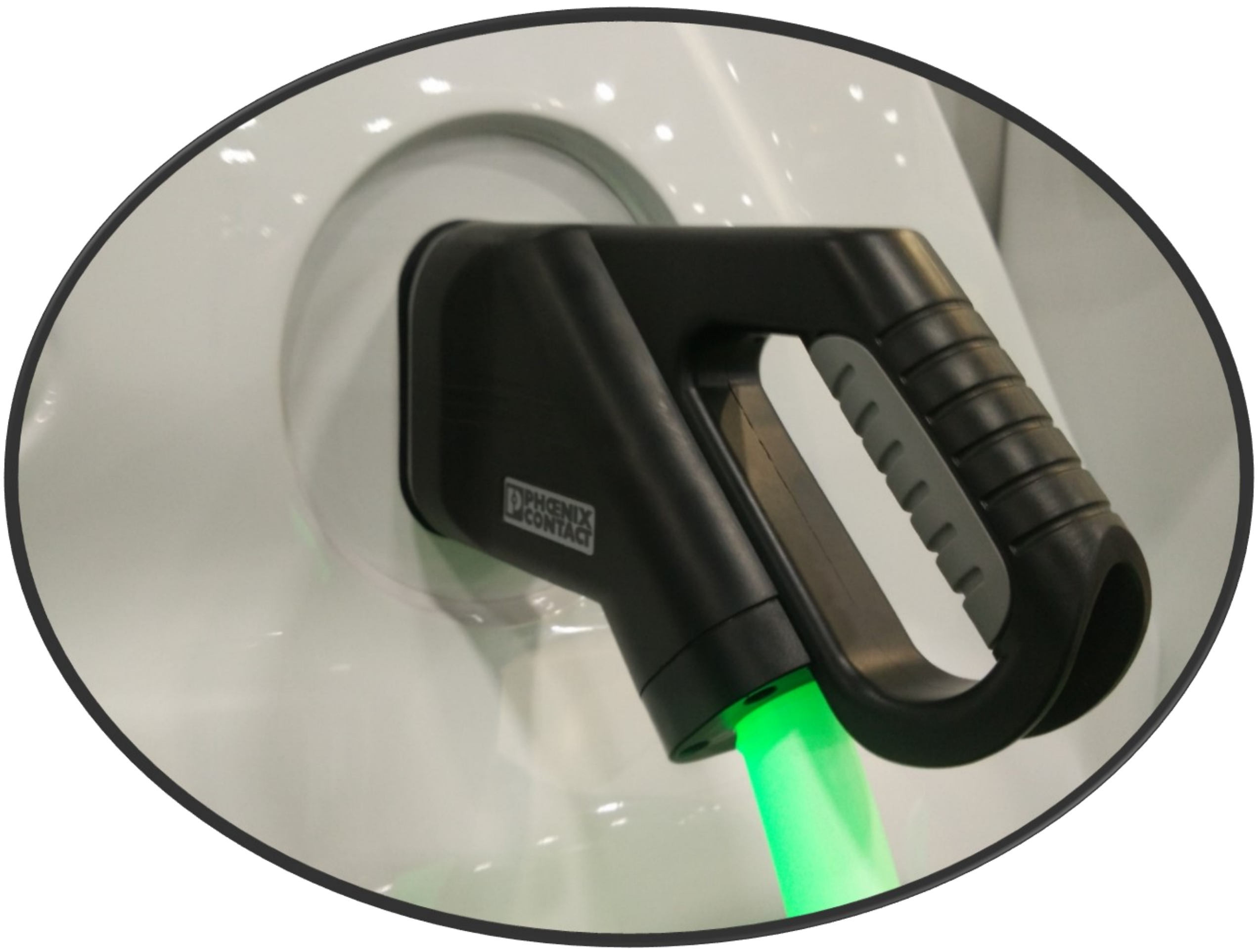
White Paper

Application of AmpCool® Coolants in Electric Vehicles

Engineered Fluids, LLC



Abstract

Since 2005, the Automotive Industry has seen rapid changes as Electric Vehicles (EVs) have become more accepted by the market and technological advances have increased their reliability and range. These changes have introduced new requirements for lubricants and coolants to maximize the potential of the new technologies. Electric Vehicles need coolants, electrical insulating fluids, hydraulic fluids and lubricants in various applications on each vehicle. One of the problems that this has brought about is the number of different types of fluids on today's vehicles

