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Test methods for evaluating electrified vehicle fluids

***Matt Jackson**, Director, Fuels and Driveline Lubricants Research, Southwest Research Institute (SWRI)*

Drivetrain fluids for electrified vehicles (EVs), both hybrid and full electric, have differing requirements from conventional fluids. Traditional performance needs such as oxidation protection, material compatibility, aeration resistance, and wear protection are still important, but new challenges exist in the form of electrical conductivity, heat transfer, high speed durability, compatibility with new and different materials, and battery cooling. Conversely, friction performance – critical to applications employing wet clutches - is now of lesser importance as the range of system operating speeds is now covered by variable speed motors, rather than conventional step gear transmissions. Adding to the complexity of the electrified drivetrain space are the myriad hardware configurations as each drive unit manufacturer seeks their own solution to transmit power to the wheels. There are no "one size fits all" solutions.

While many existing systems employ automatic transmission fluids in their electrified drivetrains, these fluids may not be optimal for each solution, as they were designed around the needs of more conventional applications. In order to improve fluid performance in electrified vehicles, it is vitally important that formulators designing these fluids have tests at their disposal that properly correlate to real world systems.

Suitable tests for conventional fluids have been developed and improved over decades. These controlled test methods are used to assess fluid performance and allow the evaluation of formulation changes against known standards. Unfortunately, similar tests for electrified vehicles simply do not exist, or are at best in early stages of development.

There are industry efforts underway to adequately identify the performance needs of EV fluids and develop tests to evaluate them. SAE International has authored "Information Report J3200 on Electric Drivetrain Fluids (EDF)" as a guide to understanding the terms related to EV fluid properties and existing tests that may have applicability to EV fluid evaluation. Southwest Research Institute's Advanced Fluids for Electrified Vehicles (AFEV) Consortium is a joint industry project whereby member companies pool resources to explore precompetitive concepts to properly characterise EV fluids.

Ultimately, new tests will need to be developed that address the specific needs of EV fluids. These new tests will need to assess performance with respect to electrical and thermal properties, compatibility with materials unique to EV systems, high speed durability, oxidation and aeration resistance, and battery performance.

Electrical properties

Prominent among the new requirements for EV fluids are suitable electrical properties. As fluids are exposed to electric fields within drive units, it is vital to understand the effects of these fields on their performance. The chemical makeup of a fluid (both base stock and additive package) will determine how it performs in an electric field and how the effects of the field may change the fluid as it ages.

Unfortunately, the standard tests that are currently available to assess a fluid's electrical properties have limitations when applied to EV fluids. Many are constrained by limited ranges of operating frequency, temperature, and electrode spacing. Among these are tests for electrical conductivity (ASTM D1169), dielectric breakdown (ASTM D1816), dielectric constant (relative permittivity) and power factor / dissipation factor (ASTM D924).

If electrical conductivity is too high, current may 'leak' from the system, which will decrease its efficiency and, in extreme cases, cause a shock hazard. If electrical conductivity is too low, a static charge may develop, discharge of which may cause damage to bearings and other components. Fluids with lower dielectric constant will demonstrate a reduced ability to store an electric charge. Low power factor fluids are less efficient and may lose electric power to heat. If a fluid is not able to withstand sufficient applied voltage, dielectric breakdown may result. Electro-rheology (fluid flow in the presence of an electric field) and electro-tribology (wear in the presence of an electric field) are also important areas of study when assessing EV fluid performance.

In electric drive units, there is a tendency of electric currents to seek a ground path through the bearings. This can lead to fluting damage at the bearing race. The Flucon E-Lub tester replicates electrical discharge machining (EDM) using test bearings and either oils or greases. In this test, grounding of current induced by the rotating motor occurs through the test bearing. This phenomenon is also under investigation by the AFEV Consortium.

Heat transfer

As advances in electric drive units continue, the need exists for increased power levels in smaller motor packages. Designers of wet motors look to the EV fluid to cool the drive units, making good heat transfer properties a must. The fluid's ability to store and transfer heat are defined by thermal conductivity, thermal diffusivity, and specific heat capacity.

Thermal conductivity refers to the rate of heat transfer in a fluid via conduction through a unit area. Thermal diffusivity refers to the measurement of the rate of heat transfer through a material, expressed as the ratio of thermal conductivity to specific heat and density. Specific heat capacity is the amount of heat required to raise the temperature of a unit mass of material by 1°C. Existing tests that can be used to quantify a fluid's fundamental heat transfer properties include ASTM D7896 (thermal conductivity, diffusivity, and heat capacity), ASTM E1269 (specific heat capacity by differential scanning calorimetry), and ASTM E2716 (specific heat capacity by sinusoidal modulated temperature differential scanning calorimetry).

