Thermal Management of Li-Ion Batteries With Immersion Cooling

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***Abstract* – Development of effective thermal management techniques is essential in enabling further technical advances and wide public acceptance of lithium-ion based battery electrical storage. Thermal management of battery arrays has sometimes been accomplished by circulating a water-based coolant solution around or on the batteries. This approach uses large amounts of water in locations where it is sometimes scarce.**

Immersion cooling in a dielectric coolant can eliminate water use in this application and provide more stable temperature regulation. Engineered Fluids has recently completed a series of experiments demonstrating the high efficiency of Single-phase Liquid Immersion Cooling (SLIC) technology for the thermal management of Li-ion batteries. This paper reviews the results of these experiments and discusses some of the issues and solutions for battery thermal management, and outlines the proper design of battery thermal management systems. We will discuss such topics as active cooling versus passive cooling, liquid cooling versus air cooling, cooling and heating versus cooling only systems, and relative needs of thermal management for VRLA, NiMH, and Li-Ion batteries.

Index Terms - #immersioncooling, #thermalmanagement, #batterycooling #SLIC

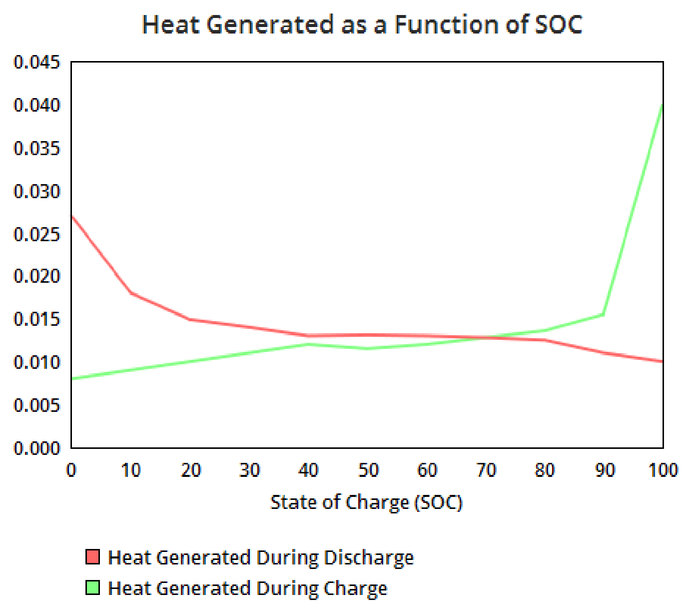
Introduction

I. Heat Generation in Batteries

Significant quantities of heat are created inside lithium-ion (Li-Ion) battery cells during the charge and discharge cycles. This heat is generated by exothermic chemical reactions, primarily, as well as losses from activation energy, ionic migration resistance, and chemical transport. [4] [5] [6] The majority of heat is generated at charge and discharge extremes; there is normally little heat generated at a State of Charge (SOC) between 20 and 80%, [1,2] as shown in Figure 1.

Heat generated by Li-ion battery cells during operation is increased by several factors and the combinations of these factors further increases the heat energy created. The following factors increase the heat generated by a li-ion cell: faster (shorter time duration) charge or discharge cycle, shorter "rest" periods between charge/discharge cycles, battery aging due to the degradation of ion migration pathways. Increases of 35% to 70% above nominal rated values are not uncommon, according to battery manufacturers. [3] Heat generation also increases at lower temperatures throughout the battery's life.

Figure 1. Heat generated through a cycle at 1 C-rate showing heat generated as a function of State of Charge



II. Heat Transfer in Battery Cells and Modules

Battery energy storage systems are most commonly composed of multiple individual battery cells of identical voltage, Amp-hour rating, and chemistry connected in series and parallel across their tabs to create a single battery module of the desired voltage and Amp-hour rating. Such battery modules include a framework or casing in which to house the cells to maintain their orientation and in many cases facilitate individual cell cooling. Today, most stationary battery array systems use air as the medium to cool the battery modules. In electric vehicle battery systems, either air-cooling or indirect "cold plate" cooling is used, or in some cases a hybrid of air and cold plates is used for battery module cooling.

The steady state heat transfer equation that describes battery cell cooling is:

$$Q_{BAT} = U'A(T_{BAT} - T_{Avg2,3})$$

Where ***U'*** [units: W/°C] is a combined heat transfer coefficient that uses both conductive heat transfer from the inside of the cells to the surface of the cells and the cell tabs as well as convective heat transfer from the cell surface and tabs to the air. The cooling surface is most often the external casing of the battery module and/or the metallic tabs. [4]

This equation can be simplified to one that uses only the heat transfer medium's (air, water, or dielectric coolant) characteristics:

$$Q_{BAT} = (F \ \ r \ \ C_p(T_3 - T_2)$$

Where:
F= flowrate (cm^3/second)
Cp = heat transfer coefficient of the battery material
T3= high temperature
T2= low temperature

In order to adequately cool the battery cells, two conditions must be met. First, the sum of all heat removed must be greater than all heat generated, or in equation form:

$$U' > \frac{Q_{BAT}}{T_{BAT} - T_{AMB}}$$

(Dictating that the sum of heat transfer coefficients must be greater than the heat generated by the battery divided by the delta-T allowable between battery temperature and ambient air temperature)

Second, the mass of heat transfer medium (air, water, or dielectric coolant) in contact with the battery cells must be sufficient to absorb the heat that the cells generate [5]:

$$F > \frac{Q_{BAT}}{r \cdot C_P \cdot \Delta T}$$

III. Battery Thermal Management Requirements

Thermal management affects the life of the battery in several ways:

1. By maintaining the battery cell's temperature in their optimal zone for operation.
2. By minimizing temperature variance and cycling. Beyond maintenance of the temperature inside a band that is optimum for the cells' performance, thermal cycling, or excursion has been identified as a key failure mechanism of electronic assemblies in general, and battery chemistry, in particular. Minimization of thermal cycling is key to obtaining maximum efficiency and service life from batteries. [6]
3. By minimizing thermal stratification within individual cells. During charge/discharge cycles, ion migration inside the cell results in non-uniform heating, which lowers the cell's charge/discharge rate, and ultimately, its service life.
4. By maintaining homogeneous temperature distribution from cell to cell. Temperature variation from cell to cell in a battery module leads to different charge/discharge cycling behavior for each cell.
5. This, in turn, makes the cells in the module electrically unbalanced, which reduces the overall module performance [6]. The design of a battery module dictates its temperature distribution. Heat generated by each cell in a module may not be spatially uniform due to several factors: physical form factor, aspect ratio, number of cells and geometry of the cells and module, thermal conductivity of the module framework and case, placement of the positive and negative terminals, the size of the tabs on the cells, and the size and position of the cell's electrical interconnects within the module. Non-uniform heat generation leads to non-uniform temperature distribution in the module.

IV. Air Cooling vs Liquid Cooling

Traditionally, batteries have been cooled with forced air, and Li-ion batteries are no exception. Air cooling uses the principle of convection to move heat from the cell or module into the surrounding air mass. Ambient or cooled air is directed to flow across the surface of the battery cell or module, which may feature cooling fins or another means of increasing the surface area of the module to facilitate the transfer of the heat generated internally to the surrounding or flowing air mass. Although generally considered an inexpensive means of cooling, thermal management with air requires a significant amount of air be directed or forced over the surface of the battery module, typically this is accomplished with active fans and ducting or purely convection to move the air mass into and around the module.