This study shows how AmpCool® Coolants by Engineered Fluids can replace multiple of the different fluid components of today's Electric Vehicles, leading to lower weight, lower manufacturing and ownership costs as well as an increase in reliability as measured by Mean Time Between Failures (MTBF) of the vehicles in service

Synthetic AmpCool dielectric coolants deliver significant performance benefits compared to lubricants and coolants made with petroleum oils or water/glycol mixtures. AmpCool Coolants can be used in thermal management of motors, battery systems, to cool and insulate high voltage charging systems and electronics assemblies, used to cool kinetic energy recapturing devices and act as a power transfer fluid in brake systems. Compared with petroleum products, AmpCool Coolants work better at both low and high temperatures and have better lubricity, which decreases friction. This raises the efficiency of the electric drive train, extending vehicle range and service life.

Taken as a whole, EV driveline fluid development presents new challenges, and AmpCool Coolants provide an excellent balance of lubrication, thermal and electrical properties for EV applications.

AmpCool Coolants

AmpCool is a family of synthetic dielectric heat transfer fluids made by Engineered Fluids, LLC. AmpCool Coolants are made from purpose-built hydrocarbon molecules, having a high dielectric strength and excellent heat transfer properties. AmpCool Coolants are highly biodegradable, non-toxic, and have been tested and awarded a "Food Grade" designation by the NSF.

This study focuses on AmpCool AC-110, which is the most widely used AmpCool product. AmpCool AC-110 does not boil, remaining in the liquid phase at all application temperatures. AC-110 Coolant can be used at temperatures from -66 C to 200 C. It also has a low viscosity, which enhances its heat transfer efficiency.

Figure 1: AmpCool AC-100

Characteristics of the AmpCool product line can be seen in Appendix A

AmpCool products have been made with material compatibility in mind. They're tested and guaranteed to be compatible with a wide variety of materials. A complete Materials Compatibility Guide can be found at www.engineeredfluids.com/materials-compatibility

Electric Vehicle Applications for AmpCool Coolants:

DC Motor Cooling

AmpCool Coolants are ideal for thermal management of brushless, high-torque electric motors. With excellent heat transfer and oxidation stability characteristics, AmpCool AC-110 can be used to maintain thermal control over both radial- and axial flux motor designs.

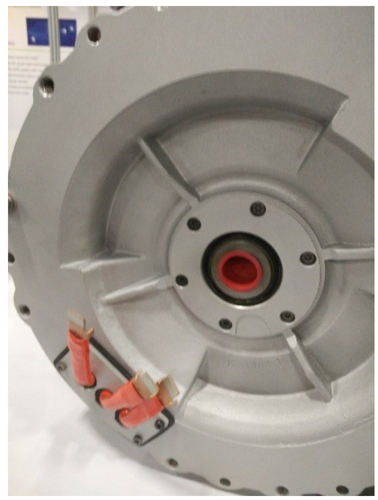


Figure 2: High Torque Motor

One approach to cooling electric motors includes a cooling water jacket incorporated into the housing that surrounds the stator. The water jacket is typically cooled with a mixture of water-ethylene glycol (WEG). Cooling of the electric traction drive motors in some vehicles is accomplished by impinging jets of dielectric fluid onto the copper windings. Automatic Transmission Fluid (ATF) is sometimes used in this direct cooling design. Direct end-winding cooling with ATF is practical because ATF has some electrically insulating properties. The ability to use a dielectric fluid to directly cool the rotor or end windings has significant advantages for removing heat. (1)

Immersion cooling the end windings of the motor greatly reduces the thermal resistance for removing heat generated within the windings.

However, compared with AmpCool Dielectric Coolants, ATF is a poor choice as a coolant for electric machines. Transmission Fluid has a high viscosity and low thermal conductivity, a low flash and fire point and environmental characteristics.