Material compatibility

Electrified vehicle fluids must be compatible with a variety of materials, including copper at connection points, coatings on motor windings, structural plastics, and wire insulation. Fluids must guard against copper corrosion, both for submerged components and in the vapour space. A copper wire corrosion test has been developed for this reason. The wire is partially submerged and is also exposed to the vapour space above the fluid. A small current is passed through the wire to monitor its condition. As the copper corrodes, the diameter of the wire decreases, causing its resistance to increase.

Copper compatibility may also be assessed using a conductive deposit test. For this test, multiple test cells are placed in a temperature-controlled bath. Voltage is applied and resistance is monitored until a failure point is reached, either in the form of a short caused by deposits, or an open circuit due to corrosion of the copper. These tests can be lengthy, lasting up to 1000 hours, although recent work suggests shorter tests may be possible. Another option is the traditional ASTM D130 copper corrosion test. The subjective nature of the visual rating required to assess the results of this test can present challenges in its application, although modifications to length and vapour phase exposure have shown promise.

Fluid compatibility with structural plastics can be investigated using ASTM test method D638. The method can be used to evaluate the tensile strength of plastics following their exposure to lubricants. Volume change and hardness can also be assessed. Additionally, methods are in development by the AFEV Consortium to determine the degree to which EV fluids are compatible with the coatings used to protect motor windings in wet motor applications.

Figure 1: *Test methods are in development to determine the degree to which EV fluids are compatible with the coatings used to protect motor windings.*

High speed durability

Motor speeds in electric vehicles approach 20,000 to 30,000 rpm. Many platforms use a gearbox to reduce the speed from the electric motor to the wheels. Use of a single fluid in these applications means that the lubricant must work equally well in both the high speed, low torque condition at the motor and at the low speed, high torque condition at the output of the gearbox. Conventional test methods such as the FZG tests for scuffing and pitting, the L-37-1 (low speed, high load), and L-42 (shock load) axle lubricant tests could be applied to the reduction gears, but there are currently no standardised automotive test methods for evaluating gear or bearing performance at high speeds. Evaluation of high speed lubricant performance is one of the tasks of the AFEV Consortium.

Oxidation and aeration resistance

Electric motors provide an ideal environment for EV fluid oxidation. Catalyst materials present in the motor (insufficiently coated copper leads or windings, for example) and elevated temperatures may accelerate oxidation reactions. This can lead to increases in fluid acidity, viscosity, sludge, and varnish formation.

There are a number of existing tests used to assess oxidation, including the Aluminum Beaker Oxidation Test (ABOT), DKA Oxidation Test (CEC L-48), L-60-1 (ASTM D5704), and Indiana Stirring Oxidation Test (ISOT). These methods were developed for conventional fluids and may not have direct applicability to the materials and operating temperatures of electrified vehicle drivetrains. It remains to be seen if additional methods will need to be developed that are specific to EV fluids.

Aeration refers to the condition in which air is entrained below the surface of a fluid. This differs from foam, which exists as air present at the fluid surface. Aeration is undesirable in a drivetrain fluid, as it can cause reduced heat transfer, increased churning losses, reduced gear protection, and increased fluid compressibility. While many tests are available to assess a fluid's foaming tendency (e.g. ASTM D892, ISO12152, ASTM D3427), the number of true aeration tests is limited. The DEXRON® Aeration Test, developed by GM and Southwest Research Institute (SwRI), determines the degree to which a transmission fluid will aerate, as well as the speed at which both aeration and de-aeration occur. As with other conventional fluid tests, there is some question regarding applicability to the unique operating conditions presented by current and future EV drive units. Smaller sump sizes result in increasingly limited residence times, which in turn require reduced aeration levels and faster air release. SwRI has developed a test to quantify increased aeration levels caused by the higher operating speeds of modern electric drive units.

