BATTERY THERMAL MANAGEMENT IN SUBMARINE APPLICATIONS

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Developments in battery technology have yielded compact energy storage systems that output higher voltages than ever before. Manufacturers of submarine equipment have taken advantage of these new power sources, designing high power propulsion and electronics systems into the latest generation of their equipment. With higher voltage systems, thermal management of the entire electrical system becomes a more important design consideration. The batteries themselves should be maintained within a narrow band of optimal operating temperatures. Power electronics can generate temperatures that exceed the ability of traditional air cooling to dissipate. Making things even more difficult, compact submarine design usually doesn't allow enough room for traditional air cooling to be effective.

This article will show how these challenges can be solved with a cooling technology called Single-phase Liquid Immersion Cooling (SLIC). SLIC Technology cools 2000 times more efficiently than air, and in tight spaces where air cooling won't work.

What is Single-phase Liquid Immersion Cooling?

SLIC Technology refers to a cooling technique where a battery or electronics assembly is immersed directly in a bath of a non-conductive heat transfer fluid. The coolant fluid acts as an electrical insulator, with a dielectric strength of tens of thousands of volts, so high voltage electronics can be submerged without a problem. Any type of electronics can be immersed, without any protective covering. In a UAV, the entire battery and electrical connection system can be immersed. The dielectric fluid is then circulated via a small pump to a heat exchanger, where it is cooled, and then recirculates back to the hot components. There is no boiling, vapor or noise.

On land-based battery and electronics cooling, heat can be transferred into the air via a small radiator system. In marine and submarine applications, a heat exchanger is often built into the hull of the vessel, or heat can be transferred directly through the hull into water.

SLIC Technology is being used today in other industries to cool thousands of different electronic and electrical applications. Immersion cooling is embedded into electric automobiles and heavy vehicles, electric personal watercraft, stationary battery arrays, and data centers.

Immersion Cooling can pack a lot of cooling into a small space. Dielectric coolants are 1500-2000 times more efficient in moving heat than air is. A cooling system of only 20 liters of volume can cool more than a kilowatt of generated heat. Another advantage of immersion cooling is that it extends the life of batteries and electronics assemblies because they're protected from dust, pollution, water and vibration. In addition, hot air is not exhausted inside the submarine enclosure.

Thermal Management of Battery and Charging Systems

Charging and discharging batteries generates heat inside them, and the more rapid the charge/discharge cycle, 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. Battery 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 within each cell to a minimum.

The efficiency of Immersion Cooling to keep batteries at their optimal temperature was proven in a set of experiments performed at Engineered Fluids, Inc. In these experiments, an array of Samsung Model 286s prismatic 94 aH cells were subjected to a series of rapid charge/discharge cycles, once while being cooled with forced air and then again while immersed in an Engineered Fluids Dielectric Coolant. Through this data it is easy to see that Immersion Cooling showed huge advantages over air cooling:

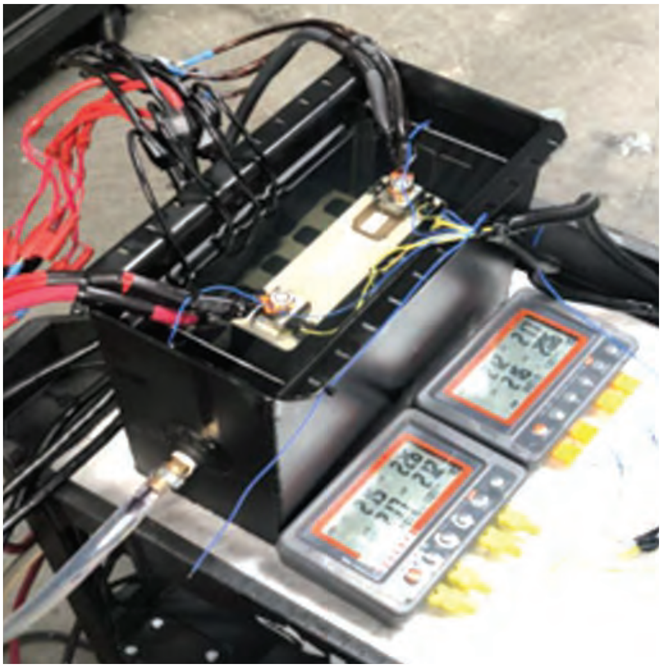


Image courtesy Engineered Fluids Inc.

With Immersion Cooling, the average battery temperature was five degrees C lower than for those cooled with air. Relating this to expected battery service life, this 5 C lower cell temperature translates to an approximate extension of battery life by a factor of 1.4

Test Results: Comparison of Battery Temperatures with Air Cooling and Immersion Cooling:

Parameter	Results for Air Cooling	Results for Immersion Cooling
Coolant 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

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. Immersion Cooling also kept temperatures steady and even inside the test cell. Air-cooling allowed temperature stratification inside the cell, lessening the battery efficiency and service life.

Another aspect of thermal management of battery systems is the case when temperatures are too low to allow efficient use of the battery system. Lithium-ion batteries lose efficiency and amp-hour capacity (which translates to vehicle range) quickly when battery temperatures approach 5 C., and are severely degraded at temperatures below that. SLIC Technology, unlike other 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.