Figure 3 shows a cross section of a motor incorporating a stator cooling jacket and impinged-oil cooling within the rotor end windings (Illustration courtesy of NOAA)

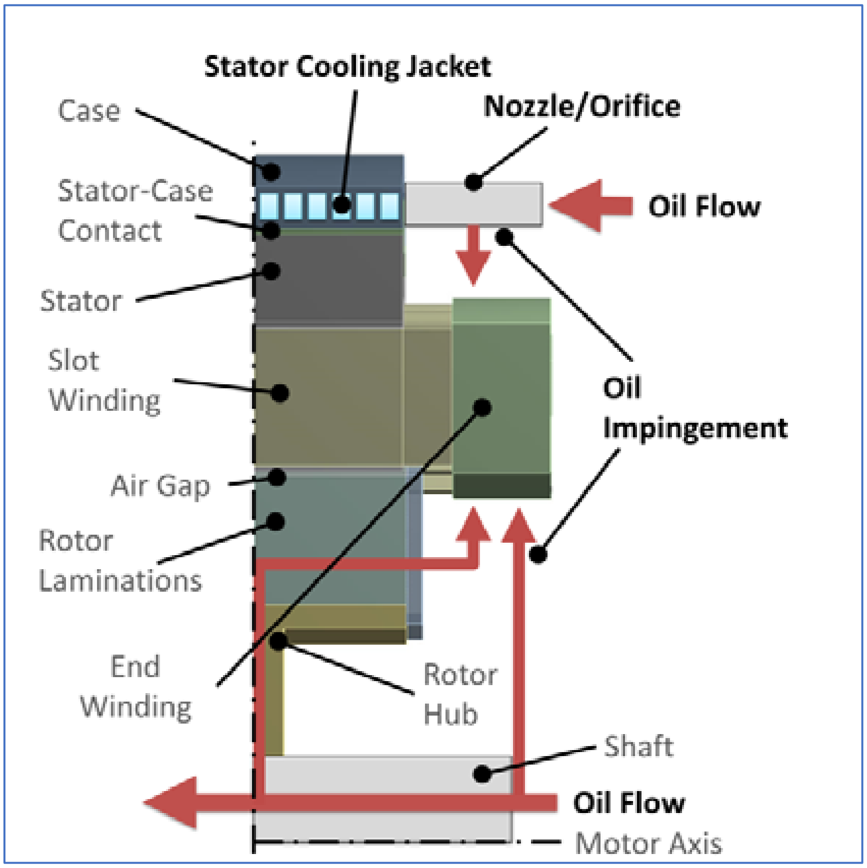


Figure 3: Cross Section of Electric Machine, (photo courtesy of NOAA)

Table 1 shows a comparison between AmpCool AC-110 Dielectric Coolant and Mercon® ATF (2)

Table 1: Comparison Between AmpCool AC-110 and Mercon® ATF

Characteristic:	AmpCool AC-110	Automatic Transmission Fluid
Kinematic Viscosity @ 40C	8.1 cSt.	36 cSt.
Flash Point, C.	193	160
Pour Point, C	-65	-40
Dielectric Strength	60 KV	35 kV
Thermal Conductivity,	0.1403 W/mK	0.1324 W/mK
Biodegradation CEC-L33b	94%	very low

It can be seen that AmpCool AC-110 has advantages over Transmission Fluid for electric motor cooling:

- A much lower viscosity, combined with higher thermal conductivity means that AmpCool AC-110 is more efficient at heat transfer. Implications of this are that both lower fluid volumes and fluid flowrates are required to maintain the motors at their optimum operating temperature.
- Higher flash and fire points of AmpCool add a significant margin of safety against fire and explosion.
- Higher dielectric strength indicates that high voltages can be safely used in the motor, yielding higher axial torque.
- Lower pour point allows AmpCool to remain fluid at lower temperatures
- A higher biodegradation rate is better for our environment in case of a spill.

Thermal Management of Battery and Charging Systems

While advances have been made in electric vehicle batteries that allow them to deliver more power and require less frequent charges, one of the biggest challenges that remains for battery safety and longevity is an effective cooling system.