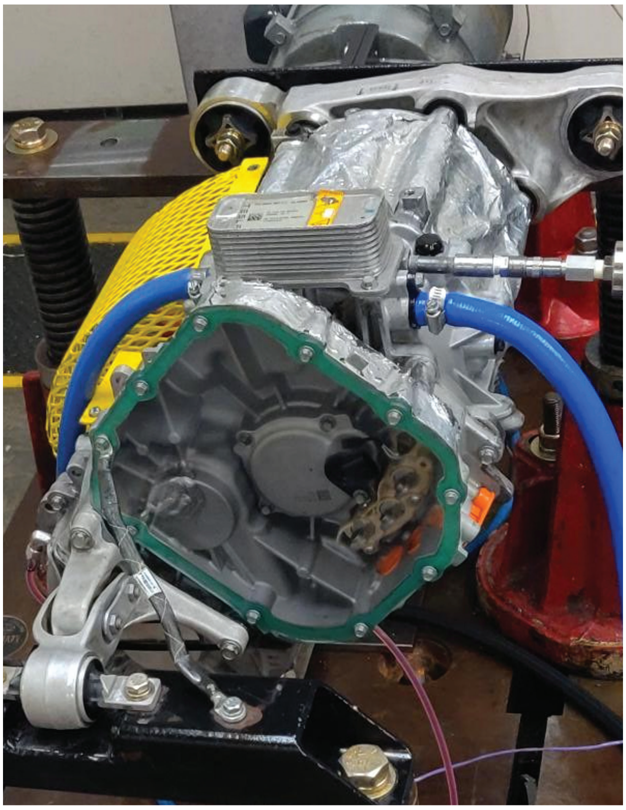

Figure 2: *A test has been developed to quantify increased aeration levels caused by the higher operating speeds in modern electric drive units.*

Aging effects

There is currently limited data on how EV fluid properties change as they age. To address this, mileage accumulation efforts are underway at SwRI using heavily-instrumented battery electric and hybrid electric vehicles. These projects assess the degree to which chemical properties, electrical properties, and performance change over the life of a fluid in an electrified system. The studies also seek to determine the effects of aging on both fluid and full-vehicle efficiency.

Direct liquid battery cooling

Immersive coolants are used in EV applications to conduct heat away from battery cells in the absence of a cold plate. This allows the battery pack to operate at lower temperatures, which improve its charging and discharging performance. It also provides a safety benefit. Without direct liquid cooling, a battery cell failure may lead to thermal runaway, which can spread to adjacent cells and cause a fire. Direct cooling contains the thermal runaway to individual cells, potentially allowing the battery pack to continue to operate safely with individual failed cells. The advantages of immersive cooling should be considered against associated weight and packaging concerns.

Testing is required to determine a fluid's suitability for use as an immersive battery coolant. Material compatibility tests assess the ability to prevent corrosive degradation in contact with battery cell materials such as copper, aluminum, nickel, and polypropylene. Tests designed to determine fluid heat transfer properties must be applicable to the battery environment.

Abuse testing

Battery abuse testing is necessary to determine if the immersion fluid can mitigate thermal runaway and limit propagation to adjacent cells in extreme conditions. This type of testing includes evaluations of combustibility, resistance to failure induced by physical damage, and heat induced failures.

Combustibility may be assessed by heating the test fluid in a specially-designed enclosure and introducing a "blank" cell that has been heated to 800+ °C (representative of thermal runaway conditions). The blank is immersed in the fluid adjacent to "dummy" cells and the temperature of the blank, dummy cells, fluid, and air are monitored. A spark source is active throughout the test to ignite any combustible gases. Resistance to physical damage is evaluated using the Nail Penetration Test. For this test, thermocouples are installed on each battery cell and in the test fluid. The test module is conditioned and charged to 100% State of Charge (SOC) at 25 °C, at which point a nail physically penetrates the first cell in a group. The test is then monitored to determine if a thermal runaway event occurs due to the nail penetration and if the runaway propagates to nearby cells.

Heat induced failure testing uses a test apparatus similar to the nail penetration test but without the use of the nail. Instead, a heater wire is placed on the target cell and the module is conditioned and charged to 100% SOC at 25 °C. The heater wire is then energised and the test monitored for thermal runaway induced by the heated wire. If thermal runaway occurs, the test can determine the fluid's ability to sufficiently transfer heat away and prevent propagation to adjacent cells.

Performance and life testing

Tests may also be performed to assess an immersive coolant's ability to improve charging performance, and prolong the life of the battery. For each of the following tests, a module and container are housed in a test chamber, plumbed to a circulation system, and wired to a battery cycler.

Performance testing targets a temperature rise when the module is subjected to a fast charge profile and is used to determine the degree to which charging and discharging performance are improved in the presence of an immersive coolant. Life testing involves subjecting the module to a repeated fast charge profile in order to accelerate aging under high stress. Module health is assessed at intervals using a reference performance test to quantify degradation.

Conclusion

There is little debate that electrified vehicles will ultimately dominate the automotive landscape. As the industry transitions away from traditional applications, it is vital to understand the unique fluid needs of EVs of various design. Electrical and heat transfer properties, high speed durability, material compatibility, oxidation and aeration performance are all of considerable importance when selecting a fluid for use in an EV drive unit.

Fluids for battery cooling must be able to remove heat from the system while protecting against flame propagation and thermal runaway, and can have positive effects on battery life and performance. Fluids currently in use were likely designed for legacy drivetrains and may not be optimised for electrified vehicles. The lubricants industry is rapidly developing the test methods that will be needed to assess the performance of the next generation of EV fluids.

*The Advanced Fluids for Electrified Vehicles Consortium (**afev.swri.org**) is a joint industry project whereby member companies pool resources to explore precompetitive concepts to properly characterise EV fluids.*

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