Air has a very low heat capacity (Cp = 1.006 kJ/kg K at standard temperature), so a large volume of air must be used, particularly when the delta in temperature between the battery module casing and the ambient air temperature is low. Another challenge of air cooling is that a battery's heat transfer surface must be exposed to air, so its physical location is restricted to those locations where air flow is available or where the air can be channeled. This may create the need to add additional infrastructure and volume to the system to ensure the total mass of air needed to cool the system is available, not to mention any filtering or conditioning that maybe required to prevent corrosion or degradation of the battery module materials.

This approach is being challenged due to new application demands placed on batteries, as well as changing battery chemistries. The application demands that require more efficient thermal management include:

- faster charge/discharge cycles (higher amperages)
- reduced rest periods between cycles (faster cycling)
- longer service life (more charge/discharge cycles)
- higher battery voltages
- The need to maintain more stabilized, constant voltage output during discharge and over the service life of the battery.

One alternative to traditional air cooling is indirect liquid cooling, in which a water/glycol solution or dielectric liquid coolant flows through a heat sink or "cold plate" within the battery framework or structure of the battery module, cooling the battery cells through conduction via their direct thermal bonding with the heat sink within the module case. Aqueous glycol coolants are by their composition highly electrically conductive, which means that aqueous coolants cannot be brought in direct contact with the battery tabs and wiring. The conductive nature of aqueous coolants limits their use to indirect cooling methods, such as water jackets around battery modules or cold plates placed within the battery module.

Water/glycol coolants have very high heat capacity (Cp = 3.777 kJ/kg K at 26.7C) and are efficient at removal of heat from the heat sink. However, this efficiency is mitigated because the heat must be conducted through walls of the jacket/container or fins. In addition, because many battery modules are composed of a high quantity of pouch or cylindrical cells it is important that the heat sink is thermally bonded to the entire surface of the battery cell walls and tabs to ensure proper conduction of the heat to the cold plate or jacket. Any air gaps left between the battery cells act as thermal insulation rapidly degrading the cooling efficiency of the system. This typically results in the use of high precision manufactured aluminum frameworks and cold plates along with dielectric thermal grease or epoxy bonding agents to ensure there are no air gaps between the battery cells' surfaces and the framework. The cost of fabrication of such systems can be expensive, yield rates low, and failure rates high due to the overall complexity of the system. In particular manufacturers and users have noted that the reliability of aqueous indirect cooling systems for Li-ion batteries is critical to ensure no aqueous solution leaks into contact with the batteries, wiring, and/or other electrical components causing them to short to each other, cold plate, and/or battery module casing, potentially causing thermal runaway in the effected cells or injury to the user due to the high amperage and voltages involved.

The rate of heat transfer through the battery itself, through the walls of the battery module, and then through the electrically insulating water jacket, or heat sink framework and cold plate, is a function of temperature gradient and the thermal conductivity coefficients of the different materials involved in each of these layers.

Direct immersion cooling systems using single-phase dielectric liquids are another means of cooling battery cells and modules. In direct liquid immersion cooling, often called Single-phase Liquid Immersion Cooling (SLIC), the battery cells are fully immersed in a dielectric heat transfer fluid (dielectric coolant). The dielectric coolant is typically circulated with a pump in order to ensure a constant flow of dielectric coolant within the system design to ensure continuous contact with all the cell walls, tabs, and electrical wiring within the battery module. The flow of directric coolant absorbs the heat generated by the cells through direct conduction and is then circulated to a heat transfer device such as a radiator or heat exchanger to transfer the heat energy to the environment, or, if the heat load is low enough, can be passively cooled by convective air flow through the walls of the battery module or cell.

The rate of heat transfer between the walls of the battery cells and the dielectric coolant depends on several factors, including its thermal conductivity, viscosity, density, and velocity of the dielectric coolant. For the same volumetric flow rate, heat-transfer with dielectric coolants is much more efficient than with air because of the thinner boundary layer and higher thermal conductivity of the liquid (approximately 1.3 -1.4 kJ/kg K). This high heat capacity allows a much lower flowrate with a dielectric coolant than with air.

Liquid coolants have higher thermal conductivity and heat density than air, and therefore perform very effectively as a cooling medium. Of these options, direct immersion in liquid single-phase dielectric coolants (SLIC) will theoretically deliver the best performance for maintaining battery cells and modules in the correct temperature range, with a minimum of temperature variation and at the lowest cost and complexity for the system. The reduced complexity comes from the elimination of the need for any intermediate heat sink framework or complex manufacturing of a precision framework to hold the cells, and any thermal bonding requirements as the dielectric liquid coolant is in direct contact with all parts of the system.

A key safety advantage that dielectric SLIC coolants have over water glycol and other conductive coolants is that they can be brought into direct contact with all components of the system without causing thermal runaway of the cells, shorting failures of electronics, or shock hazard to users. In addition, with biodegradable, non-toxic, food grade rated dielectric liquid coolants the safety and environmental issues related to leaking and disposal of hazardous aqueous glycol coolants are avoided.

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V. Liquid Immersion Testing

Objectives of testing battery thermal management with Single-phase Liquid Immersion Cooling (SLIC) technology are:

- Determine compatibility of battery cells and modules with the dielectric liquid coolants
- Evaluate heat transfer properties of the solution and impact to battery module
- Compare heat transfer characteristics with air cooling
- Hypothesize impact on safety, capital expenditures, operating and maintenance costs, and system level improvements
- Finalize system level design for immersion cooling

VI. Experimental Procedure

The efficiency of SLIC technology for thermal management of batteries was proven in a set of experiments performed at Engineered Fluids' Application Development Laboratory. In these experiments a prismatic 68AH cell (Samsung Model 286S) was subjected to a series of four charge/discharge cycles, while being cooled with forced air and subsequently using the same cycle pattern while fully immersed in Engineered Fluids' AmpCool™ AC-110 Dielectric Coolant cooled to ambient air temperature through the use of a pump, radiator and fan.[1]

The test cycle parameters for Phases 1 and 2 are shown in figures 2 and 3 respectively.

Figure 2: Phase 1 Charge/ Discharge Test Parameters

ACTIVITY	DURATION (MIN)	ENDING SOC
REST - INITIAL	1	30%
CHARGE - CYCLE 1	110	100%
REST	20	99%
DISCHARGE - CYCLE 1	60	0%
REST	60	1%
CHARGE - CYCLE 2	110	100%
REST	20	99%
DISCHARGE - CYCLE 2	60	0%
REST	60	1%
CHARGE – CYCLE 3	110	100%
REST	20	99%
DISCHARGE – CYCLE 3	60	0%
REST	60	1%
CHARGE - CYCLE 4	110	100%
REST	20	99%
DISCHARGE - CYCLE 4	60	0%
REST	60	1%

Note: The charging cycle time of 110m / .55C to achieve 100% State of Charge (SOC) was necessitated by the limitation of the charging equipment's maximum output of 40 Amps.

