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Using Multi-physics System Simulation to Predict Battery Pack Thermal Performance and Risk of Thermal Runaway During eVTOL Aircraft Operations

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Negative effects of greenhouse gas emissions from internal combustion engines has motivated a global trend towards electrification of transportation powertrains. Additionally, electrification of vehicle prime movers has enabled novel powertrain configurations such as electric distributed propulsion. Electric vertical take-off and landing (eVTOL) aircraft are a novel transportation mode developed at a confluence of emerging technologies including electric powertrains. eVTOLs are poised to institute a major change to urban mobility by increasing the speed and efficiency of urban travel. To facilitate safe and reliable operations, eVTOL battery packs must reliably provide adequate electrical power for mission requirements while sustaining pack health and cycle life over the course of hundreds of missions. These packs are under considerable thermal stress during flight, and must be designed to meet the challenges caused by these thermal stresses, including keeping individual battery cells below temperature limits. Using system simulation can be instrumental in providing optimal design of battery pack layouts and thermal management strategies. A multi-physics system simulation model has been constructed to predict the electrical-thermal-fluid performance of the A³ Vahana eVTOL battery pack with comparison to test data derived from a notional eVTOL mission profile. The model predicts outputs including individual cell currents, cell temperatures, cell voltage, environmental temperatures, and impact of different thermal management strategies on eVTOL battery pack design. The thermal profile predicted during flight is then passed to a predictive model for battery life using GT-SUITE simulation software. The model is then configured to simulate a thermal runaway event, where one cell is heated to the point of runaway, and response of the pack is predicted under different cooling strategies.

I. Nomenclature

eVTOL	=	electric Vertical Take-Off and Landing
PTC	=	Positive Temperature Coefficient

II. Introduction

Electric vertical take-off and landing (eVTOL) vehicles must be light weight and provide adequate electrical power from their battery packs for sustained flight. These packs are under considerable thermal stress during flight, and must be designed to meet the challenges caused by these thermal stresses, including keeping individual battery cells below temperature limits under extreme environmental and power loading conditions. Using system simulation can be instrumental in guiding optimal design of battery pack layouts and thermal management strategies.

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Existing literature discusses thermal performance of electric aircraft during flight. For example, Falck et al. [1] showcase trajectory optimization of an electric aircraft while subjected to thermal constraints of the electrical components of the aircraft. This paper analyzed performance from a low fidelity perspective without analyzing detailed behavior of the cells in the battery pack.

Fredericks, et al [2] showcased the typical transient electrical power profile during an urban flight. Profiles similar to this profile will be used for the scope of this paper to define the loading condition on the cells in the pack.

Governing bodies also provide requirements for battery thermal runaway and proper venting during runaway events. For example, the DO-311A standard [3] describes different venting categories based on the battery system design ranging from (a) no emissions allowed in the event of thermal runaway, to (b) emissions are allowed to escape through a designated vent with a sealed connection to an aircraft exhaust system, to (c) emissions are allowed to escape from the battery system without any venting provisions. The aircraft examined in this paper fall under category (b). Furthermore, this same standard outlines the procedure to test the onset of thermal runaway and containment of thermal runaway due to overcharging and overheating. In a test, the worst-case scenario should be performed with the highest risk cell or set of cells that could cause thermal runaway propagation, and it must be shown that propagation does not occur. Due to the magnitude of eVTOL battery pack stored energy, cost, and the explosive nature of packs undergoing thermal runaway it is not practical to test thermal runaway for many pack design configurations. Use of a simulation model will allow many scenarios to be tested virtually prior to physical testing.

Additionally, the high discharge C-rates used in eVTOLs causes much more heat to be generated in the pack when compared to ground vehicles [4]. This places greater importance on pack thermal management design to ensure acceptable cell performance and eliminate the risk of thermal runaway propagating beyond a single cell.

Some research has been performed to estimate the heat release during cell thermal runaway. For example, Walker et al [5] have used calorimeter testing to calculate the heat release of a variety of cylindrical cells. This heat release rate is an important quantity to have as an input to a thermal runaway model.

This paper describes the process of creating a physical model to represent the battery pack of an eVTOL vehicle from a multi-physics perspective through integrating the electric, thermal, and fluid physics domains of the battery pack to predict realistic pack performance over a flight profile.

III. Physical System Setup

The specific battery pack studied in this paper involves the pack used on the Airbus A^3 Vahana Technology Demonstrator. The vehicle has two 19kWh packs, each of which consists of 18650 cells in an 84 series x 21 parallel arrangement. A pack is shown in figure 1.

Fig 1. Picture of one of the battery packs used on the A^3 alpha flight demonstrator on a test lab bench.

The rough dimensions of the high voltage portion of the pack are 18cm wide, 26cm tall, and 153cm long. The packaging is hexagonal with some gaps between the cells, and two cells deep. The hexagonal configuration is depicted in figure 2.

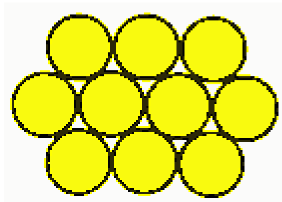

Fig 2. Hexagonal configuration of the cells in the battery pack, with a small gap between the cells.

IV. Modeling Process

The process for creating a multi-physics model representation of the battery pack involves the following steps:

1. Create a predictive electrochemical model of the battery cell using GT-Autolion by GT-SUITE software.

2. Run a virtual HPPC test to characterize the electrochemical model of the cell as an electrical equivalent model with open circuit voltage, internal resistance, and optional R-C branches as a function of current and temperature. The result is a faster-running electrical equivalent battery cell model. As an alternative to using the electrochemical model to create an electrical equivalent model, one could use test data directly to create the electrical equivalent cell model. The model in this paper uses the open circuit voltage and internal resistance values directly from the test data for the electrical equivalent cell model.

