that has this function, Koehler Instruments claims that “it is the next generation of completely automatic viscometry systems” [14].

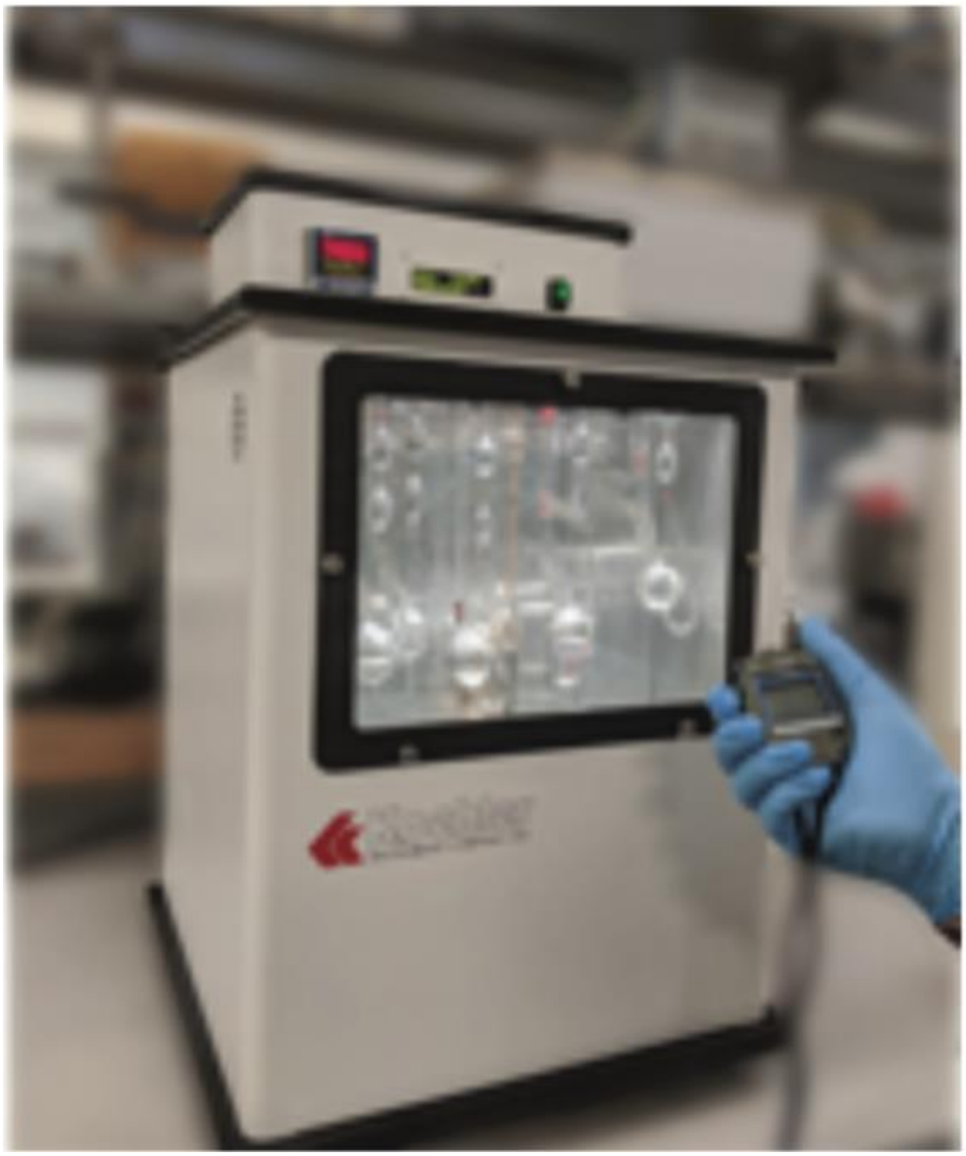

Figure 2: Kinematic viscosity bath developed by Koehler Instruments Co.

1.3 Electrical Bearing Failures

Under complicated environments with high speeds pressure and presence of electric fields, bearing failures occur on all contact/sliding surfaces of components, while bearings are the most vulnerable. The traditional bearing failures can be grouped into three categories: fatigue spalling, fretting, and corrosion. In addition to these failure modes, the presence of shaft voltages and bearing currents can cause new failures, which can be classified into morphological damages and the lubricant degradation [9].