The test utilized "constant current charging and discharging." The first phase (Phase I) of the experiment utilized a charge cycle of 110 minutes using 40A equal to 0.55/C and a discharge cycle using a 68A load at 1/C per the battery manufactures specification. Because the cell is designed for use with air cooling, we followed the manufacturer's recommendations for rest and stabilization time between the charge/discharge cycles. The cell was allowed to rest for 20 minutes between charge and discharge to allow the cell's voltage to stabilize. The cell was also allowed to rest after each full discharge for 60 minutes to allow the battery temperature to stabilize, again per manufacturer's recommendations.

During the second phase (Phase II) of the experiment, the time period for all rest periods was set at 20 minutes and the discharge cycle was accelerated to 30 minutes, reducing by half the Phase I 60 minutes cycle, resulting in a 2/C discharge cycle. The purpose of this test was to determine the ability of Single-phase Liquid Immersion Cooling to manage more rapid and higher temperature variation and higher thermal stress on the battery cell.

Figure 3: Phase 2 Charge/ Discharge Test Parameters

Activity	Duration (min)	Ending SOC
REST - INITIAL	1	30%
CHARGE - CYCLE 1	110	100%
REST	20	99%
DISCHARGE - CYCLE 1	30	0%
REST	20	1%
CHARGE - CYCLE 2	110	100%
REST	20	99%
DISCHARGE - CYCLE 2	30	0%
REST	20	1%
CHARGE – CYCLE 3	110	100%
REST	20	99%
DISCHARGE – CYCLE 3	30	0%
REST	20	1%
CHARGE - CYCLE 4	110	100%
REST	20	99%
DISCHARGE - CYCLE 4	30	0%
REST	20	1%

During each full testing cycle, the temperature of the cell was monitored on each of the battery cell's tabs (positive and negative as well as on two sides and top of the cell using type-K thermal probes thermally bonded to the cell. The temperatures were recorded in 10secd intervals.

Parameters for these tests were:

Ambient Air Temperature: 21C +/- 3C

Air Cooling Test (Control)

Air Input Temp:	23.0 +/- 5.0C
Air Volumetric Flowrate:	28.4 liters per minute

Liquid Immersion Cooling Test:

Liquid Coolant Input Temp:	23.0 +/- 0.5C
Liquid Coolant Flowrate:	0.5 liters per minute

The temperature and volume of air flow specified for cooling was per the manufacturer's recommendations. The volume of the liquid coolant flow was determined as the lowest speed setting of the circulation pump used in the test setup.

Battery cell charge and discharge cycles were performed with the use of a Cadex 8000 Battery Charger/Tester having all four 10A outputs interconnected and slaved to channel one for a total charging capacity of 40A at 12VDC, and a B&K Precision 8518 DC Battery Load with a maximum load of 100A at 12VDC. Figure 4 shows the electrical connections from the Test Battery, the Battery Charger/Tester and the Battery Load. Figure 4 describes the electrical charge and discharge equipment setup.

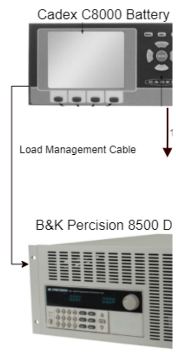
The fluid cooling unit used was a Koolance ERM-3K3UA Liquid Cooling System, Rev1.1 which has been retrofitted to be material compatible with the AmpCool AC-110 coolant. The retrofit required the replacement of all rubber seals and O-rings with FMK and the replacement of all vinyl hoses with Tygon tubing. The cooling unit at maximum cooling capacity of 2kW @ 20C ambient air temperature using AmpCool™ AC-110 coolant. Figure 5 describes the liquid and air-cooling equipment setup.

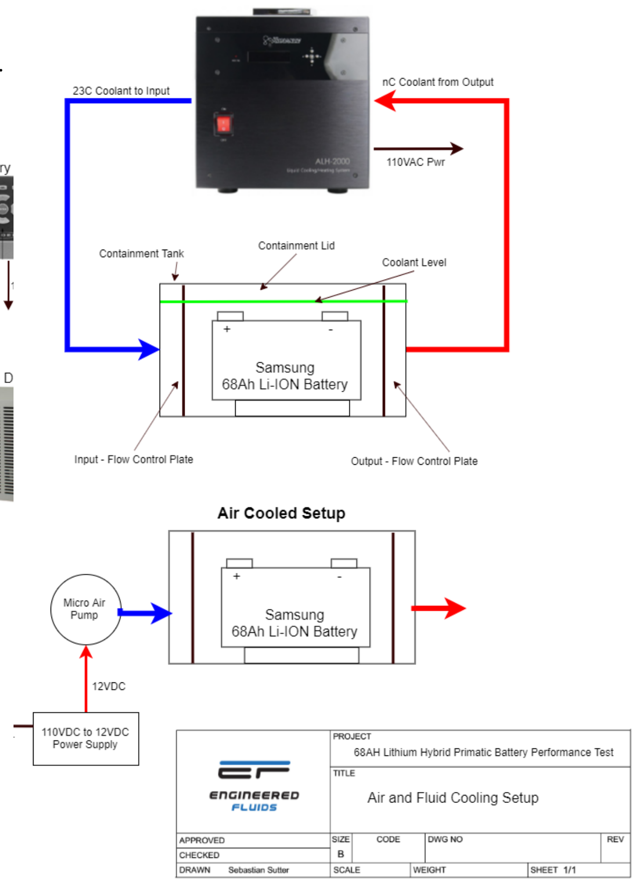
The coolant used in this study is AmpCool™ AC-110, a liquid synthetic dielectric (electrically non-conductive) coolant made by Engineered Fluids specifically for thermal management of electric motors and batteries. AmpCool™ AC-110 Coolant is clear, has no smell, is biodegradable, nontoxic and has been granted Food Grade Status in the US. (1). AmpCool™ AC-110 Coolant does not boil, remaining in the liquid phase at all application temperatures from -66 C to 280C. It has a low viscosity, which enhances its heat transfer efficiency. Figure 6 describes the characteristics of the Engineered Fluids' AmpCool™ AC-110 Dielectric Coolant.

Figure 7 is a photo of the steel test tank used for both battery and air testing. The steel plates visible inside the tank on each narrow end are removable baffles used during liquid testing to provide even liquid coolant flow over all the surfaces of the battery. These baffles were removed during air testing as they degraded the air-cooled performance. A foam cover was sealed into the top of the test tank during both air and liquid testing to isolate the internal environment during testing. During liquid test the battery cell was completely immersed in

Figure 5: Battery Cooling Test Setup

Figure 4:





the AmpCool™ AC-110 Dielectric Coolant such that 25mm of coolant were present on all sides of the battery. The net volume of the liquid coolant present in the tank during testing was 2.786 Liters.

Figure 8 is a photo of the liquid immersion test rig with the battery fully immersed in AmpCool AC-110 prior to the cover being placed on the rig. Figure 7 shows the placement of thermocouples on the Li-ion battery cell.