3. Using the electrical equivalent cell model, connect cells together in the 84s 21p layout of the physical pack.

4. Build a thermal representation of the pack through lumped masses of each cell, and mass of conductors between cells.

5. Build a physical flow space representation of the pack including the gaps between the cells where heat from the battery cell can be rejected and dissipated into the flow space of the pack.

6. Run the simulation model over a flight mission to predict individual cell temperatures or configure the boundary conditions of the model to perform "what-if" scenarios during onset of thermal runaway of a cell or set of cells.

7. Utilize notional mission current profiles during pack charging and discharging, along with the temperature of the cell over the same cycle and input this data back into the GT-Autolion model created in step 1 to predict the degradation of the cell and battery cycle life.

In the first step, the representative cell is defined in an electrochemistry model using GT-Autolion by GT-SUITE, with characteristic inputs including cell size (i.e. cylindrical 18650), weight, as well as inputs for the cathode, anode, separator, and electrolyte including material properties, thickness, height, concentration, and more. The cell model is then calibrated to match test discharge data at various temperatures and C-rates. In figure 3, the model and test are compared over 5 different conditions for cell voltage and temperature vs. time, with good agreement overall between model and test.

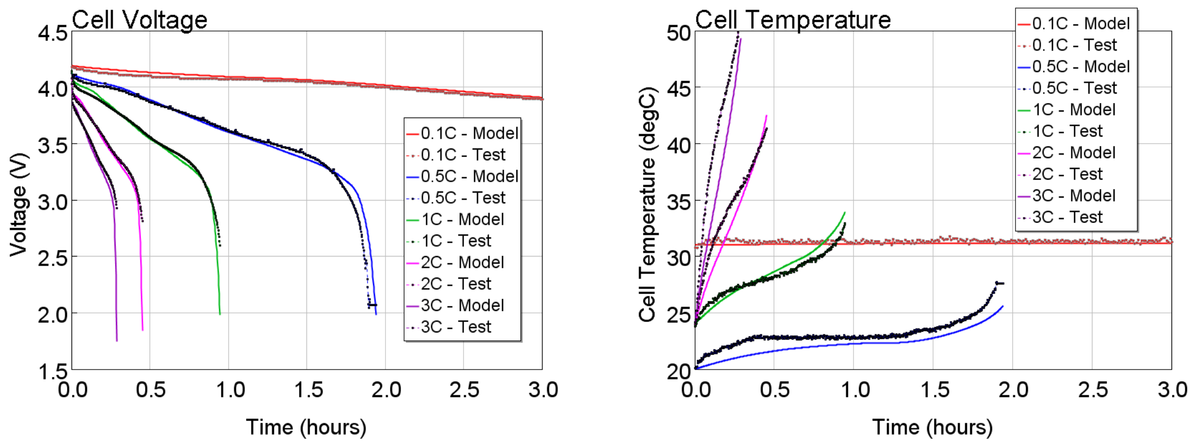

Fig. 3 Comparison between electrochemistry model and test for cell voltage and temperature during various discharge and temperature conditions.

V. Pack Model Overview

The electrical-thermal-fluid integrated model of the pack is shown in figure 4, where the colors of the different links showcase the different physical domains.

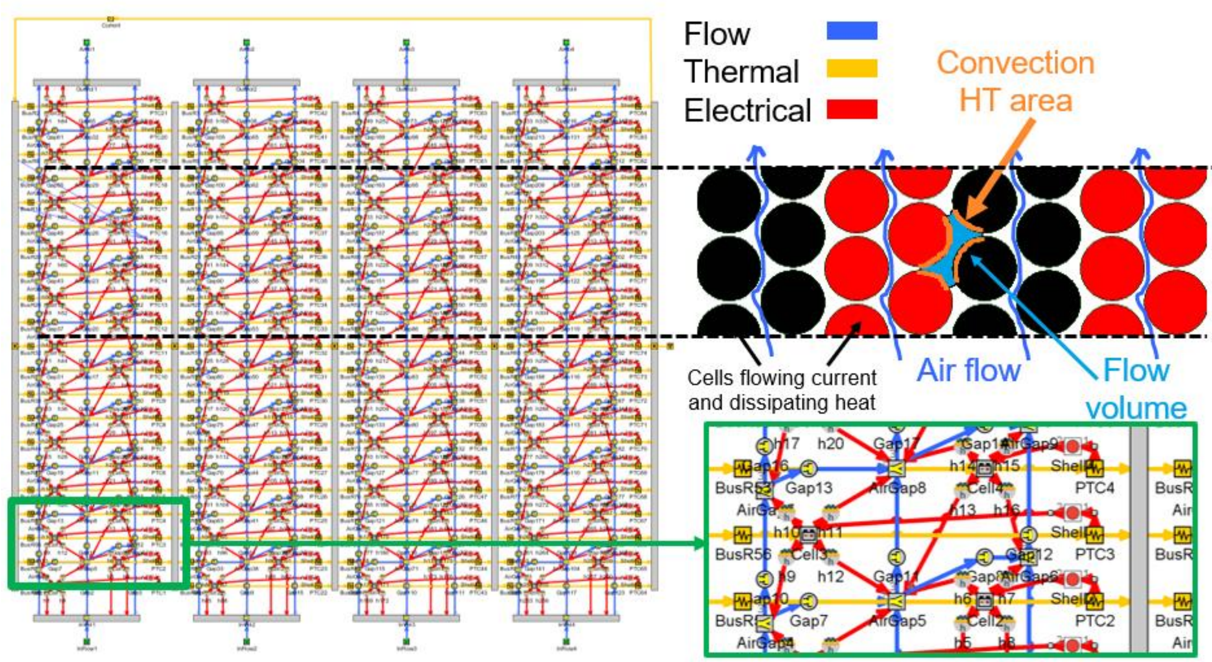

Fig. 4 Model schematic of the portion of the battery pack, with integration of different physical domains.