Similar to internal combustion engines (ICEs), the powertrain of EVs and HEVs demands different performance characteristics and unique physical properties of lubricants [21, 22, 23, 24]. One of the most important requirements for these lubricants is their low impedance property. Both EVs and HEVs are operated by battery packs that output a single DC voltage. In their fundamental design, an inverter rapidly switches the voltage input to the motor [23, 24]. The pulse-modulated input cannot be fully controlled by the electric motor. This input can generate additional current leaks from the rotor of the motor to the ground. This additional current can run across the tribo-pairs supporting the rotor and into the surrounding environment. Besides that, these tribo-pairs can function as a capacitor when the lubricant impedance is high. Dependent on the breakdown voltage of the lubricant film between the tribo-pairs, a large current surge can occur between the surfaces. Without proper control of this current surge, it can cause both electric interference and mechanical damage to electric vehicles.

Besides the dielectric breakdown of the lubricant, this bearing current can cause electronic magnetic interference to the adjacent components [23, 24]. It can also cause destructive damage or wear to bearings and transmission. This wear damage is induced by EDM or tribo-corrosion process [19 - 24]. The EDM damage can cause diverse types of wear that depend on the bearing type and the respective lubricant properties, which can be classified according to their morphological damage into electric “pitting,” “fluting,” and “frosting” indicated damages caused by many electric discharges.

1.3.1 Morphological damages

Morphological damages due to shaft voltages and bearing currents can be categorized into frosting, fluting, pitting spark tracks, and welding. Frosting originates from small but dense discharges. Frosting surfaces can be microscopically due to the appearance of small craters each indicating a melting effect when EDM occurs. Meanwhile, the surface area-to-volume ratio increases, enhancing the subsequent chemical corrosion. Pitting damage is characterized by larger craters since the discharge or current is more intense and lasts longer. Komatsuzaki et. al reported that the key factor to the electrical pitting process was bearing current instead of shaft voltage, proving that a current of 90mA potentially enhanced pitting [22]. Fluting is a critical stage in bearing tests, a phenomenon in which the contact surface partially melts when exposed to arcing induced by an electric current passing through a thin film of oil. Due to periodic currents, fluting is the most common damage along the circumference of the bearing raceway. It occurs across the board of dark and bright strips. Prashad et al. studied the relation between the resistance of the contact area and the damage mode. They demonstrated that low-resistance contacts caused decomposition of grease and eventually fluting while high resistance contacts induced pitting [23]. The initial stage of fluting is characterized as the formation of a plasma channel between the roller and outer raceway. Movement of electric current between the rolling elements results in conditions similar to a capacitor, whereby a voltage is able to build-up along the rolling surfaces. Upon reaching a certain voltage, discharging occurs and the melting of the surface leaves behind distinct micro-craters, which vary in size between the roller and outer raceway. The size difference was theorized to result from a barrel-shaped plasma in which the anode (roller) had a wider and shallower vapor bubble, while the outer raceway (cathode) had a narrower and deeper one. Figure 3 depicts scanning electron micrograph of microcraters, which form on corrugations marks [24]. By analyzing the wear debris, Liu et al. [24] proved that the nature of fluting was an abrasive wear caused by the vibration of the bearing currents. Combining the mechanical and electrical discharge effects can explain the presence of fluting in local areas [24]. ASparks caused by the irregular scratches due to the askew of direction of motion produces spark tracks. Although spark tracks solely look like mechanical scratches, electricity plays a key role. Spark tracks are caused by debris blasted out of the surface by electrical discharges causing the bottom of the scratch to have a sharp and melted shape, and rounded corners caused by the mechanics. Welding occurs in house splits and pads and is attributed to the thermal effect when many currents pass through a bearing. According to different working parameters, including rotation speed, bearing type and lubricant conductivity, the appearance of electric damage varies greatly.

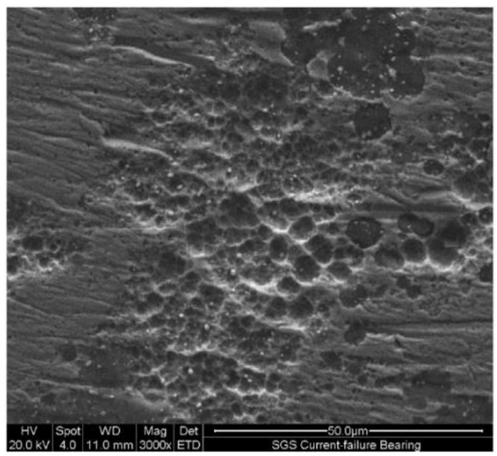

Figure 3: ESEM imaging at 3000x magnification of corrugation marks found on the surface of rolling bearings which depict microcrater formation [24].

