35th International Electric Vehicle Symposium and Exhibition (EVS35)
Oslo, Norway, June 11-15, 2022

A multi-disciplinary approach for the electrical and thermal characterization of battery packs – case study for an electric race car

Claudio Santarelli[1], Christopher Helbig[1], An Li[2], Thomas Nyhues[3], Fabian Böhm[3]

[1]*Siemens Industry Software GmbH, Am Kabellager 9, 51063 Köln Germany*

claudio@santarelli@siemens.com, christopher.helbig@siemens.com

[2]*Simens Digital Industries Software, 19 bd Jules Carteret, 69007 Lyon France*

an.li@siemen.com

[3]*Eurie Aix - Formula Student Team RWTH Aachen e.V., Templergraben 55 52062 Aachen Germany*

thomas.nyhues@rwth-aachen.de, fabian.jonathan.boehm@rwth-aachen.de

Summary

A novel, multi-disciplinary approach is presented where experiments, system simulation and Computational Fluid Dynamics are combined for the electrical and thermal characterization of a battery pack. As a case study, a Formula Student race car is considered and the procedure proposed consists of three steps: 1) experimental characterization of the battery cells under several thermal conditions; 2) thermal and electrical modelling of the battery stack with system simulations; 3) three-dimensional, time-dependent Conjugate Heat Transfer simulation of the whole battery pack to investigate the cooling performance of the chosen design, and to access fundamental quantities of the batteries such as state of charge, temperature, ohmic heating, etc.

Keywords: BMS (Battery Management System), cooling, simulation, testing processes, thermal management

1 Introduction

The transition towards electric mobility brings many challenges and one of the most important is the Battery Thermal Management (BTM) where several disciplines such as electronics, heat transfer and controls need to be combined to guarantee a safe and efficient cooling of the batteries. Commonly, many automotive manufacturers acquire the cells from suppliers and need to characterize the cells before integrating them into the vehicle, to optimally design the cooling system in the development phase. Hence, a novel approach is here presented that leverages experiments, system simulations (SYS) and Computation Fluid Dynamics (CFD) for the thermal and electrical characterization of cells and battery packs. The case study chosen to present this concept is an electric Formula Student race car (as described in Section 2) and this approach consists of three steps. First, a single cell is experimentally investigated to identify the parameters of the equivalent circuit model (Sec. 3). Afterwards, a system simulation is set up to represent a part of the battery pack as an ensemble of characterized cells (Sec. 4). Successively, the battery pack is exported by means of the Functional Mockup Interface (FMI) standard [1] and embedded in a Conjugate Heat Transfer (CHT) simulation, to simulate the cooling of the battery pack (Sec. 5). In this framework, fundamental quantities of the battery such as the state of charge, the temperature and the ohmic heating can be accessed for an optimal dimensioning of the cooling system.

2 Case study

The case study addresses the electric race car *eace09* [2] shown in Figure 1 (left), designed and built by the RWTH Aachen's Formula Student team Ecurie Aix. The *eace09* is a 4-wheel-drive car with up to 32 kW traction power per wheel hub motor, with an overall peak power of 80 kW (limited by the competition rules) and a recuperation capability of up to 60 kW. Four IGBT inverters supply the PMSM motors with power, both systems are water cooled. The drive train is powered by a high-power Li-Ion battery pack with a capacity of roughly 6 kWh.

(a) (b)

Figure 1: Picture of the eace09 on the Hockenheim Ring (a) and of the battery pack (b)

The energy is stored in 288 high power Li-ion pouch cells. 24 of these cells are in an 12s2p configuration form one module, held together by a 3D-printed cage that also contains a secondary controller of the BMS. A total of 12 of the described modules are placed in an aramid container, together with the BMS master controller and periphery devices such as a fuse, some relays, and an insulation monitoring device. This yields an overall battery configuration of 144s2p and a theoretical voltage range of 432 V – 600 V (upper limit defined by the rules). To accomplish the lightweight construction requirements, the battery cells are air cooled. Three fans at the back of the battery container provide induce a mass flow through the air vents on both side of the monocoque and the effect of the instantaneous car velocity is negligible with respect to the mass flow imposed by the fans. The air streams over the heat sinks that are mounted on the cell tabs (Figure 1, right) and leaves the car at the rear end. The first generation of the air-cooling system as described above was developed as a conservative, oversized proof-of-concept design.

At the formula student competition, the cars compete in various dynamic disciplines, with the endurance race being the most prestigious but also most challenging one: Over a track length of 22 km the cars must drive as quickly and efficient as possible. Not only the fastest overall time, but also the lowest net energy consumption will be rewarded with points. An efficient energy and thermal management of the battery is therefore necessary to get the most out of the race. The race car is designed to operate closely to the limits of its performance, considering lightweight construction, energy efficiency and thermal design. Since the system must maintain acceptable temperatures for 22 km, the cooling system can be even smaller than a conservative design approach would suggest: an improvement of the first proof-of-concept design is the pivotal motivation of the *Batterie Aix* project described here.

To optimize the BTM for the endurance race, proper knowledge of the battery's dynamic behavior in terms of thermal and electrical aspects is mandatory: hence, a multi-disciplinary approach for the investigation of the battery cooling was developed by Ecurie Aix in collaboration with Siemens Digital Industries Software, as described in the present document. The main motivations of this projects are: 1) gain deep insight into the behavior of the current battery pack/cooling system; 2) derive trustworthy models can be used in the design phase of the next generation's cooling system e.g., towards alternative cooling strategies and/or improved overall BTM concepts. 3) to get a better understanding of the electric-thermal properties of the system in different scenarios. In the present paper we focus on the first goal of the projects and the new approach is described below.