The pack model is run against a defined current profile. Optionally, any of the cells in the pack can be heated to the point of cell thermal runaway. A depiction of the eVTOL current profile modeled is shown in figure 5.

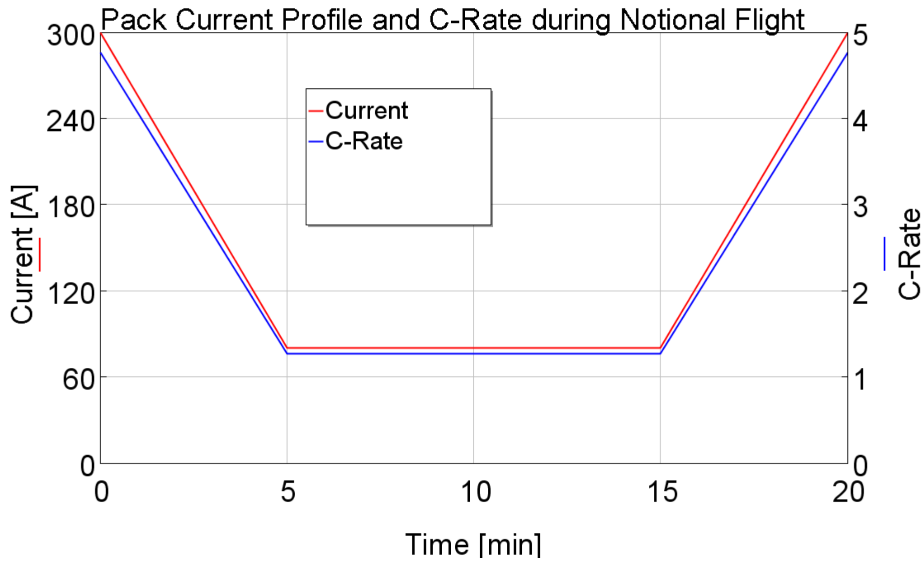

Fig. 5 Pack current profile and C-rate of a given cell over a notional flight mission.

For the purposes of predicting eVTOL battery pack performance and informing future eVTOL battery designs, the model has been applied to the following distinct scenarios:

- Pack thermal performance during a notional mission for packs designed with both natural air convection cooling and forced liquid cooling.
- Pack cycle life modeling during a notional mission for packs designed with both natural air convection cooling and forced liquid cooling.
- Propensity for neighboring cell thermal runaway propagation given single cell thermal runaway during a notional mission for packs designed with both natural air convection cooling and forced liquid cooling.
- Comparison of pack model results and representative eVTOL flight test data

VI. Pack Thermal Performance During a Notional Mission

Pack thermal performance was studied given the current profile in figure 5 for two cooling strategies: natural convective air cooling and indirect forced liquid cooling. In the natural air-cooling scenario, under normal flight operation, there is up to 30°C variation in temperature between cells in the pack, and cell currents have roughly even distribution as shown in figure 6.

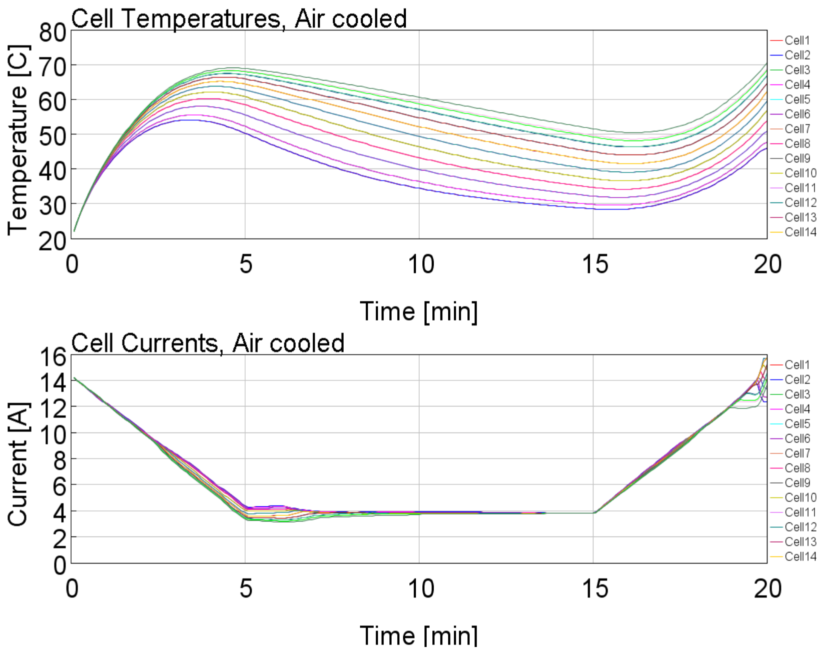

Fig 6. Predicted cell temperature and current in the pack in air cooled scenario under normal flight conditions.

In the same model configuration, the thermal management strategy can be modified to consider indirect single-phase cooling. In this case, the method of cooling uses a "bandolero roll" where the walls of the cooling channel directly touch the walls of the cylindrical cells, as shown in figure 7.