In Electric Vehicles, charging and discharging the battery generates heat; the more rapidly you do either to a battery, the more heat is generated. Because batteries are only manufactured to work between certain temperature extremes, they will stop working if there is no thermal management system to maintain them within the working range. Cooling systems need to be able to keep the battery pack in the temperature range of about 20-40 degrees Celsius, as well as keep the temperature variation inside the battery pack to a minimum (no more than 5 degrees Celsius). If there is a large temperature difference inside of battery cells or between one battery cell and another within the same pack, it can lead to different charge and discharge rates for each cell and deteriorate the battery pack performance. Potential thermal stability issues, such as capacity degradation, thermal runaway, and fire or explosion could occur if the battery overheats or if there is non-uniform temperature distribution in the battery pack.

One way to cool automotive batteries is with a Phase Change Material. Phase Change Materials (PCM) absorbs heat energy by changing state from solid to liquid or from liquid to gas. While changing phase, the material can absorb large amounts of heat with little change in temperature. In practice, most PCM cooling systems use a low-temperature boiling liquid that vaporizes on contact with a hot component. These “two-phase” cooling systems can meet the cooling requirements of the battery pack, however there are operational issues to consider, such as capture and recondensation of the vaporized coolant.

Another method of battery cooling is by passive air cooling. In this method, cooling fins are added to the battery case, which enhance the transfer of heat through the case to the atmosphere. Heat is transferred from the battery pack to the fin through conduction, and from the fin to the air through convection. Fins have a high thermal conductivity and can achieve some cooling goals, but they add a lot of additional size and weight to the pack. Using fins to cool EV battery systems, however, has fallen out of favor as the additional weight of the fins outweighs its cooling benefits.

Active Air Cooling uses the principle of convection to transfer heat away from the battery pack. As air is forced over the surface of the case, it will carry away the heat emitted by the pack. Air cooling is simple and easy, but not very efficient, compared to other cooling methods. Air cooling was used in earlier versions of electric cars. As electric cars are now being used more commonly, safety issues have arisen with purely air-cooled battery packs, particularly in hot climates.

Liquid Cooling is very efficient because liquids have higher heat conductivity and heat capacity than air. Liquid cooling systems have advantages like compact structure and ease of arrangement. Of the options available to engineers, liquid coolants deliver the best performance for maintaining a battery pack in the correct temperature range and uniformity.

It is important to distinguish between direct and indirect liquid cooling systems. In indirect cooling, the coolant fluid is usually water-based, so it's electrically conductive, requiring a casing or piping system that carries the coolant so that it doesn't come into direct contact with the battery itself. An indirect liquid cooling system for EV batteries is similar to the water/glycol-radiator cooling system found in conventional internal combustion engines The coolant used is also similar to coolants used in conventional engines, made of water/glycol (WEG) with an additive package providing protection against corrosion.

In direct liquid cooling systems, the battery cells are submerged in flowing dielectric fluid so that there is intimate contact between the battery cell and the coolant. The coolant fluid removes heat from the battery cells and carries it away for transfer to the atmosphere Water jackets, piping systems and housings around the battery case are not needed because the nonconductive dielectric fluid prevents battery short-circuits and corrosion. These Single-phase Liquid Immersion Cooling (SLIC) designs have been in the development stage for years, but now Engineered Fluids is able to manufacture coolants that can be commercialized in electric vehicles.

Table 2 summarizes the differences and relative advantages of direct and indirect liquid cooling of batteries:

Table 2: Comparison of AmpCool Immersion Cooling with Water/Glycol Indirect Cooling:

Parameter	AmpCool Immersion Cooling	Water/glycol Indirect Cooling
Equipment Size	Smaller - hot components are bathed in dielectric coolant; no cold plates or jacketing needed	Larger - jacketing and cold plates required
Equipment Weight	Lighter - because no cold plates or jacketing	Heavier – Metal cold plates or coolant jackets adds weight and size to components
Efficiency	Immersion Cooling is the most direct, efficient way to transfer heat	Water/glycol mixtures are efficient, but indirect cooling equipment is highly inefficient
Flexibility for change	Flexible – easily change immersed components as needed	Inflexible – Water Jackets and Cold plates are specific to components or component sets
Fluid Safety	AmpCool is nontoxic, Food Grade and Biodegradable	Glycol is toxic and not biodegradable. Not Food Grade