1.3.2 Lubrication Failures

In addition to morphological damages, there are lubrication failures which have attracted a lot of attention in the past years. However, the presence of a continuously changing electrical environment within EVs or HEVs prompts the development of specialized lubricants, which minimize or directly circumvent reasons leading to lubrication failure. Improper lubrication can lead to unstable operations, increased wear and tear, thus reducing the bearing's lifetime. Generally speaking, lubrication failures in EVs occur due to degradation of lubricants, microbubble effects, and interfacial stress.

In a bearing, the lubricant should be capable of reducing friction and wear, transferring heat and maintaining component cleanliness. In a well-lubricated running bearing, the rubbing surfaces are separated by a thin lubricant film, avoiding direct contact. The higher presence of Cu and the charged environment in EVs result in greater oxidation of the lubricant leading to degradation. Specifically, the degradation process involves the unwanted formation of carboxyl compounds and other devastating products in base oils and thickeners of the lubricant, which heavily decrease lubricity, viscosity, and promotes agglomeration of nano-additives [25]. Therefore, the traditional mode of bearing failures can be improved by suitable lubrication strategies. One such strategy involves the formation of radical groups, such as a peroxide group, utilizing free radicals in the presence of excited electrons [26]. Along with this process, lubricant additives can be applied to provide a “micro-bearing” effect [24]. Greases or lubricants, however, can experience heavy thermo-oxidation degradation in conditions commonly found in EV rolling bearings which effectively alters the chemical and physical properties of the fluid. This degradation may also render nanoadditives useless, as the change in fluid properties can promote aggregation and thereafter cause severe morphological damage due to geometric inhomogeneities [26]

The generation of micro-bubbles, a huge problem for charged lubricants, was discovered for charged lubricant films using optical interference [27]. The bubble generation was found to be related to the AC electric field frequency. Additionally, the power electronics and electric motors utilized in EVs operate at much higher temperatures than conventional ICEVs. Without proper lubrication, excessive heat can cause the base oil to evaporate thus inducing microbubble formation. This process is further driven by pressure gradients, viscous drag, and dielectrophoretic forces [25]. The production and popping of micro-bubbles destabilize the lubrication, leading to additional noise and vibration in the bearing [25][28]. The process of micro-bubble generation and motion under elastohydrodynamic lubrication are exemplified in Figure 4 [29]. Importantly, the micro-bubbles tend to appear more in electrode coated insulating layers than uncoated electrodes [30]. Xie et al. provided a comprehensive model based on theoretical and experimental results for the existence of microbubbles in liquid films, which serves as an exemplary study on the characterization of bearing failure modes [30]. Similarly, electrowetting is the interfacial stress induced by an electric field on a nonpolar lubricant, and primarily alters the wetting abilities of a fluid on hydrophobic surfaces. As the electrostatic stress increases, the lubricant tends to breakdown and spread thus reducing effectiveness [21]. Xie et al. [31] further proved that nonpolar dielectric lubricants, for example in the contact area of a steel ball and a smooth metallic plate, will undergo electrospreading along the surface through thermocapillary force. In analyzing the movement of a droplet coalescence on a Cr layer surface, an “electric wind” phenomenon was used to explain the driving force of the droplet behavior as compared to dielectrophoretic and electrowetting actuation mechanisms. Subsequent studies on emulsion droplet behavior analyzed the effect of electric field intensity and droplet separation. Droplets have shown to either belong in three distinct behavior types: stable, coalescence, and partial merging [32]. In coalescing, the droplet front propagates, while partial merging results in a heterogeneous droplet front [32]. An alteration of oil film properties upon exposure to a variable voltage source and temperature was also connected to the “electric wind” phenomenon. Xie et al. [33] discovered the emergence of funnels present in the oil film upon introducing a voltage up to a critical value. Specifically, the funnels formed as a result of a momentum transfer of drifting ions induced by the electric wind. The funnel diameter increased as a variable of temperature due to an increase in oil viscosity, although less funnels appeared at higher temperatures as compared to negative ac voltages and low temperature conditions [33].