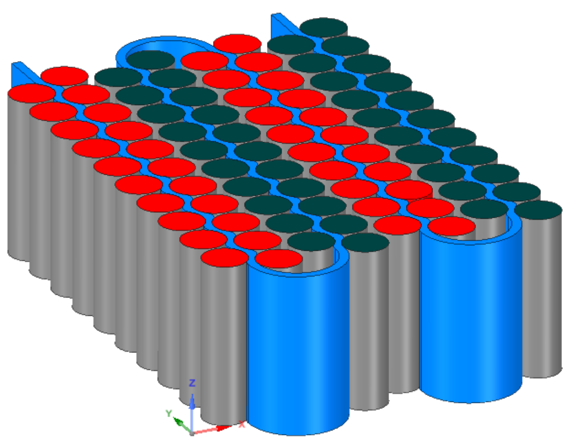

Fig 7. Indirect liquid cooling arrangement flowing through "bandolero roll" (in blue).

In the same flight mission scenario with active cooling, cell temperatures and current have less variation as shown in figure 8 compared to the air-cooled thermal management strategy in figure 6.

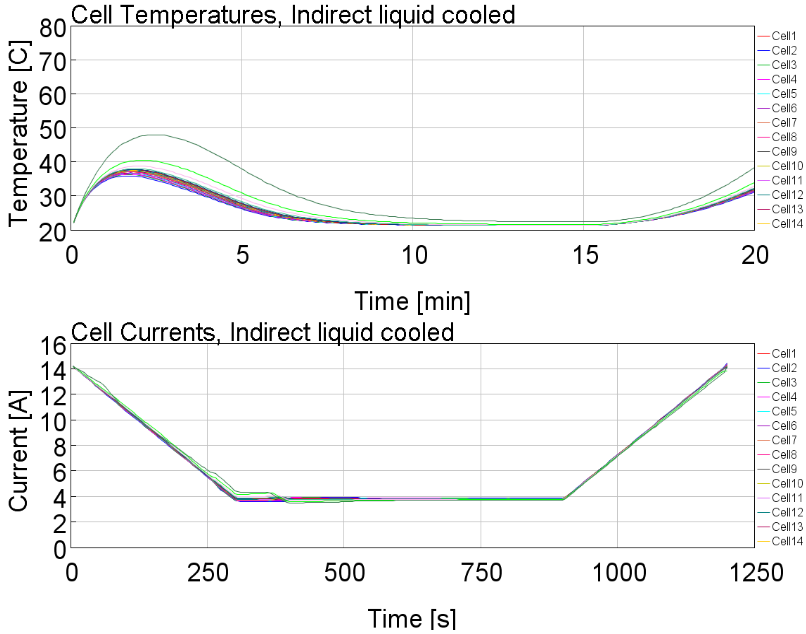

Fig 8. Predicted cell temperature and current in the pack in water cooled scenario under normal flight conditions.

VII. Pack Cycle Life During a Notional Mission

Based on the performance of the pack during the notional flight mission, the average cell temperature and current in the pack is used as an input to the cell electrochemistry cycle life model. To study evolution of cell state of health, the cycle model is setup to first simulate the notional flight mission with proper current and temperature, then charge the cell for a period of 1 hour (1 C charge rate), then rest the cell for a period of 1 hour. The input current and temperature for the combined mission-charge-rest cycle is shown in figure 9 for the two cooling strategies.

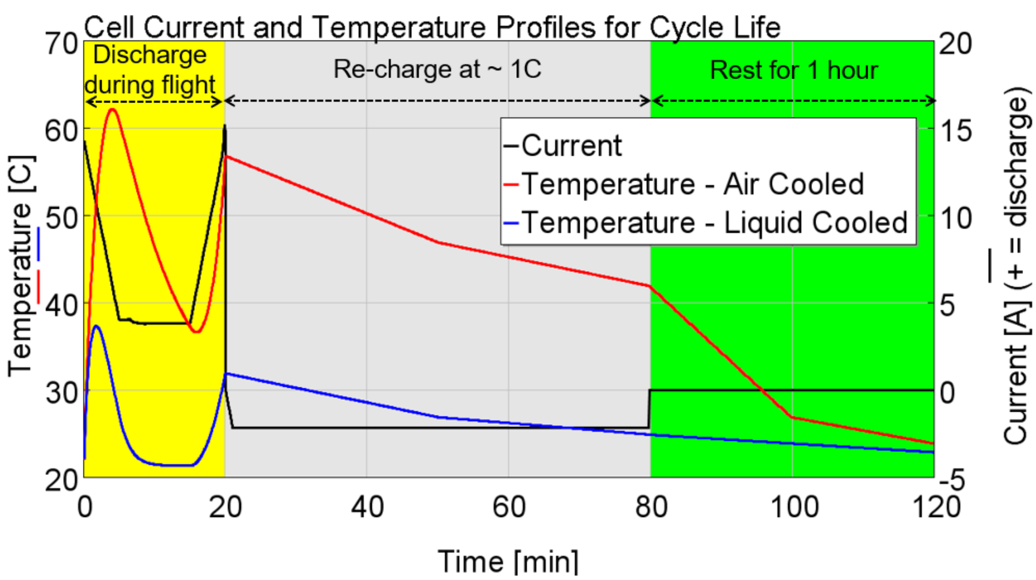

Fig 9. Input current and temperatures profiles for combined mission-charge-rest cycle to predict cell cycle life for two cooling strategies.