Proof of SLIC Technology: AmpCool's safety and efficiency was proven in a set of experiments performed at Engineered Fluids' Sausalito Development Workshop. In these experiments, a Samsung Model 286s prismatic 94 aH cell was subjected to a series of four charge – discharge cycles over a period of 15 hours, once while being cooled with forced air and again when immersed in AmpCool AC-110 Coolant.[1]

Through this data and the accompanying graphs on the following page, it is easy to see that the cells that were immersed and cooled with AmpCool showed huge advantages over air cooling:

The average battery temperature was five degrees C lower for the cell cooled with AmpCool AC-110. Using the Arrhenius Rate Equation of chemical reaction kinetics, this 5 C difference in average cell temperature translates to an approximate extension of battery life by a factor of 1.4

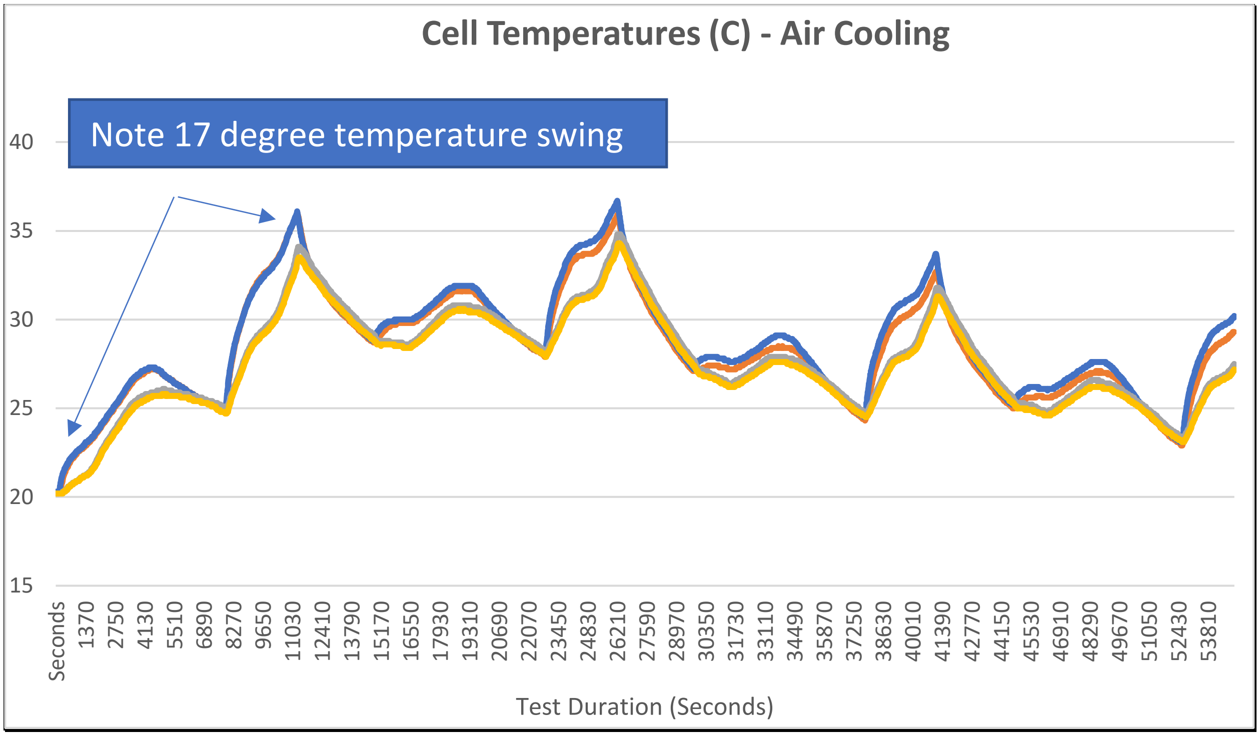
Immersed in AmpCool Coolant, the battery was held at its optimum operating temperature for the duration of the test. The battery cell cooled with forced air experienced temperature swings from 20 to 37 C., with five times the standard variation around the average.