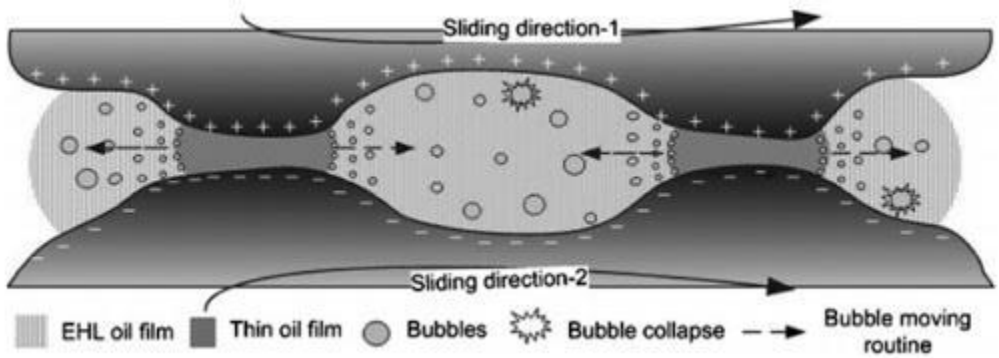

Figure 4: Schematic diagram of the microbubble generation and motion in the electrohydrodynamic lubrication (EHL) oil film under charged condition [29].

In addition to the failure modes, the shaft voltage and bearing currents have other effects. For instance, the presence of an interfacial electric field surely effects the relative performance of a lubricant. Fundamentally, the process of lubrication involves weak electrostatic interactions. In EVs or HEVs, static charges and transient polar superficial charges induced by surrounding electric fields enhance these electrostatic interactions. The overall effect of external electric fields on lubrication and wear is complex. However, it is understood that adhesive wear is dominant at low potentials, while abrasive wear is dominant at high potentials. Additionally, external electric fields have also led to unwanted structural changes and the formation of an oxidative transfer film in certain materials (i.e., graphite-graphite, graphite-copper). This change in the material's surface chemistry can remarkably decrease lubrication efficacy and increase wear [25]. Furthermore, a notable reduction in the confined liquid film was observed under an electric field [33].

2. Electrical and Thermal Heat Transfer Characteristics for Lubricants in EVs and HEVs

Automotive lubricants or cooling fluids specifically designed for EVs and HEVs should include appropriate electrical and thermal heat transfer properties to guarantee protection from corrosion and be well-suited with insulating materials [34-36]. It is important to note that the molecular structure of the base oil is the primary determinant of the thermal capacity and conductivity of a lubricant [37]. Molecular structures, in which there are multiple vibrational and rotational quantum states, require a greater input of energy to increase the average kinetic energy [38]. Additionally, the thermal conductivity can also be related to the molecular diffusivity in a fluid [39]. The viscosity is a fundamental physical parameter, which defines molecular diffusivity and is likewise related to molecular quantum state density. As a result, an indirect correlation can be established between the viscosity and the thermal conductivity of a base fluid, as both macroscopic properties depend upon similar molecular properties. Therefore, lubricants suitable for the high operating temperatures present in EVs must balance these properties. Viscosity and thus lubrication, however, remains paramount, which prompts the need to further improve thermal properties through the incorporation of additives.

Two considerations are vital for applications in EVs: the electrical conductivity must be high to promote little resistance between electrical bearing contacts, however simultaneously the electrical conductivity of lubricants or greases cannot exceed a certain value as current leaking or excessive lubricant oxidation can occur. The application of additives, which are conductive as compared to lubricants which are dissipative, help to increase conductivity in addition to lubrication performance of the lubricant. Upon sufficient incorporation, researchers must evaluate and compare different nanofluid compositions utilizing established test methods for parameters applicable in the EV industry. Characterization of these special properties are important, and often require specialized instruments. The elevated temperature wheel bearing grease tester, for example shown in Figure 5, evaluates the elevated temperature stability of automotive wheel bearing greases [24]. The test continues for 20/4 hour on/off cycles every four days in a week until grease breakdown causes drive motor torque to increase past its normal endpoint [25].

Figure 5: The K18500 High Temperature Wheel Bearing Grease Tester employs 25 lbf thrust loads, 1000 rpms in the rotating motor, and 160 degrees Celsius spindle temperatures to induce grease deterioration and failure. It also consists of changing front wheel hub bearings that are assembled in a constant temperature oven and a variable speed-drive motor [25].