Using the current and temperature input over a discharge/charge cycle, the predictive electrochemistry cell model can be used with aging turned on to predict the cell capacity as a function of number of cycles. The aging model has several aging components including:

- Anode SEI layer growth
- Cathode film growth
- Cathode active material isolation (not used in this model)
- Anode active material isolation
- Lithium plating (not used in this model)

Using three of the five aging components, the cell model has been calibrated to cell supplier specification life cycle test data for a cycle with CC/CV charge to 4.2V with a 100mA cutoff, followed by a constant current discharge of 20A with a 2V cut-off. Using this cycle, the model cell capacity is predicted to be 2.43A-h after 200 cycles, which correlates within 3% of the supplier test. In order to achieve the calibrated result, many of the input parameters for aging were left to their default values, but several were changed, including the SEI rate constant, cathode film growth constant, anode isolation constant, and porosity if the SEI layer and cathode film.

Next, the calibrated electrochemistry model was extended to simulate the eVTOL charge/discharge/rest cycle in figure 9 for the air cooled and indirect liquid cooled strategy. The cell capacity for both strategies is shown in figure 10. The model prediction is clear that with a liquid cooled pack, the cycle life will increase significantly. It should be noted that this model is not yet validated to cell test data of an eVTOL cycle.

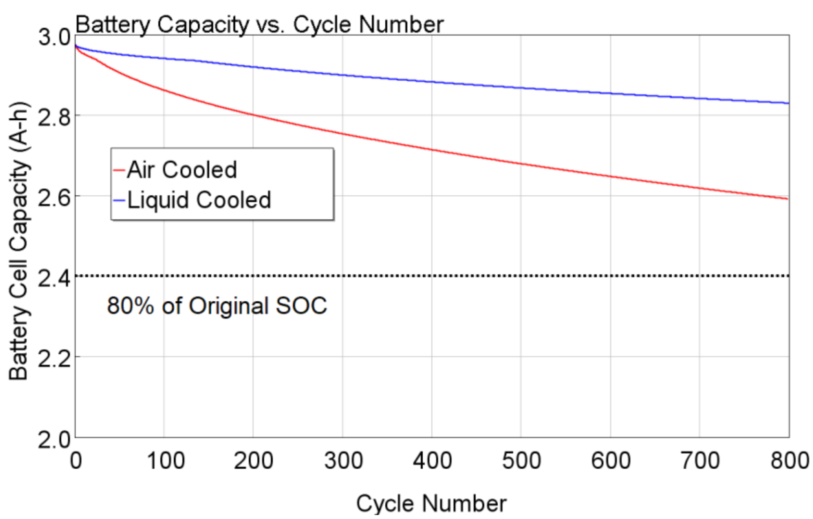

Fig 10. Predictions of cell cycle life for combined eVTOL mission-charge-rest cycles for two cooling strategies.

VIII. Modeling of Pack Performance Under Single Cell Thermal Runaway

To simulate thermal runaway of a single cell within the pack, the pack is modeled under a heat soak condition at maximum operating temperature. Thermal runaway in a single cell is induced by heating this cell beyond maximum operating temperature at a constant power load up to the temperature that induces thermal runaway.

The model is configured with all cells in the pack initialized at 88°C, with relatively cooler 54°C surrounding air in the gaps between the cells. The current imposed on the pack is set to 300A to setup the worst-case loading during flight as shown in figure 5. During this event as shown in figure 11, the single cell that is heated reaches a critical temperature around 30 seconds into the simulation, to the point where the cell is no longer actively participating in the pack, and requires the other cells to pick up the load, causing neighboring cell temperatures to increase further, to the point of uncontrolled behavior.

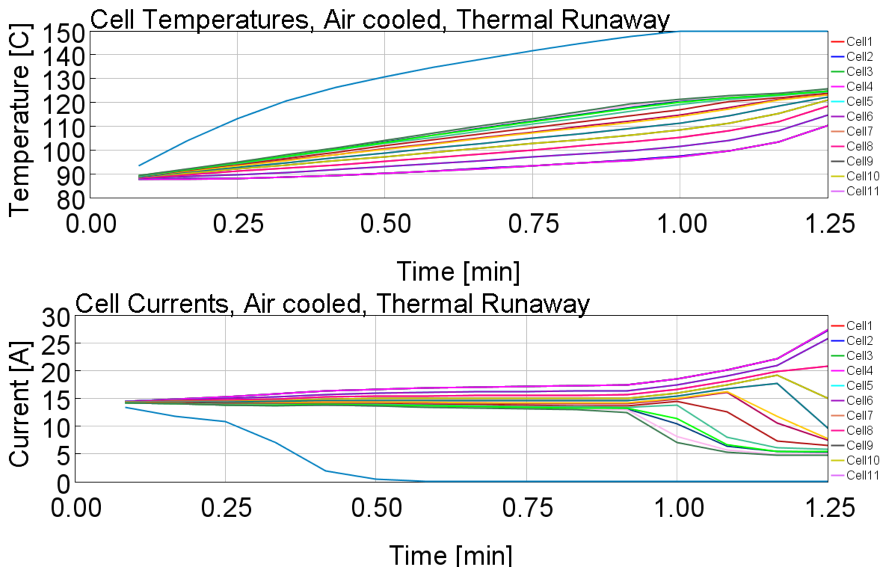

Fig 11. Predicted cell temperature and current in the pack in air cooled scenario when one cell is subjected to heating to the point of thermal runaway.

Using the same scenario as the air-cooled pack, the thermal runaway event is modeled with indirect liquid cooling with 20°C 50/50 EGL/water mix at the cooling inlet to the pack. As shown in figure 12, the current is more evenly distributed, and the cell heat does not propagate as strongly to neighboring cells compared to the air-cooling case.