Figure 6: Characteristics of AmpCool AC-110 Coolant

Product ID	AC-110
Applications	Stationary and vehicular battery cooling
ISO 4460 Particle Count (Avg.)	10/10/2012
Appearance	Clear
Refractive Index nD20	1.462
Dielectric Constant	2.3
Dielectric Strength, kV	>60kV
Resistivity (ohm-cm)	>1x1014
Pour Point (°C)	-55
Flash Point (°C)	180
Density, g/cc @ 16 °C	0.8113
Coefficient of Thermal Expansion, vol./ °C	0.00068
Viscosity (cSt) @ 40 °C	9.58
Viscosity (cSt) @ 100 °C	2.68
Thermal Conductivity (W/m*K) @ 40 °C	0.1373
Specific Heat (kJ/kg*C) @ 40C	2.2032
Biodegradability (28 Days)	>96%
Global Warming Potential	0

Figure 7: Placement of Thermocouples on Battery Cell

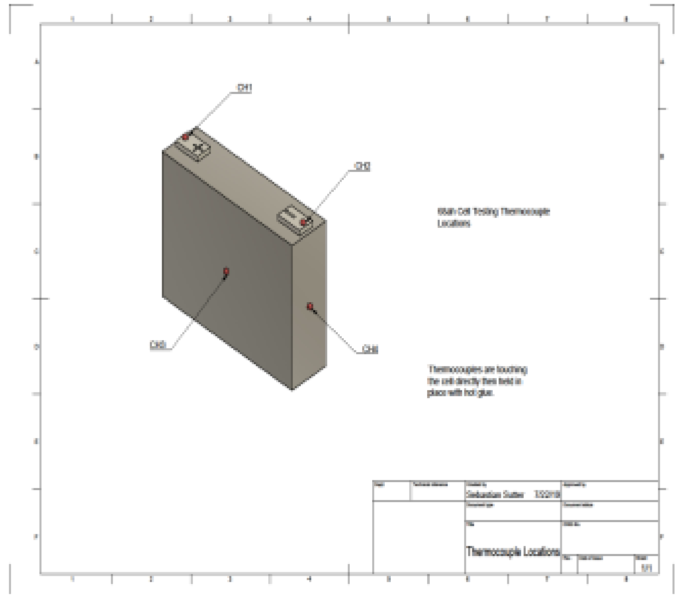


Figure 8: Steel Test Tank with Battery Cell

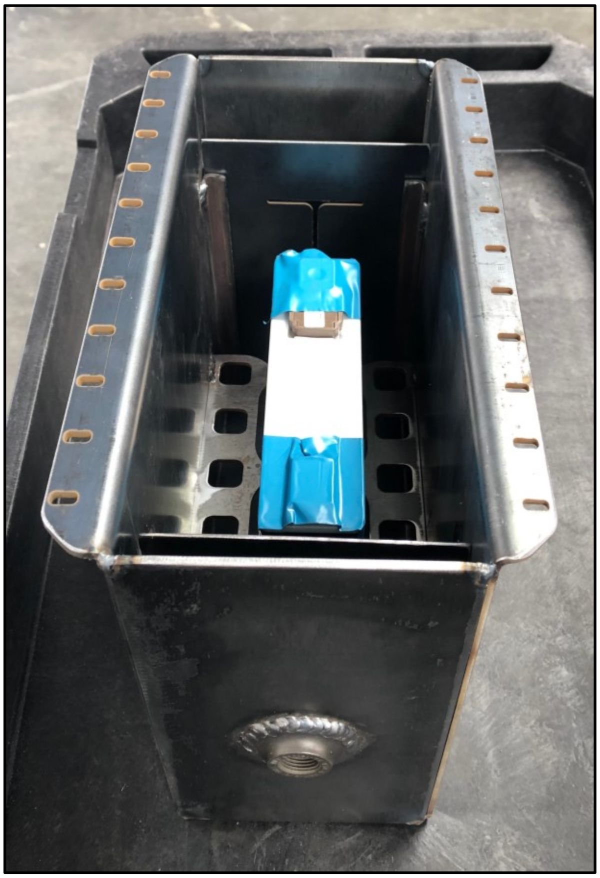


Figure 9: Liquid Immersion Test setup with Battery in AmpCool™ AC-110

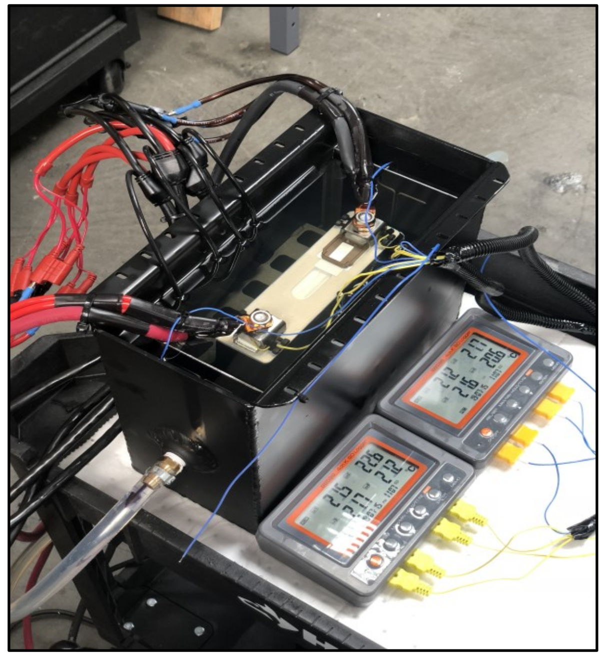


Figure 10: Dimensions of Battery Cell and Fluid Volume in Test Tank

Battery and Coolant Volumes	68AH Battery Cell	Test Tank Fluid Depth
Length, mm	174	224
Width, mm	46	96
Height, mm	126	176
Total Volume, mm^3	999,988	3,784,705
Total Volume, liters	0.999	3.785
Net Volume Coolant	2.786 Liters	

Figure 10 provides the dimensions of the internal volume of the steel test tank that was used to contain the battery cell during testing. The tank was constructed of steel 12 cold rolled steel as a measure of safety during the testing should the cell go into thermal overload. Even with the added stress of very aggressive discharges while being liquid cooled, we were never able to push the battery cell temperatures above 27C which is not close to 120C thermal runaway temperature.

Figure 11 provides the characteristics of the Samsung Model 286S hybrid chemistry battery cell that was used throughout the testing. The same cell was used for both air and liquid testing to maintain consistency of the test results. The Air testing was conducted first in accordance with the manufacturer's recommendations.