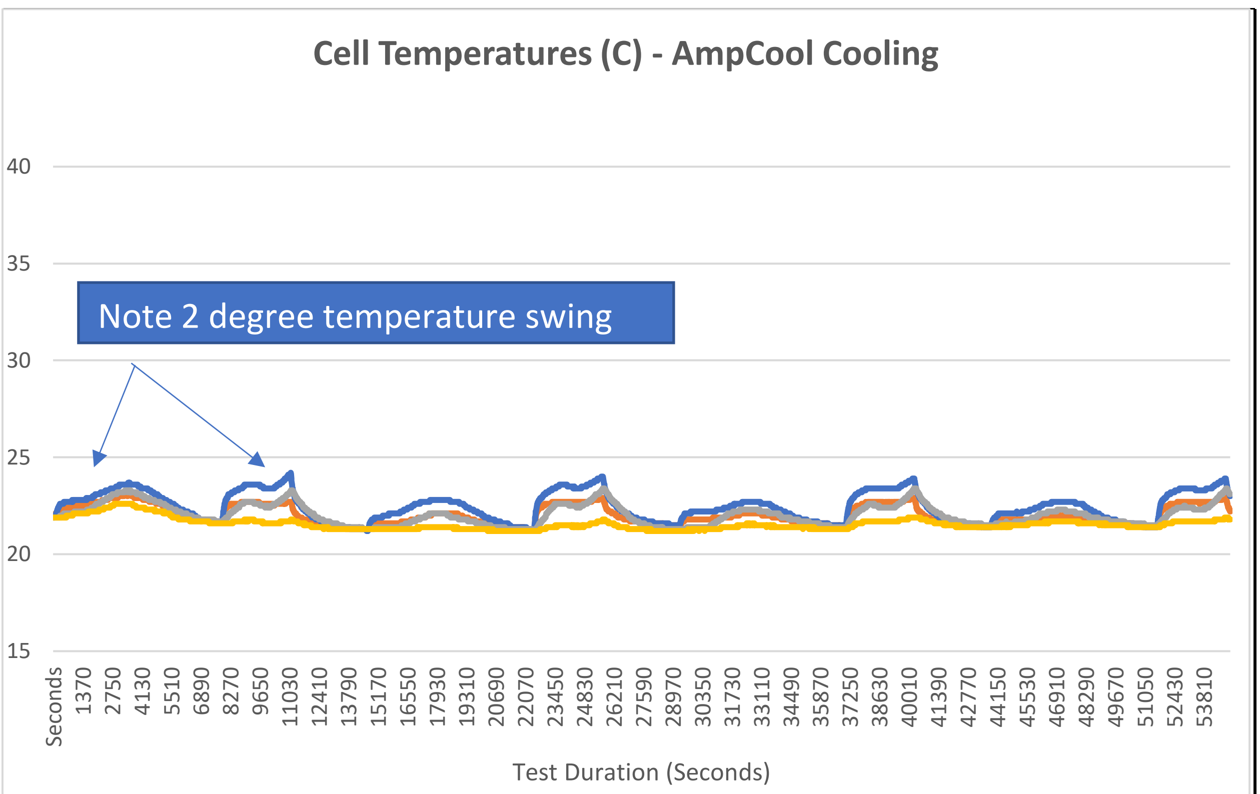
AmpCool Coolant kept temperatures steady and even inside the test cell, air-cooling allowed temperature stratification inside the cell, lessening the cell's efficiency and service life.

Test Results: Comparison of Air Cooling with Immersion Cooling in AmpCool

Parameter	Results for Air	Results for AmpCool
Air or AmpCool Temp	23 +/- 5C	23 +/- 2C
Flowrate	1 liter/min	1 liter/min
Minimum Battery Temp	20.2 C	21.3 C
Maximum Battery Temp	36.7 C	23.1 C
Temperature "Swing" Range	16.5 C	2.2 C
Average Battery Temp	27.7 C	22.0 C
Relative Standard Deviation	0.103	0.023

[1] For more information, please request a copy of Engineered Fluids Technical Paper: "Thermal Management of Li-Ion Battery Cells by Immersion Cooling"


Cell Temperatures (C) - Air Cooling
Note 17 degree temperature swing
40
35
30
25
20
15
Seconds
1370
2750
4130
5510
6890
8270
9650
11030
12410
13790
15170
16550
17930
19310
20690
22070
23450
24830
26210
27590
28970
30350
31730
33110
34490
35870
37250
38630
40010
41390
42770
44150
45530
46910
48290
49670
51050
52430
53810
Test Duration (Seconds)