2.1. Bench Test Measurement of Electrical and Thermal Heat Transfer Characteristics for EV and Hybrid Vehicles

2.1.1 Lubricant Thermo-physical Properties Measurement of EV/HEV (Reference ASTM Test Standard Handbook 34-38)

In this following section, all current bench tests developed for characterization of electrical and thermal heat transfer properties for automotive lubricants or coolants used in EVs and HEVs are summarized. Among those, several ASTM Test Standard Tests for lubricant properties are used to assess the following basic lubricant properties such as viscosity, density, thermal conductivity, electrical conductivity, and heat capacity / specific heat. Besides that, other standard tests for evaluation of tribological properties of automotive lubricants are summarized in Table 1 to supplement their performance characterization.

Table 1: Developed standard tests for electrical conductivity, thermal conductivity, and fluid properties which are crucial to meet HEV or EV performance requirements **[40--44]**

Test Name(s)	Characteristic	Description
ASTM D7896	Thermal Conductivity & Diffusivity	Transient Hot Wire method allows for simple measurements without the need for calibration of temperature ranges
ASTM D445	Kinematic Viscosity	10 mL sample is placed inside a Viscometer and the time taken to travel a certain length is measured at a certain temperature
ASTM D7042	Dynamic Viscosity & Density	A small amount of sample is rotated at a certain temperature and rate using a Stabinger viscometer
ASTM D7896	Thermal Conductivity & Diffusivity	Transient Hot Wire method allows for simple measurements without the need for calibration of temperature ranges
ASTM D4052 ASTM D1298 ASTM D1657	Density & Specific Gravity	D4052: Small volume of sample oscillates in a U-tube within an density meter changing in frequency D1298: Hydrometer method D1657: Pressure Hydrometer
ASTM D1903	Coefficient of Thermal Expansion	10 mL sample is placed inside a Viscometer and the time taken to travel a certain length is measured at a certain temperature
ASTM D2624 ASTM D4308	Electrical Conductivity	D2624: A portable meter measured electrical conductivity in the range of 0-2000 pS/m, 0-20,0000 pS/m, and 0-2M pS/m, though less precise

		D4308: A precision meter using a DC conductivity setup measures for 700 mL samples.
Electro-rheology	Viscosity	A fluid sample's viscosity is measured while an AC or DC current is producing an electric field across the sample.

Additional Tribological Lubricant Properties

Lubricant properties operating in EVs and HEVs must demonstrate sufficient tribological properties such as coefficient of friction, wear volume, wear rate, etc. These properties should be measured for lubricants or fluids in the presence of external electric or magnetic fields. In addition, the lubricant properties interacting with different compatible materials are required as contact pairs, as well as longer experiment durations. Besides the tribological requirements, all newly developed driveline lubricants or fluids must first perform across wide operating conditions to meet their driveline or thermal management requirements.

2.2. Automotive Coolants and Interfaced Material Compatibility Studies with Polymers and Metal Alloys [45, 46]

EVs and HEVs consist of major electronics and thermal management cooling components. In general, these components are interfaced with polymers and metal alloys [45]. These polymer components are primarily comprised of three types of polymers (commodity plastics, engineered thermoplastics, and elastomers) and four types of metals (aluminum, brass, copper and stainless steel).

The following fluids [45, 46] are commonly used in EVs/HEVs driveline and electronics cooling component applications:

1) Water: Excellent heat transfer, low viscosity, non-flammable and low cost. Narrow operational range and susceptible to freezing or boiling. Susceptible to biological fouling which inhibits heat transfer. May contain impurities with potential corrosive effects; deionization may reduce initially, though impurities may be extracted over time from wetted surfaces.
2) Ethylene glycol (EG): EG controls biological growth, lowers freezing point and elevates boiling point when used in solution with water, ranging from 10% to 90% EG. Lower cost than refrigerants or dielectrics. Water in solution may still promote corrosion, degrading coolant over time. Highly toxic, requires careful handling.
3) Propylene glycol (PG): PG controls biological growth when used in solution with water, ranging from 10% to 90% PG. Lower cost than refrigerants or dielectrics. Lower thermal

conductivity and higher viscosity than EG. Water in solution may still promote corrosion, degrading coolant over time. Low toxicity for easier handling and disposal.