Figure 11: Characteristics of Samsung Model 286S Battery Cell

Battery Cell	Parameters	Specification
	Shape	Prismatic
	Battery chemistry	NCM/LMO blend
	Dimension (L x W x H), mm	173.9× 45.6 × 125.6
	Weight, kg	1.91
	Nominal capacity, Ah	68
	Nominal voltage, V	3.65
	Nominal energy, Wh	248.2
	Operational voltage, V	3.1 ~ 4.1
	Charging method	CC-CV

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Figures 12, 132, and 14
Transient Temperature Rise in a 68AH Battery Cell During Charge and Discharge by Cooling Method

Comparison of Cell Temperatures with Air Cooling
vs. Single-phase Liquid Immersion Cooling (SLIC) with AmpCool™ Dielectric Coolant

Chart Legend:
Blue line: Temperature at Positive Tab
Red Line: Temperature at Negative Tab
Yellow line: Temperature at Short side wall
Green Line: Temperature at Long side wall

Figure 12: Air Cooled Battery Test – Phase 1 Charge / Discharge Cycle

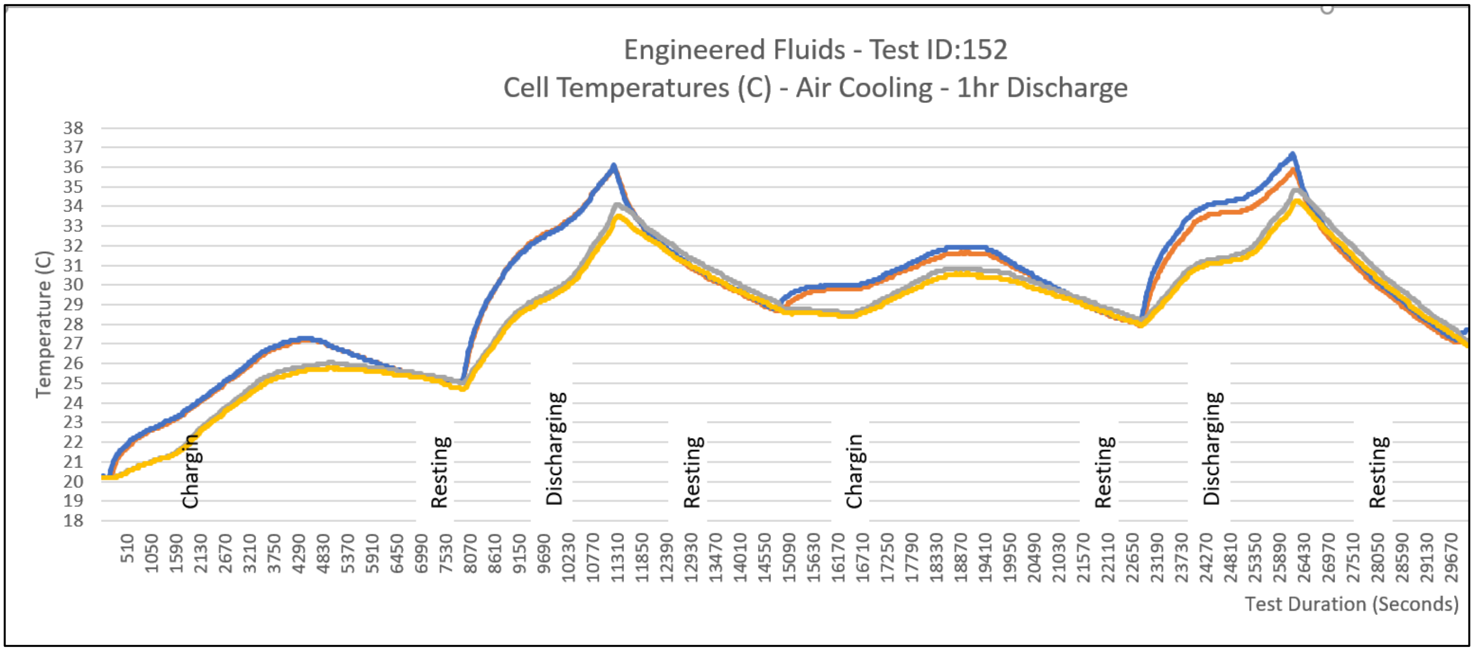


Figure 13: Liquid Cooled Battery Test – Phase 1 Charge / Discharge Cycle

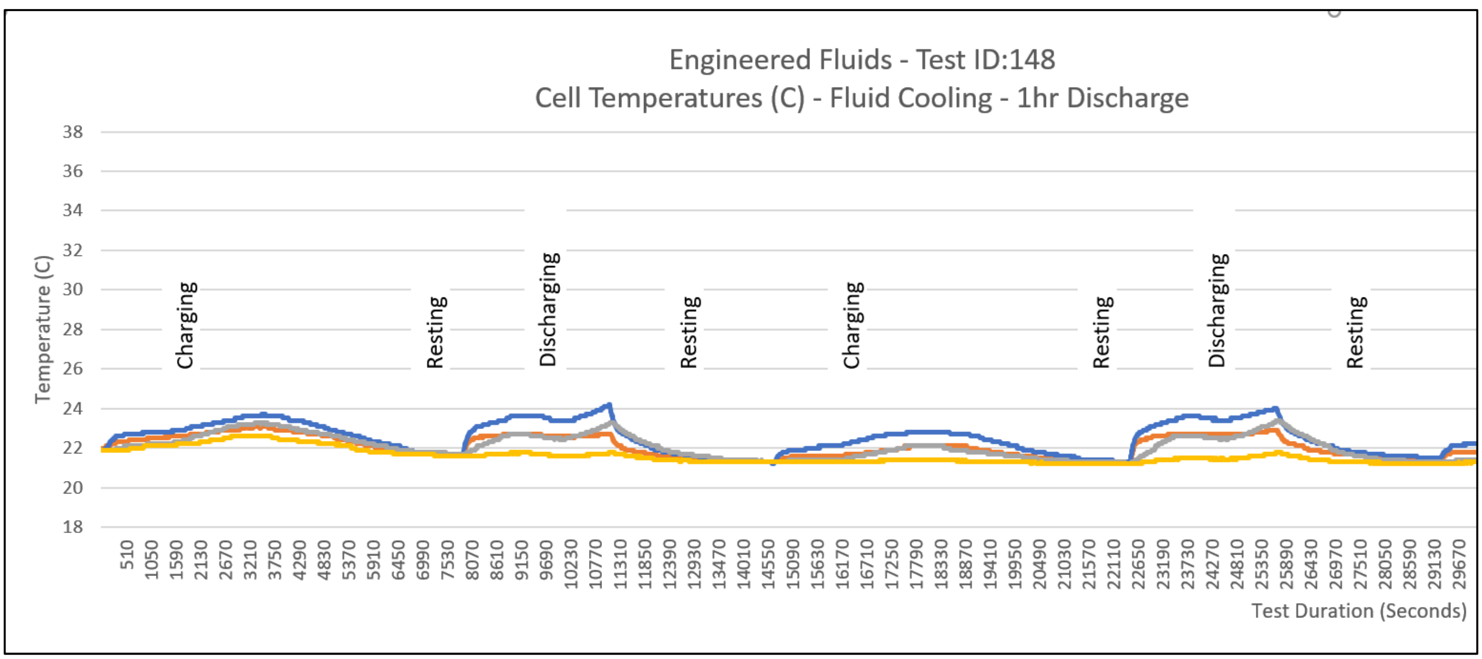


Figure 14: Liquid Cooled Battery Test – Phase 2 Charge / Discharge Cycle

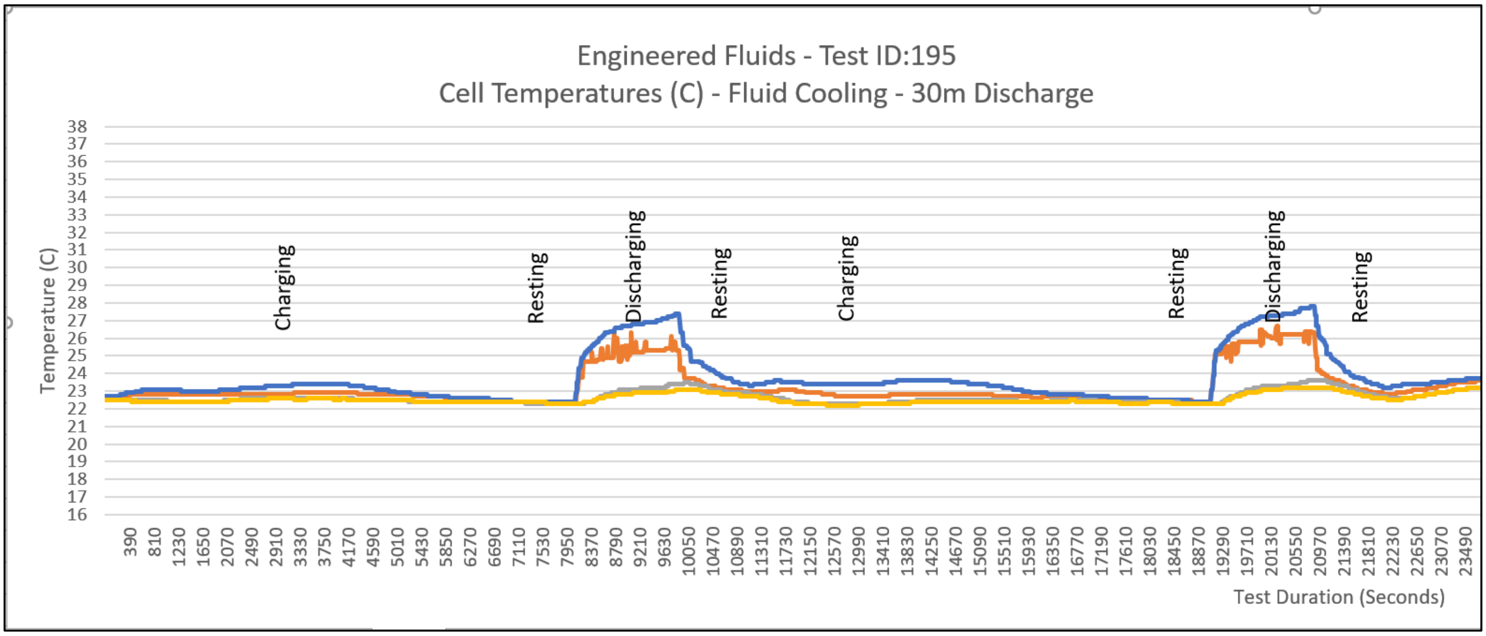


Figure 15: Summary of Maximum and Minimum Cell Temperature by Location and Cooling Method

		Test ID 152 - Air Cooled - 1hr Discharge				*TEST 148 - Liquid Cooled - 1hr Discharge*				*Test ID 152 - Liquid Cooled - 30m Discharge*			
Cycle	**Status**	**Terminal + Max °C**	**Terminal- Max °C**	**Long Wall Max °C**	**Short Wall Max °C**	**Terminal + Max °C**	**Terminal- Max °C**	**Long Wall Max °C**	**Short Wall Max °C**	**Terminal + Max °C**	**Terminal- Max °C**	**Long Wall Max °C**	**Short Wall Max °C**