Cell Temperatures (C) - AmpCool Cooling
40
35
Note 2 degree temperature swing
30
25
20
15
Seconds
1370
2750
4130
5510
6890
8270
9650
11030
12410
13790
15170
16550
17930
19310
20690
22070
23450
24830
26210
27590
28970
30350
31730
33110
34490
35870
37250
38630
40010
41390
42770
44150
45530
46910
48290
49670
51050
52430
53810
Test Duration (Seconds)

Battery Heating
Another aspect of thermal management of battery systems is the case when environmental temperatures are too low to allow efficient use of the battery system. Lithium-ion batteries lose charge/discharge efficiency and amp-hour capacity (which translates to vehicle range) quickly when battery temperatures approach 0 C., and are severely degraded at temperatures below that. (5) SLIC Technology, unlike phase change, air or indirect cooling methods, can easily be used to warm the batteries to their optimum temperature range, ensuring efficient charging, full range capacity and maximum battery life.

Electronics Cooling
Electronics assemblies on board EVs, like their stationary counterparts, are now smaller, while having increased power capacity. Modern EVs have several assemblies of power-dense electronics components that all require advanced thermal management:

- Motor and battery management electronics
- passenger entertainment and communications electronics
- kinetic energy recovery systems
- intelligent driving features (lane control, self-parking, etc)
- enhanced vision and object detection, RADAR, LIDAR

Cooling electronics by immersion through SLIC Technology has been shown to be the most efficient and lowest cost means of thermal management (6) Cooling electronics by direct immersion in a single-phase dielectric coolant has advantages over air or phase-change cooling, and increases the MTBF (Mean Time Between Failures) of electronic components and circuit board assemblies:

Immersion cooling <u>eliminates failure of electronics assemblies caused by corrosion,</u> impurities and pollution in the air – no acids, no more buildup of conductive films, no dust or dirt buildup and no filters to change.

Immersion cooling greatly <u>reduces electronics failures caused by vibration</u>. Vehicles, by their nature, experience numerous sources of low-frequency vibration: bumps, jars, jolts, propeller or road vibration. Vibration has been found to be a primary failure mechanism of electronics assemblies of all types. Immersion cooling dampens

<u>Elimination of fans.</u> The fans that are used to force air through electronics chassis are a major source of failure in themselves, they also impart additional high-frequency vibration to the electronics chassis and circuit boards. Again, dampening this vibration and elimination of its source increases the useful life of electronics components.

<u>Elimination of corrosion</u>. In AmpCool or ElectroCool Coolants, corrosion cannot occur. Engineered Fluids products displace and protect against moisture. Electronics are protected from airborne corrosive acids. And, unlike petroleum oils, there is no corrosive sulfur in Engineered Fluids coolant products, so there will not be any sulfur-based copper corrosion. Galvanic corrosion is stopped.

<u>Elimination of temperature swings</u>. Along with vibration, wide temperature variation and swings is the other major failure mechanism of electronic devices (9). Immersion cooling in AmpCool coolant can keep even high-power electronics at an optimal temperature for efficient application and long life.

Thermal Management of Other Assemblies:
In addition to the thermal management applications discussed here, AmpCool Coolants are used in many other functions:

<u>Cooling high powered lighting, LEDs, or RADAR transmission equipment</u>. AmpCool is optically clear and very effective in thermal management of bulbs, antennas and power electronics.

<u>As a hydraulic or power transfer fluid</u>. AmpCool Coolants are available with enhanced lubricity, allowing its use to cool and lubricate low pressure hydraulic actuators

Cooling and electrically insulating <u>EV charging stations and hoses</u> – AmpCool's high dielectric strength, excellent environmental friendliness and wide materials compatibility profile make it ideal for use in high voltage charging centers.

Summary:
Electric Vehicles have several sets of electrical assemblies that need to be cooled, insulated and protected: EV motors, batteries, charging assemblies, electronics, lights and entertainment systems are all operating at higher temperatures and higher voltages. Immersion cooling with AmpCool Dielectric Coolant can protect these assemblies from overheating, from corrosion and contamination, from temperature swings and from the threat of fire and explosion. AmpCool Dielectric Coolants can

replace many of the different fluids currently used in EVs, leading to lower costs.