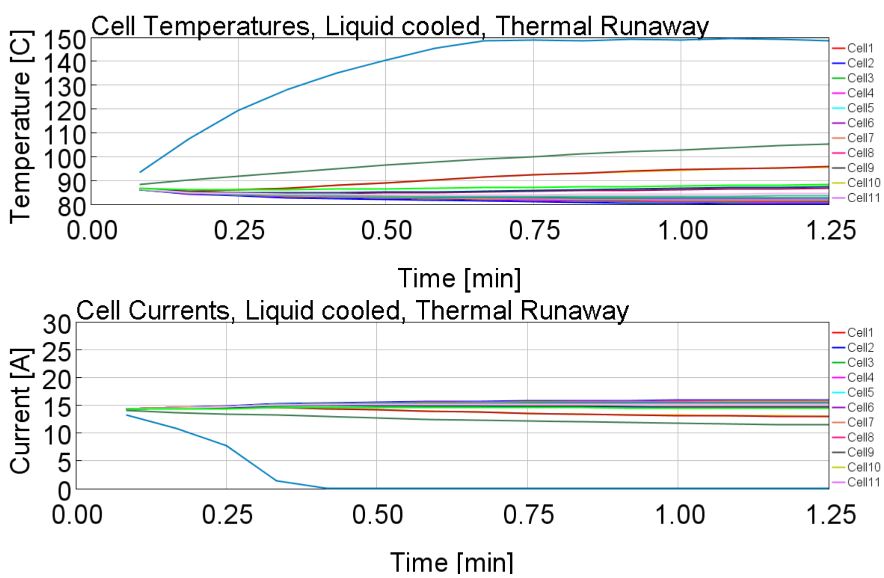

Fig 12. Predicted cell temperature and current in the pack in liquid cooled scenario when one cell is subjected to heating to the point of thermal runaway.

IX. Comparison of Pack Model Results and Representative eVTOL Flight Test Data

Battery pack performance data representative of the notional mission profile from the Vahana flight test campaign was utilized to evaluate the pack model against experimental data.

A schematic of the Vahana vehicle electrical distribution model is shown in figure 13, where two battery packs on the left and right side of the fuselage supply power to the eight individual motors.

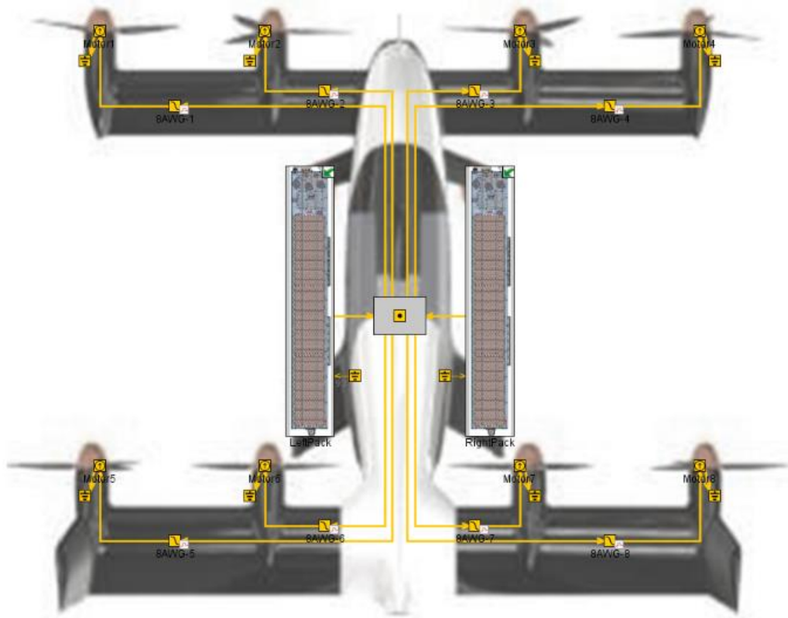

Fig 13. Vahana vehicle electrical distribution model with two packs providing power to eight motors.

The two packs are identical, and each pack is arranged in an 84S 21P manner. One of the 84 "bricks" is represented with a thermal fluid network surrounding each of the 21 parallel cells in the brick, as shown in figure 14. The thermal assumptions in the network include having natural convection transfer heat from each cell to the surrounding fluid gap between cells, and a recirculation loop inside the pack carries the heat and fluid from the bottom cell in the pack to the top through buoyancy effects, where it then flows down the side wall and exchanges heat with the cooler ambient environment.