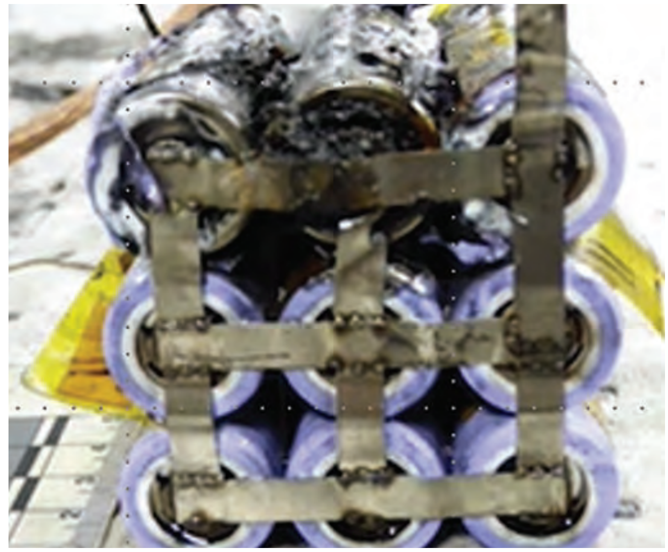
Battery Safety

Another consideration of Battery Thermal Management is fire safety. When short-circuited or overheated, lithium-ion battery cells can enter into "thermal runaway", an intense exothermic reaction. Temperatures of a failed cell can reach 1200 C, and often will involve adjacent cells by overheating them, causing their failure. A set of experiments at Southwest Research Institute demonstrated the ability of Immersion Cooling to remove and absorb enough heat from a thermal runaway event to prevent damage to neighboring cells.

Battery packs of nine Li-ion cells were formed by binding cells with 0.5 mm spacing between them. One battery pack was cooled with air, the other by immersing it into Engineered Fluids' AmpCool™ Fluid. In each battery pack, a nail was driven through one of the cells in the middle of the pack, short-circuiting it and initiating a thermal runaway situation.

The pictures below show the results of the experiment. In the air-cooled pack on the left, the punctured cell began an intense fire which soon enveloped the other cells in the pack, destroying all of them. In the pack immersed in AmpCool Coolant, on the right, the punctured cell began an intense fire, but the energy was absorbed and contained by the coolant fluid. Ad-

Images courtesy Engineered Fluids Inc.



This experiment has since been replicated with other batteries and cell configurations, and demonstrates the inherent fire safety of SLIC Technology.

jacent cells were not affected, and continued to operate normally. Only the punctured cell failed.

This experiment has since been replicated with other batteries and cell configurations, and demonstrates the inherent fire safety of SLIC Technology. Images courtesy Engineered Fluids Inc.

Electronics Cooling

Electronics assemblies on board marine and submarine vehicles are now smaller, while having increased power capacity. Modern UAVs have several assemblies of power-dense electronics components that all require advanced thermal management:

- Motor driver and battery management electronics
- communications electronics
- energy recovery systems
- navigation electronics
- 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. Cooling electronics by direct immersion in a single-phase dielectric coolant has advantages over air or "cold plate" cooling, increasing the MTBF (Mean Time Between Failures) of electronic components and circuit board assemblies:

Elimination of fans. 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.

Elimination of component corrosion. Immersed in a dielectric fluid, corrosion cannot occur.

Moisture displacement. Condensation in humid environments cannot occur.

Elimination of temperature swings.

Summary

Marine and Submarine Electric Vehicles have several sets of electrical assemblies that need to be cooled, insulated and protected. Along with batteries, propulsion motors, charging assemblies, electronics, navigation and vision systems are all operating at higher temperatures and higher voltages. Immersion cooling can protect these assemblies from overheating, from corrosion and contamination, from temperature swings and from the threat of fire and explosion. Immersion cooling can lower total vehicle weight and raise its reliability. Immersion Cooling is a proven, safe, and clean technology.

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About the Author

Dr. David Sundin is Founder and Chief Scientist of Engineered Fluids, Inc., a provider of thermal management of batteries, EVs and data centers via Immersion Cooling. He has over 30 years' experience developing and applying specialty electrical cooling fluids and has held leadership positions in a variety of IEEE and ASTM Committees.

Image courtesy Kystdesign

currents, SMD explains. The flight control system can also link to other SMART systems unlocking autonomous functionality. They use unique electric propulsion technology that offers extreme performance in fast-moving water, but not at the expense of fine control. "All this adds up to a range that can work where current generation vehicles can't, that opens up the operating weather window and delivers higher quality results. All while being more environmentally friendly," SMD says. Looking to the future of work class ROVs, SMD shared, "Work class ROVs are a multipurpose tool. And as with any tool there is always a focus on how well it does the job, its reliability, and its dependability. But the offshore energy mix is changing. And we are also seeing changes to the way people work (and go to sea) with much more emphasis on work-life balance and the environment. So, the robotic tools that construct and maintain energy infrastructure need to evolve.

In the future, the tools we today call work class ROVs will need to be suitable for uncrewed vessel and resident work; we may see less cabled connections to the surface and onboard power systems; we will probably see AI start performing tasks, with a move from person in loop to person on loop-command to control. It will be easier and faster to undertake tasks and see the results, with real-time information at the fingertips of stakeholders anywhere in the world."