0	STARTUP	20.2	20.3	20.2	20.2	22.0	21.9	21.9	21.9	22.6	22.7	22.5	22.5
1.1	RESTING	20.2	20.3	20.2	20.2	22.0	21.9	21.9	21.9	22.6	22.7	22.5	22.5
1.2	CHARGE	27.2	27.3	26.1	25.8	23.1	23.7	23.3	22.6	22.9	23.4	22.6	22.6
1.3	RESTING	25.6	25.6	25.6	25.4	21.8	22.0	21.9	21.7	22.5	22.5	22.4	22.4
1.4	DISCHARGE	35.6	35.7	33.2	32.6	22.7	24.1	23.1	21.8	26.3	27.3	23.4	23.0
2.1	RESTING	36.0	36.1	34.1	33.5	22.7	24.2	23.3	21.8	25.8	27.4	23.5	23.1
2.2	CHARGE	31.7	31.9	30.8	30.6	22.1	22.8	22.1	21.4	23.1	23.6	22.9	22.7
2.3	RESTING	29.1	29.2	29.3	29.1	21.4	21.6	21.3	21.2	22.6	22.6	22.4	22.4
2,4	DISCHARGE	35.6	36.3	34.2	33.6	22.9	23.9	23.2	21.7	26.7	27.7	23.6	23.2
3.1	RESTING	35.9	36.7	34.8	34.3	22.9	24.0	23.4	21.8	26.4	27.8	23.6	23.2
3.2	CHARGE	28.5	29.1	27.9	27.6	22.1	22.7	22.3	21.6	24.1	24.7	23.7	23.7
3.3	RESTING	25.7	25.8	26.0	25.7	21.6	21.6	21.6	21.3	22.4	22.4	22.3	22.3
3.4	DISCHARGE	32.3	33.3	31.1	30.6	22.9	23.8	23.2	21.9	26.3	27.2	23.2	23.1
4.1	RESTING	32.7	33.7	31.8	31.3	22.9	23.9	23.4	21.9	26.8	27.3	23.4	23.2
4.2	CHARGE	27.1	27.6	26.6	26.2	22.1	22.7	22.3	21.7	23.1	23.6	22.7	22.6
4.3	RESTING	24.3	24.4	24.6	24.3	21.6	21.6	21.6	21.4	22.4	22.4	22.4	22.4
4.4	DISCHARGE	31.1	32.1	29.8	29.3	22.9	23.8	23.2	21.8	25.9	27.1	23.1	23.0
5	RESTING	31.1	32.1	29.9	29.4	22.9	23.8	23.2	21.8	25.8	27.2	23.2	23.0
6	FINISHED	31.4	32.4	30.5	29.9	22.9	23.9	23.4	21.9	25.8	27.2	23.2	23.0

Figure 16: Comparison of Cooling Performance – Battery Cell Positive Terminal / Max Temp C