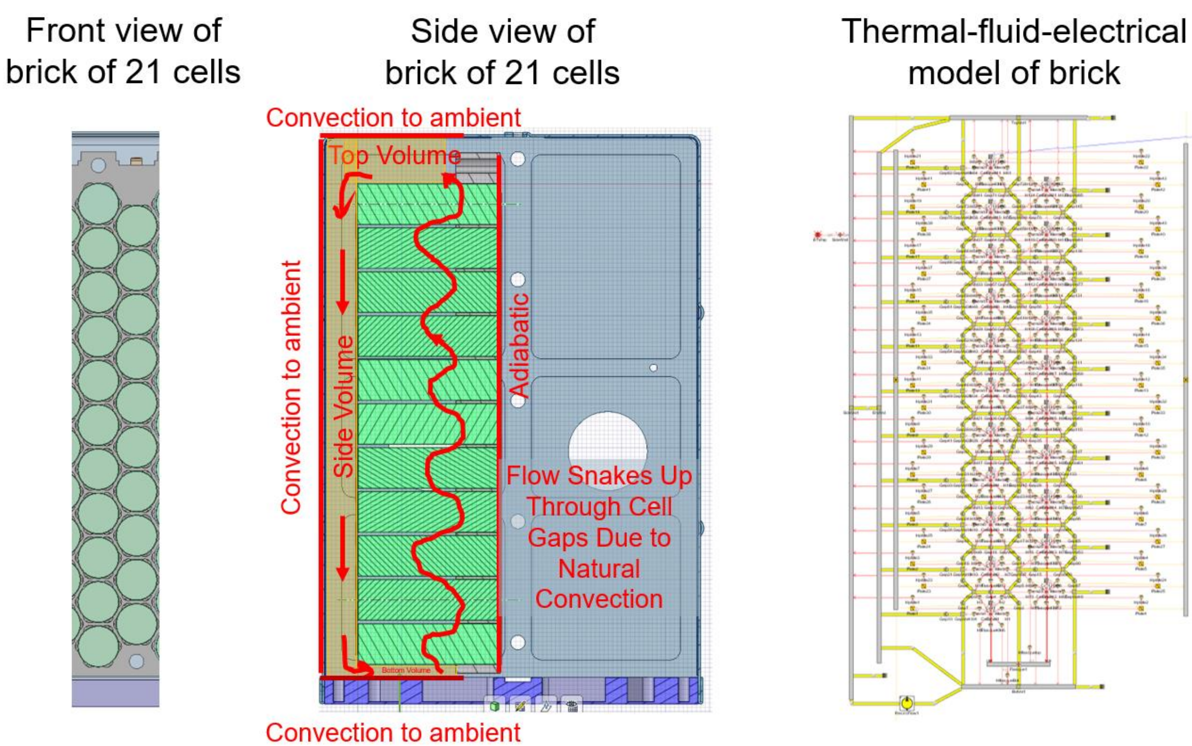

Fig 14. Thermal-fluid-electrical representation of a single brick of 21 cells in parallel in the pack.

By modeling each cell in the brick we can predict individual cell temperatures. Bricks can be strung together to account for axial temperature variation. For simplicity, only a single brick model was compared to pack test data which includes temperature measurements of each brick in the pack. The current profile derived from flight data which was imposed on each pack is shown in figure 15.

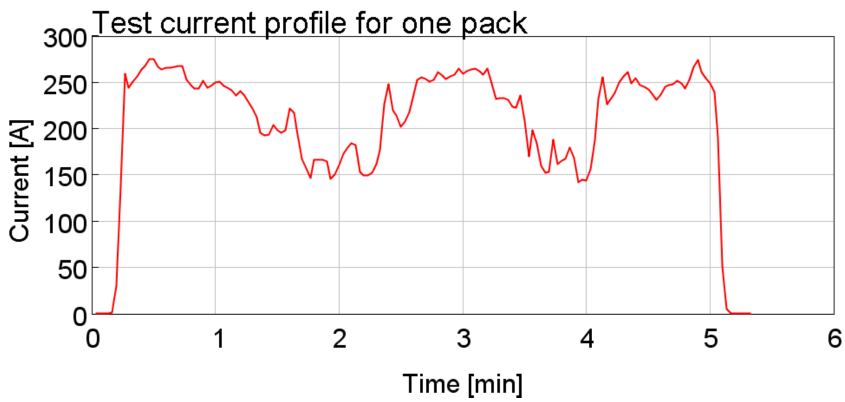

Fig 15. Current profile flowing through one pack during a flight test.

The flight test records the temperature of a single cell in each brick within the pack. The test location of the thermocouple for each brick is the top center cell in the brick. The model is setup such that it calculates the temperature of every cell in a brick. Figure 16 shows a comparison of the measured brick temperature (top center cell in each brick) and the modeled temperature of the same cell in the brick. The modeled temperature correlates well with the measured brick temperature and is within the min/max bounds towards the end of the mission cycle.

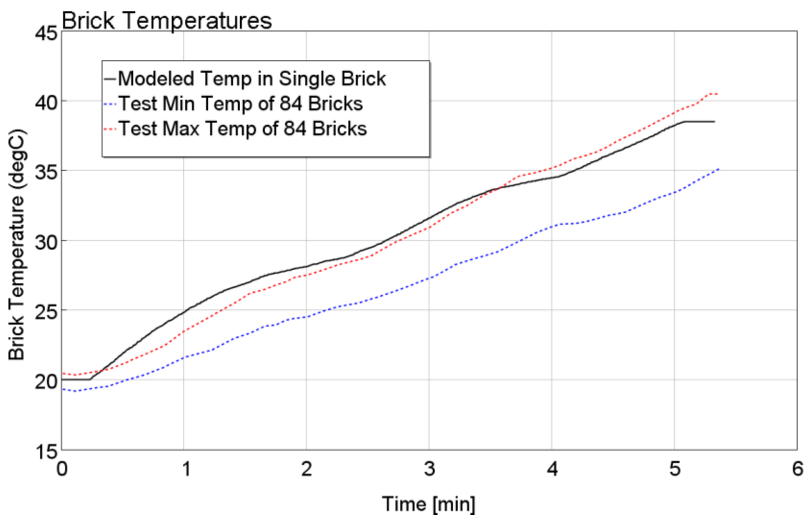

Fig 16. Comparison of modeled module temperature to test min and max temperature for all 84 modules in the pack.

To give a glimpse inside the brick, the spatial variation of temperature can be analyzed. At the end of the mission, the temperature of all components inside the modeled brick is shown in figure 17.