4) Mineral oil: Mineral oil is odorless, non-toxic and chemically inert. No evaporation or volatility. Enables immersion applications. Potential incompatibility with copper or some elastomers.
5) Refrigerants: The most common coolants with excellent thermal transfer properties. Incompatible with some plastics and elastomers. Higher cost than water, EG, PG or mineral oil. Examples include R-1234yf and R-1336 [35, 46].
6) Dielectrics Fluids: Dielectrics fluids are non-conductive engineered fluids that enable full immersion of electronics in single-phase, two-phase and direct-immersed applications. Low boiling points. Dielectrics has lower boiling points and higher chemical stability, but the higher cost compared with conventional coolants such as EG or PG. However, it has the potential incompatibility with thermoplastics or heavily plasticized elastomers.

Polymers for EV/HEV Cooling Applications

Polymer properties can vary widely based upon processing, additives, fillers, and where they are on the spectrum, from commodity to ultra-high-performance thermoplastics and elastomers. Polymers can replace metals in many areas, and often provide additional benefits. For instance, engineered thermoplastics interfaced with thermal coolants or fluids are commonly used in electronics cooling applications. Commodity plastics and some thermoplastics, may present issues in certain applications. Given the emerging prevalence of warm water-cooling systems, polymer resistance to hydrolysis has become a crucial factor. Polymers with hydrolysable links may be at risk for severe property degradation in hot water environments. The same risk may apply for fluorochemicals in contact with fluorinated polymers. As commonly known, solvents primarily dissolve solutes, which are similar in polarity, and there could be a risk of solubility of certain plasticizers or additives into the coolant fluid. Flammability may also be a concern with some polymers. Therefore, researchers must pay attention on searching for inherently non-flammable materials, specifically non-halogenated thermoplastics. Long-term exposure to a wide range of temperatures is certainly a key consideration for material selection in cooling systems. Additional risks associated with thermoplastics include chemical attacks and crazing, cracking, discoloration, and, as previously mentioned, extraction or leaching into the coolant. Fluid absorption, swelling and certainly thermal aging and degradation effects over time and also mechanical loading and an internal pressure stress are potential threats to integrity as well.

In addition, engineered thermoplastics includes polyether ether ketone (PEEK), polyetherimide (PEI), polyethersulfone (PESU), polyphenylsulfone (PPSU), and polysulfone (PSU). They have improved mechanical and thermal properties but the higher cost than commodity plastics. These high-performance polymers such as PPSU and PEEK can meet higher thermal, chemical and mechanical requirements compared to metals while providing the added benefits of reduced weight and better corrosion resistance at a potentially lower cost. Engineered thermoplastics can be an excellent choice, especially when considering effects of weight, chemical compatibility, and price over metal counterparts. When specifying thermoplastic materials look for mechanical strength, chemical compatibility, and thermal stability characteristics.

Elastomers

Elastomers can be engineered to meet a wide range of performance requirements [42, 43]. Elastomers are polymers that have the property of viscoelasticity – they are rubbery and flexible – and are construction materials commonly used in electronics cooling applications. Elastomers are low-cost materials and readily available, however, they are potential flammability and thermal degradation and shrinkage in extreme-temperature applications. Commonly used elastomers include CR, EPDM/EPM, FKM, HNBR, and silicone. It can be tailored to enhance flame retardance, durability and chemical resistance. However, it shows lower thermal conductivity and higher cost, but passivation effect can increase corrosion resistance. It is primarily used in hybrid components for fluid transport, such as tubing and hose, as well as sealing components such as O-rings and gaskets. Besides the advantages in industrial applications, the vulcanization process of curing, can create permanent cross-links in long polymer chains in elastomers. These chains ensure that when stresses are loaded and unloaded, the elastomeric component will return to its original position. At an elevated level, specifying elastomers for use in a liquid cooling application requires detailed analysis and evaluation with the selected unique coolant to ensure compatibility and long-term reliability for wide operating conditions. [45, 46] Some elastomer types may leach into fluids during thermal cycling or exposure to certain solvents, negatively impacting the driveline coolant performance.

Metal Alloys

Aluminum is commonly used for lightweight materials due to its inherently strong thermal properties. It has high potential for galvanic corrosion, especially interfaced with water-based coolants in presence of copper. Anodization treatment process can increase corrosion resistance. Brass and copper are durable metals and strong thermal properties commonly used in EV/hybrid components. It is often plated with nickel and/or chrome for improved corrosion resistance. Galvanic corrosion potential will be occurred, especially with water-based coolants in the presence of aluminum. Stainless steel shows the highest durability and stability among all metal alloys.