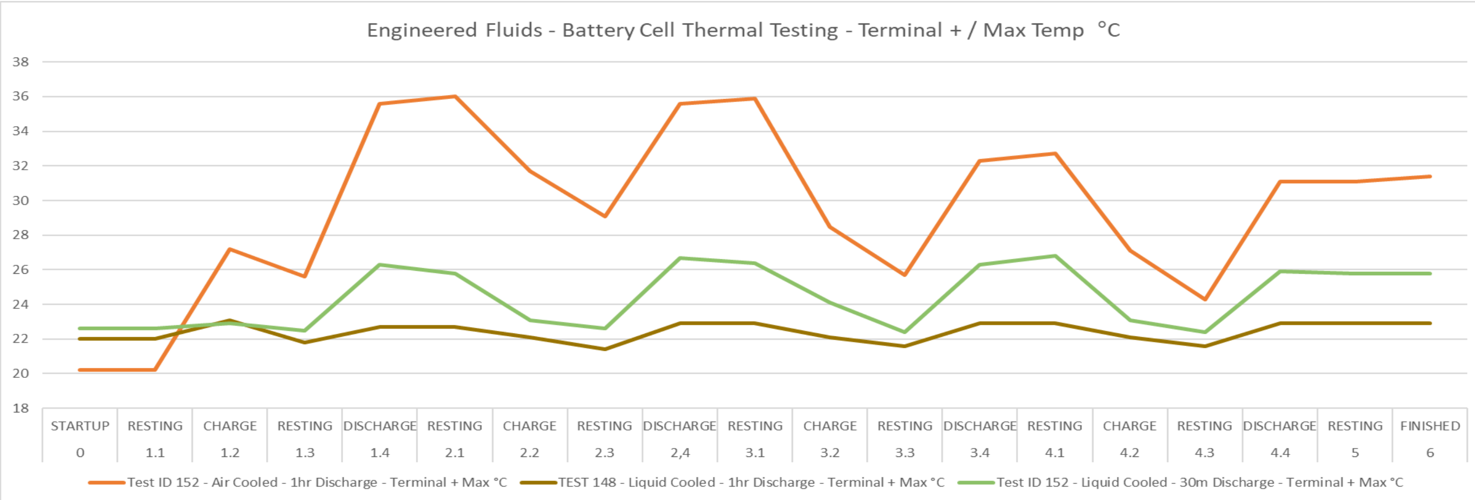


Figure 17: Comparison of Cooling Performance – Battery Cell Negative Terminal / Max Temp C

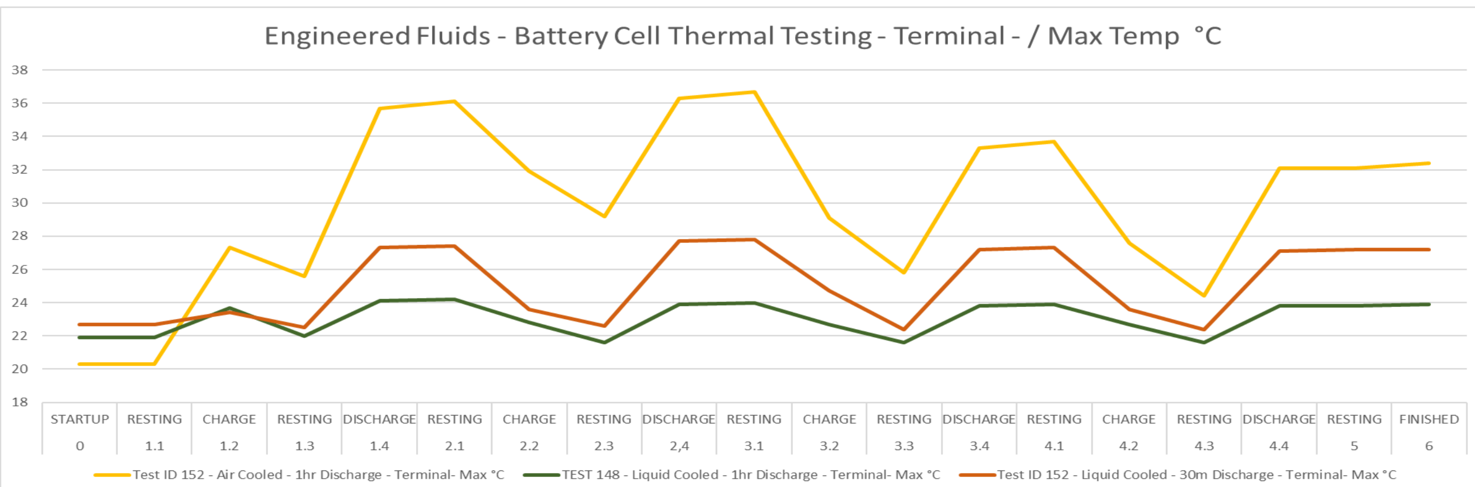


Figure 18: Comparison of Cooling Performance – Battery Cell Long Wall / Max Temp C

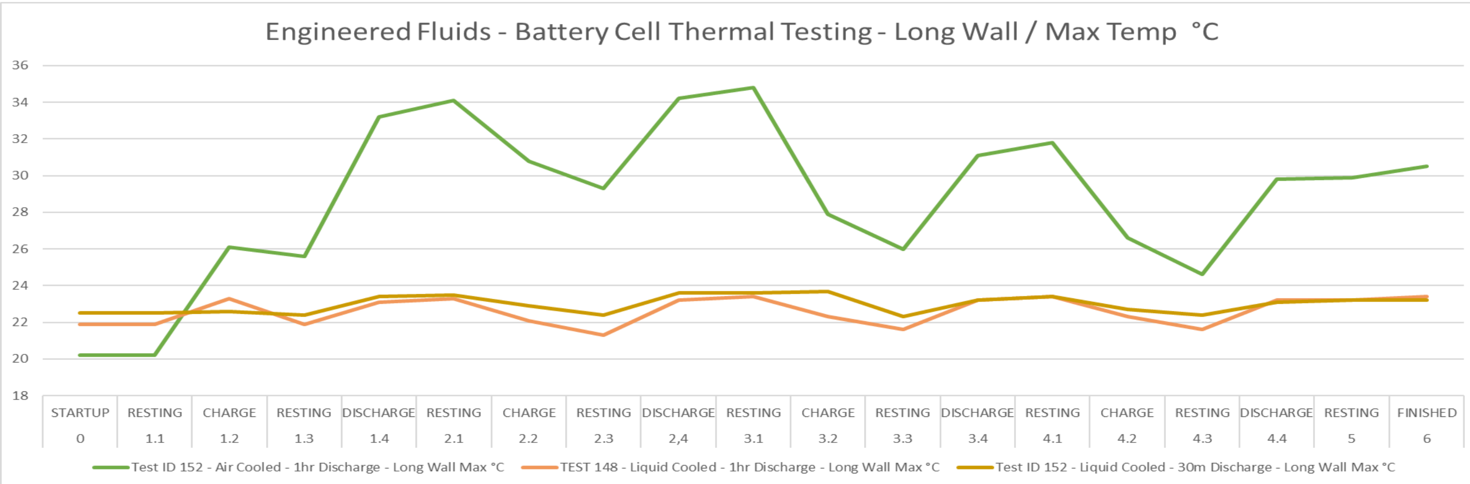
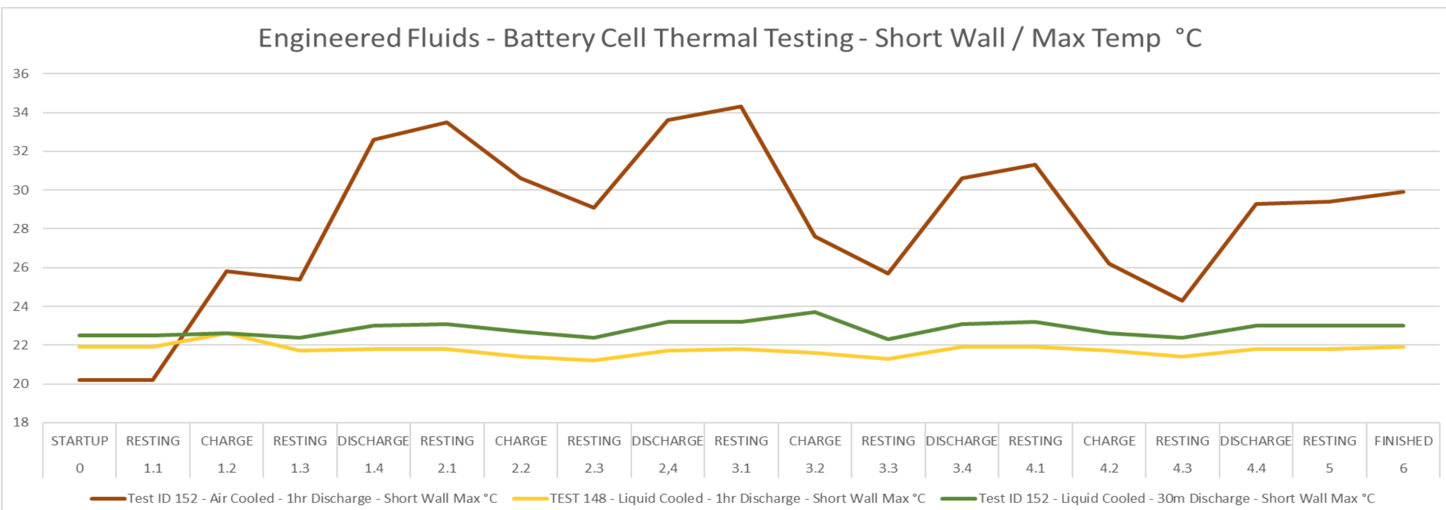