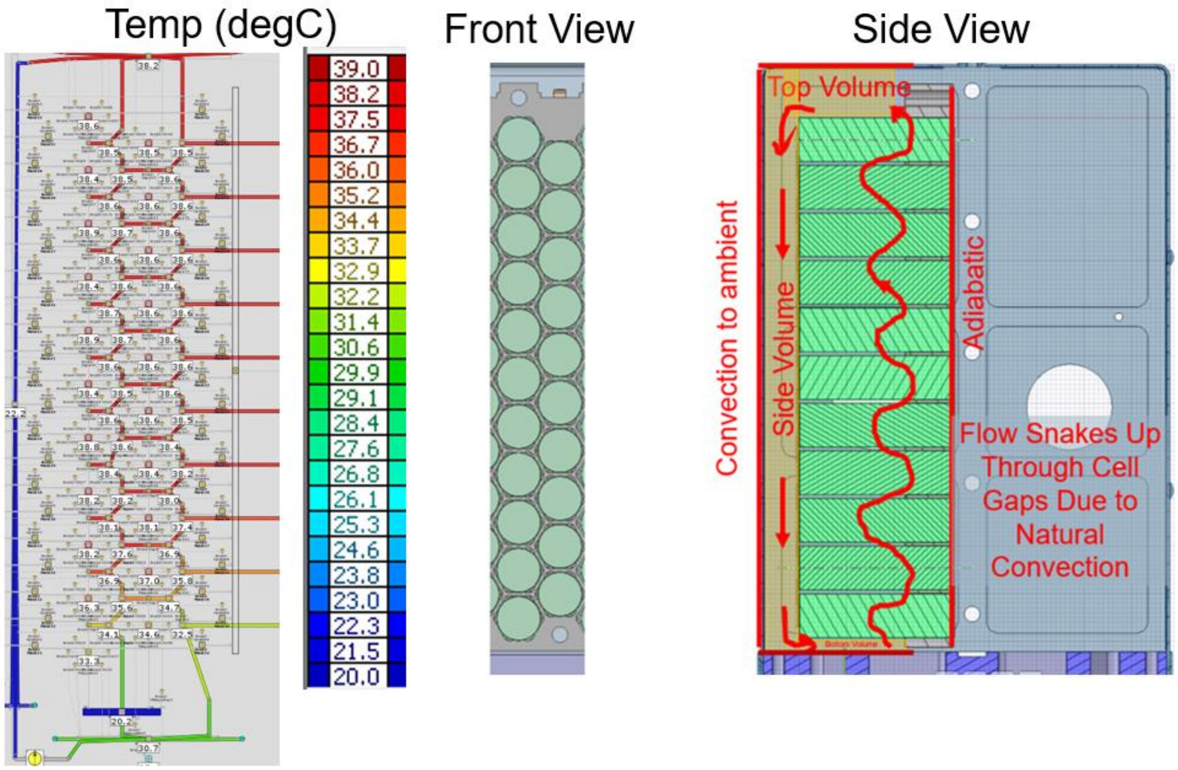

Fig 17. Spatial variation of temperature of all components inside the modeled brick of 21 cells at the end of the flight test.

For verification of the state of charge, the model SOC is compared directly to test SOC in figure 18.

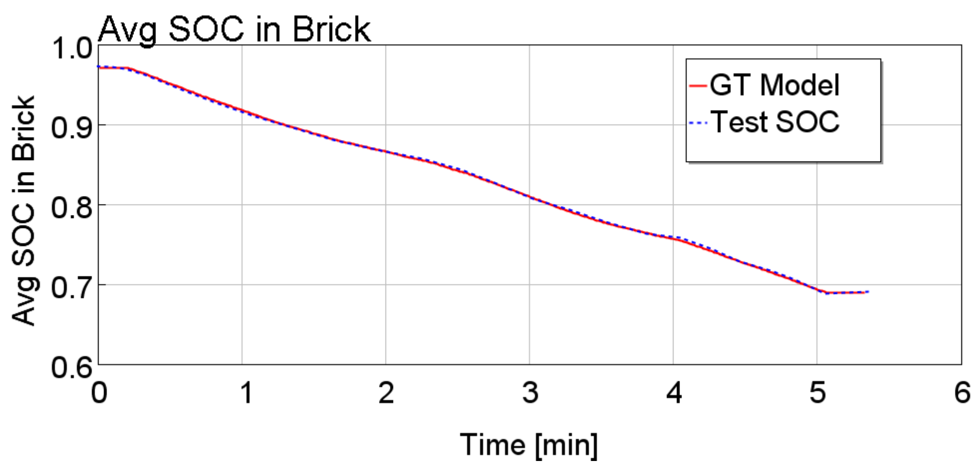

Fig 18. Comparison of SOC between model and test.

X. Conclusions

The use of a multi-physics system simulation tool allows for in-depth analysis of individual cell performance during eVTOL mission profiles. Through simulation and model verification of experimental flight test data, eVTOL battery pack performance was accurately represented with the following key results:

- Liquid cooling improves pack performance and cycle life relative to natural air convection.
- Cell to cell propagation of thermal runaway can be mitigated with appropriate pack thermal management design.
- A thermal model of an eVTOL battery pack with natural convection cooling show good correlation with test data, validating model methodology.

Development and performance improvements of future eVTOL battery pack designs can be significantly accelerated through the use of multi physics system simulation. This will allow for:

- Optimization of pack thermal management systems
- Rapid design iteration
- Determination of pack design best practices prior to investments in hardware testing
- Accurate prediction of eVTOL battery performance
- Determination of pack cooling and charging strategies that maximize battery cycle life

XI. References

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