Fluid-Material Compatibility [45, 46]

With a foundational understanding of the fluids, plastics and metals that might be employed in a given liquid cooling application, we can assess potential chemical compatibility of system components, based on their make-up, to ensure reliable, long-term operation [45]. While polymers and metals can be effective in any combination when appropriately specified, it is critical to distinguish wetted materials of construction from structural materials. Wetted materials include all components that are directly exposed to the coolant and therefore, potentially indirectly exposed to one another. Structural materials are not exposed to coolant during normal operation. Creating a list of wetted and structural materials early in the design cycle can help avoid complications down the road. A given component might potentially be built of a combination of polymers and metals, so it is important to distinguish the wetted materials from structural materials within a given component. For example, a quick disconnect like the one at the left may be constructed of nickel-plated brass and include an elastomeric O-ring seal, a polysulfide thumb latch and stainless-steel springs. However, only the interior surface of the connector and the elastomer seal would be wetted in a closed-loop cooling system, so only the compatibility of those materials need to be considered relative to the selected coolant. At an elevated level, fluids can affect polymers in two diverse ways: physically or chemically. The first is reversible while the other is not. For example, an O-ring compound in a quick disconnect might have an affinity for a certain coolant, causing the O-ring to swell, creating connection and disconnection issues that can potentially lead to leaks. Replacing the O-ring with an alternative plastic or specifying a different fluid could correct the problem. However, in a chemical interaction where a plasticizer is being extracted from a component such as tubing, the effects of that dissolved plasticizer on the fluid’s performance can have the worst influence compared with the conventional metals. General guidance for coolant material compatibility [45] can provide a useful information for automotive engineers or fluid formulators. Those fluid-material compatibility studies in this review paper can definitely provide helpful solution that is optimized for your requirements in thermal management systems.

Table 2 provides a detailed comparison of component material and coolant compatibility used in EV/HEV thermal cooling operations. [45, 46]

Material and coolant compatibility When considering wetted components in a liquid cooling system, the following combinations are:

• A = Recommended. Little or no potential for chemical reaction or corrosion.

• B = Good options. Minor potential for chemical reaction or corrosion, with limited effect on system performance.

• F = Not recommended. Mild to severe chemical or corrosive reactions likely. May impede system performance

1 **Thermoplastics may be engineered to enhance compatibility with specific refrigerants.**
2. **Most elastomers are compatible; however, EPDM is not recommended for use with mineral oil.**
3. **Elastomers may be engineered to enhance compatibility with specific refrigerants and dielectric fluids**

	WATER	ETHYLENE GLYCOL	PROPYLENE GLYCOL	MINERAL OIL	REFRIGERANTS	DIELECTRICS
Commodity plastics	A	A	B	A	F	B
Engineered thermoplastics	A	A	B	A	A to F[1]	B
Elastomers	A	A	A	A[2]	A to F[3]	A to F[3]
Aluminum	B	A	B	A	A	A
Brass (plated)	B	B	A	B	A	A
Copper	A	B	B	A	A	A

REFERENCE: Chemical resistance guide for elastomers IV, Compass Publications, 2014.

3. Future Hybrid Transmission and Driveline Lubricant Performance Characteristics

The increasing demand for advanced transmission prompts not only the minimization of friction loss, but also maximization of component durability. Performance characteristics of these driveline fluids are required to protect the functioning of transmission fluidity, pump efficiency, internal leaking, and clutch durability.

Besides the tribological benefits such as less friction, less wear, better lubrication, and advanced bearing designs, the usage of advanced driveline lubricants in EV applications have caused automotive industries to claim that EVs might require new gear oil additives and wear protection under heavy load/elevated temperature operating conditions. Also, switching to lower viscosity fluids can reduce churning, pumping losses, and increase overall efficiency.

Automotive driveline lubricants for EVs/HEVs are not specifically only designed for fuel economy purposes. In many EV advanced system designs, lubricants, like drivetrain fluids or thermal coolants, encounter the integrated electric motor and thermal management devices, which leads to the addition of thermal and electrical properties [47, 48]. High energy efficiency and long-term durability are the targets that specialized automotive lubricants or driveline fluids seek to achieve.