Figure 19: Comparison of Cooling Performance – Battery Cell Short Wall / Max Temp C



VII. Results and Discussion

Analysis of the test data shows that single-phase liquid immersion cooling of the battery cell had the following effects, when compared with air cooling:

Optimum Temperature Maintenance: In Phase 1 testing (0.55/C charge, 1/C discharge), the average battery temperature was five degrees C lower when the cell was immersed in 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.

Elimination of temperature swings: In Phase 1 testing when air cooled, battery temperatures varied more than 16 degrees from cycle to cycle. In the liquid immersion-cooled test, this temperature variation was only 1.8 degrees C. In the Phase 2 immersion-cooled test testing (0.55/C charge, 2/C the maximum temperature variation 5.1 degrees C even while maintaining the same rate of coolant flow as in the Phase 1 testing. This provides an opportunity for further testing by increasing the coolant flow rate to see if the similar 1.8 degrees C delta could be achieve during the more aggressive discharge cycle.

Immersed in AmpCool™ Coolant, the battery was held with its manufacturers recommended optimum operating temperature range of 23+/- 3C at all times during the four cycle 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, and well above the manufacturer's recommended operating temperature range.

Figure 15 shows the cooling performance in greater detail, as it tracks surface temperatures measured along the long side of the cell through one charge/discharge cycle.

Elimination of Cell Temperature Stratification: Immersion cooling maintained homogeneous temperatures inside the test cell, air-cooling allowed temperature stratification inside the cell, lessening the cell's efficiency and service life. This can be seen in the graphs above as the temperatures of the battery cell's side wall deviated from the tab, or terminal temperature. With the immersion cooled cells, this difference was not seen.

Phase 2 of this experiment tested the AmpCool™ Coolant's ability to manage higher thermal stress by discharging the battery cell at twice the design rate. In this part, discharge was done at 2/C, taking the battery cell from 100% SOC to 30% in only 30 minutes, with only 10 minutes between cycles.

The accelerated discharge rate places higher thermal stress on the battery cell, raising its internal temperature. Maintenance of the cell's temperature within the desired range recommended by the manufacturer is vital to maximizing the battery's useful life. Figure 13 and 14 show how liquid immersion cooling with Ampcool™ AC-110 Dielectric Coolant maintained the battery cell's temperature even with the additional thermal load brought about by rapid discharge and reduced rest times.

VII Conclusions: Advances in battery technology are facilitating their use in a wide range of stationary and mobile applications. Efficient thermal management of these battery systems will be a key factor in their successful adoption and application. Maintenance of battery temperatures within a narrow range maximizes the battery capacity, maximizes the rate of charging and discharging the battery, and extends the battery's useful life. [7,8] All of these factors have a major impact on the economic viability of applications for these battery systems.

Several means of controlling the temperature of batteries during charge and discharge cycles have been evaluated. Traditional air cooling cannot economically maintain the temperature within the desired range during charging and discharge cycles. Adding surface area and/or cooling fins to the battery case helps dissipate heat more rapidly, but adds too much bulk and weight to be considered for most applications.

Liquid cooling is the most effective and economical solution for keeping battery temperatures within the desired band. Liquid cooling can be done indirectly, using cold plates or pipes through which a water-based solution is pumped. This is more effective than air-cooling, but is inflexible and expensive (cold plates must be made specifically to fit every different cell shape and component to be cooled) and does not approach the efficiency of intimate contact between the battery and the heat transfer fluid.

The most efficient cooling method for batteries is direct immersion in a single-phase, nonconductive cooling fluid. Until recently, dielectric fluids were not available with the right combination of material compatibility profile, environmental impact and fire safety. Developed in 2017, AmpCool™ Dielectric Coolants are a safe and reliable way to optimize and extend the value of today's battery systems.

The experiment described in this paper used Samsung Model 286S battery cells that were subjected to multiple rapid charge-discharge cycles while being cooled with forced air and by immersion in a dielectric coolant, AmpCool™ AC-110.

The test cells that were immersed in AmpCool™ AC-110 Dielectric Coolant maintained an average cell temperature of 22.5 degrees C. with very low deviation from the mean. In contrast, when the cells were cooled with forced air, the average cell temperature was 28.7 degrees, with much greater temperature variation during charge/discharge.

The second phase of this experiment showed that immersion cooling can maintain a cell's temperature within a desired band even under high thermal stress brought about by accelerated discharge. This finding has powerful implications in terms of asset management mobile and stationary battery systems.

The experiment indicates that required relaxation times between discharge-charge cycles can be significantly reduced and battery lifetime will be extended. As battery efficiencies are raised, so are returns on battery asset investments.

As electric vehicles and stationary battery arrays become more widely used, there will be a high demand for longer battery life and higher power output. To achieve this, the battery thermal management systems will need to be able to transfer heat away from the battery module as they are charged and discharged at higher rates. The heat generated as the battery is used can pose safety threats to passengers and bystanders. Due to the high stress and temperatures generated by the batteries, having the right cooling system is fundamental to maximizing battery efficiency, service life and profitability. This experiment has shown that thermal management through Single-phase Liquid Immersion Cooling (SLIC) technology can safely and efficiently maintain target temperatures in battery cells and modules.

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