Thermal management becomes critical to the development of the next generation vehicle.

Immersion cooling with AmpCool Dielectric Coolants can lower total vehicle weight and raise its reliability. AmpCool Coolants are stable, safe, clean and biodegradable.

Contact Engineered Fluids today to discuss how we can help you implement Single-phase Liquid Immersion Cooling into your next project.

Reference:

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2. "Convective Heat Transfer Coefficients of Automatic Transmission Fluid Jets with Implications for Electric Machine Thermal Management", Kevin Bennion and Gilberto Moreno, National Renewable Energy Laboratory, Presented at the International Technical Conference and Exhibition on Packaging and Integration of Electronic and Photonic Microsystems (InterPACK) San Francisco, California July 6–9, 2015
3. "Physical and Chemical Properties of a Typical Automatic Transmission Fluid", Kemp, S P; Linden, J, U.S. Department of Energy, Presented at the 1990 Society of Automotive Engineers (SAE) International Fuels and Lubricants Conference and Exposition, Tulsa, OK (USA), 22-25 Oct 1990
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7. "Results for Liquid Submerged Server Experiments at NREL's Advanced HVAC Systems Laboratory", E. Kozubal; US DOE National Renewable Energy Laboratory
8. "Impact of Immersion Cooling on Thermo-Mechanical Properties of PCB's and Reliability of Electronic Packages", Shrinath Ramdas, Pavan Rajmane, Tushar Chauhan, Abel Misrak, Dereje Agonafer, presented at ASME 2019 International Technical Conference and Exhibition On Packaging and Integration of Electronic and Photonic Microsystems
9. "Improved Efficiency & Reliability for Data Center Servers Using Immersion Oil Cooling"; Cheryl Tulkoff, Chris Boyd; Electronic Systems Technologies Conference, May 201

Appendix A

CHARACTERISTICS OF AMPCOOL 100-SERIES COOLANTS

Product ID		AC-110	AC-120	AC-130	AC-140
Typical Application		General purpose battery and charger cooling	High performance low viscosity, battery, and charger cable cooling	Cooling of high temperature invertors, chargers, and generators	High fire resistance battery and charger cooling
Appearance		Clear			
Dielectric Strength		>60kV			
Pour Point (°C)		-57	-66	-62	-52
Flash Point (°C)		193	157	228	280
Density, g/cc @ 15.6°C		0.82	0.80	0.82	0.84
Kinematic	0°C	43.10	18.99	144.00	794.61
Viscosity	40°C	8.11	5.02	19.00	67.00
(cSt)	100°C	2.22	1.70	4.10	9.53
Global Warming Potential		0	0	0	0
Biodegradability		>93%	>93%	>70%	>50%
Materials Compatibility Warranty		Yes	Yes	Yes	Yes
Product Operational Warranties (Yrs) [1]		0, 5, 10	0, 5, 10	0, 5, 10	0, 5, 10

AmpCool 200-series products are similar, but they have been made with extra lubricity factors, for cooling submerged pumps, motors, gears and bearings:

CHARACTERISTICS OF AMPCOOL 200-SERIES COOLANTS

Product ID	AC-210	AC-220	AC-230	AC-240
Typical Application	General purpose Dielectric Cooling Lubricant	High performance low viscosity, high stability, with excellent lubricity	Cooling of high temperature electronic and power transfer	Extreme temp lubrication and cooling for motors and actuators
Appearance	Clear			
Dielectric Strength	>60kV			
Pour Point (°C)	-51	-64	-44	-47
Flash Point (°C)	194	235	270	282
Density, g/cc @ 15.6°C	0.82	0.82	0.83	0.84
Kinematic 0°C	43.47	117.00	305.00	595.00
Viscosity 40°C	8.61	17.70	39.00	69.87
(cSt) 100°C	2.40	4.00	7.24	10.19
Global Warming Potential	0	0	0	0
Biodegradability	>92%	>70%	>70%	>50%
Materials Compatibility Warranty	Yes	Yes	Yes	Yes
Product Operational Warranties (Yrs) [1]	0, 5, 10	0, 5, 10	0, 5, 10	0, 5, 10