The future development of EV/HEV technologies is encumbered by the urgent demand for thermal protection and cooling of the electrification components. The traditional method for thermal cooling can no longer be applied. New requirements have been enforced for high performance cooling on EVs' batteries, motors, and power electronics. Thermal management for electrified powertrain plays a significant role in extending the driving range for EVs, as well as maintaining the optimal working conditions of electrification components including battery system, electric motors and fluid power components. The heat generation rates in EV/HEV electrification components such as E-motor, battery, and fluid power driveline devices are continually increasing due to trends toward faster speeds and smaller features for heat transfer devices, more power output for hybrid vehicles. For instance, electric hybrid and fuel cell vehicles use power electronics to control electric motor. Power electronics require their own cooling loop including the following components: heat exchanger, pump, and radiator. Power densities exceeding 100 W/cm^2 while needing to maintain the electrification components below 125 °C, may eventually exceed 250 W/cm^2 for high power electrified powertrain systems [46-47]. In addition, thermal cooling for electrification components has become one of the top technical challenges facing high-tech industries such as microelectronics, transportation, manufacturing, and energy storage systems. Conventional methods to increase heat rejection rates relate to the use of extended surfaces such as thermal fins or cold plates. Those ineffective methods for thermal cooling have been replaced by novel nanofluids and micro-channels to dissipate heat in thermal control devices [48-50]. In addition, nanofluids are being developed to achieve ultra-high-performance cooling. Nanofluid technologies [47-49] with potential to improve the fluid's thermal properties are of great interest.

Currently new developments in thermal management extend the distance range and lifetime of how much an EV/HEV can last. Global research activities using nanographene (a major type of nanofluid used in electric motors (49-50) for thermal cooling has a high potential for cooling technologies. EV BTMS (Global Electrical Vehicle Battery Thermal Management System) is developing many new advancements to properly help manage heat transfer inside the vehicle. The EV BTMS market is projected to grow at an annual growth rate of 39% with revenue in USD of 15 bn from 2020 to 2024 [51]. The growth of EVs and HEVs are climbing; the market revenue of EV and HEVs is $2 trillion. By 2025, they will account for an estimated 30% of all vehicle sales; additionally, without many interruptions in the current future prospective advancements of electrification components in electric vehicles, 60% of all vehicle sales will be from the EV/HEV market in 2030 [52].

Conclusion

The most important aspects/advancements of automotive lubrication are in the areas of energy conversion effectiveness, driveline consistency, cooling system design and thermal management requisites.

Thermal management has become key to the development and management of electric vehicles, but still faces many challenges. Cost and durability are the major challenges to fuel cell commercialization; size, weight, thermal and water management often limit market sales of fuel cell components. Electric vehicle heat pump air conditioning is also a problem to electric vehicles because of the excessive costs to install/repair them and the high/increasing CO2 gas emissions it is producing. Major challenges that lithium batteries present include, overheating, which can lead to flammability, and their short life span. These challenges bring new research opportunities that could lead to the development of new electrification components, advanced propulsion vehicles with high energy efficiency, and reliable thermal management solutions.

The projected growth of EVs and HEVs has made evolutionary changes to the automotive industry for electrified propulsion system components. Driveline components have been enhanced by electric motors and the electrification components, including electric motors, will be integrated in this advanced configuration, with thermal management. The electric motors and power electronics will be in contact with the driveline lubricant or coolant, so that they can cool the motors, power electronics, and batteries. In addition, automotive lubricants must function as an effective coolant, reduce corrosion of copper windings, composites, and uphold wear protection for the electrified propulsion system.

In this review paper, the authors have reviewed all current bench tests developed for characterization of electrical and thermal heat transfer properties for automotive lubricants or coolants used in EVs and HEVs. Among those bench tests, several ASTM Test Standard Tests for lubricant properties have been reviewed including the following basic lubricant properties: viscosity, density, thermal conductivity, electrical conductivity**,** and heat capacity / specific heat. All bench test methods will be summarized in this paper. In addition, the other standard tests for evaluation of tribological properties of automotive lubricants will be described to supplement their performance characterization. At the end of this paper the authors provide an overview of relative compatibility between various interface materials and coolant options. Those fluid-material compatibility studies in this review paper can definitely provide helpful solution that is optimized for your requirements in thermal management systems.

About the Authors

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https://www.astm.org/DIGITAL_LIBRARY/MNL/SOURCE_PAGES/MNL372ND_foreword.pdf

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https://www.petro-online.com/news/fuel-for-thought/13/koehlerinstrument-company/dr-raj-shah-director-at- koehler-instrumentcompany-conferred-with-multifarious- accolades/53404

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