2 Cell characterization

The battery cell used in the race car is a commercial $LiCoO_2$ pouch cell from MELASTA. The cell specification is summarized in Table 1.

Table 1: Specification of the battery cell

Items	Specifications
Cathode chemistry	$LiCoO_2$
Nominal capacity	5.6 Ah
Nominal voltage	3.7 V
Lower/Upper cut-off voltage	3.0 V / 4.2 V
Maximum charge current	56 A (<2 s)
Maximum continuous discharge current	84 A
Temperature range for both charge and discharge	0 – 60 °C

To represent the battery electrical and thermal behavior, two main types of models are available in the literature:

- The electrochemical models, such as the well-known pseudo-two-dimensional (p2D) model [3] and the single particle model [4][5], allow detailed insight into different electrochemical processes inside the battery cell. However, it is not suitable for real-time applications and battery pack level simulation due to their high computational cost [6][7]. In addition, the calibration of the electrochemical models is a challenging step which requires considerable experimental effort to measure or estimate the model parameters.
- The empirical equivalent circuit models are widely used in battery applications [6][7][8]. They are simple and commonly consist of basic electrical elements (e.g., voltage source, resistance, capacitance, etc.) or electrochemical impedance (e.g., Warburg impedance or constant phase element). Due to the simplicity in model structure and limited number of parameters, the equivalent circuit models run faster compared to the electrochemical models and hence are more suitable for real-time applications and battery pack level simulation. The equivalent circuit models require at the same time less experimental effort to calibrate the model parameters from test data. When they are properly parameterized, the equivalent circuit models can give accurate voltage and temperature estimations of the battery [6][8].

In our work, the equivalent circuit models in Figure 2 are chosen because they are simple, fast, suitable for battery pack level simulation, with a good compromise of accuracy/simplicity and have been implemented in Simcenter Amesim [9], a multi-physical system simulation software of Siemens Digital Industries Software. A detailed description of these models can be found in [6].

The workflow to calibrate the equivalent circuit model parameters from the experimental data is summarized in Figure 2:

- Firstly, two types of current test profile have been designed to characterize the battery cell. The first type is a constant discharge and CC/CV (Constant Current/Constant Voltage) charge test as Figure 3 (a). The second type is a HPPC (Hybrid Pulse Power Characterization) like pulse test current profile from [6]. The pulse profile is adapted to the battery cell according to its specification in Table 1. Figure 3 (b) and (d) show the detail of the pulse test profile. This pulse test profile tests the battery at different states of charge and different current amplitudes which allows to identify the parameters of the battery equivalent circuit models.
- Secondly, the two types of test profiles have been applied experimentally to the battery cells at the Institute for Power Electronics and Electrical Drives (ISEA) of the RWTH Aachen. The battery cells were placed in a climate chamber and were connected to a Digatron battery test bench. Two battery cells were tested as shown in Figure 2 to ensure the repeatability of the test results. The constant discharge and CC/CV charge test profile was applied to the cell at 25 °C of ambient temperature to evaluate the cell's real capacity. The pulse test profile was applied to the cell at 25 and 55 °C of ambient temperature. The tested temperatures cover the operating ambient temperature range of the battery pack for the competition in summer. For all the tests, the cell current, voltage, and temperature have been measured. Figure 3 shows the experimental test results. The minor temperature variation of the pulse test at 25 °C in Figure 3 (b) is neglectable for the electrical parameter identification. In this case, an average temperature is considered (27 °C) for this pulse test.
- Finally, the Battery Electro-thermal Identification Tool in Simcenter Amesim [9] has been used to identify the electrical and thermal parameters of the equivalent circuit models from the experimental test data. The voltage and temperature estimation of the identified battery models are also shown in Figure 3.

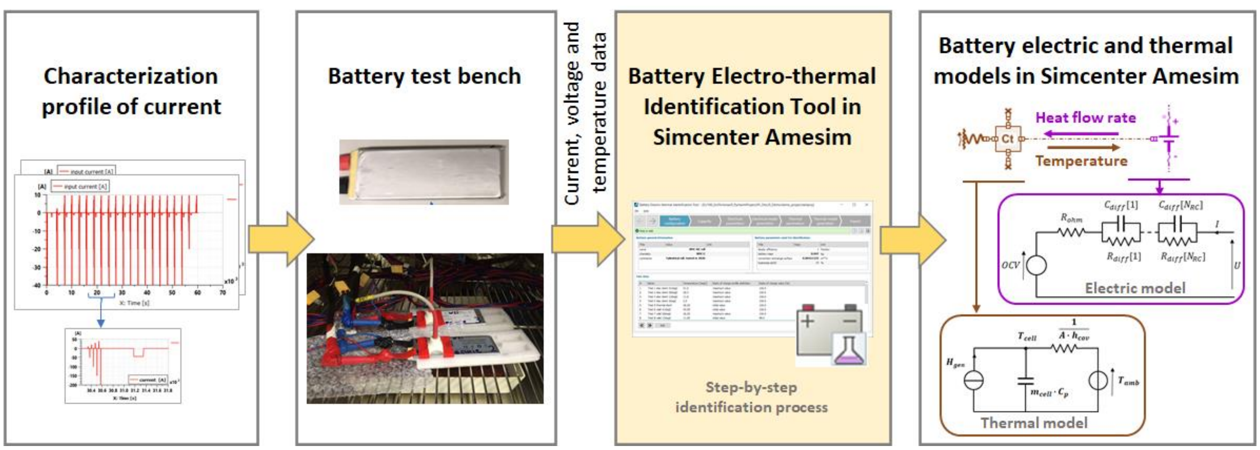


Figure 2: One-dimensional cell model parameterization workflow

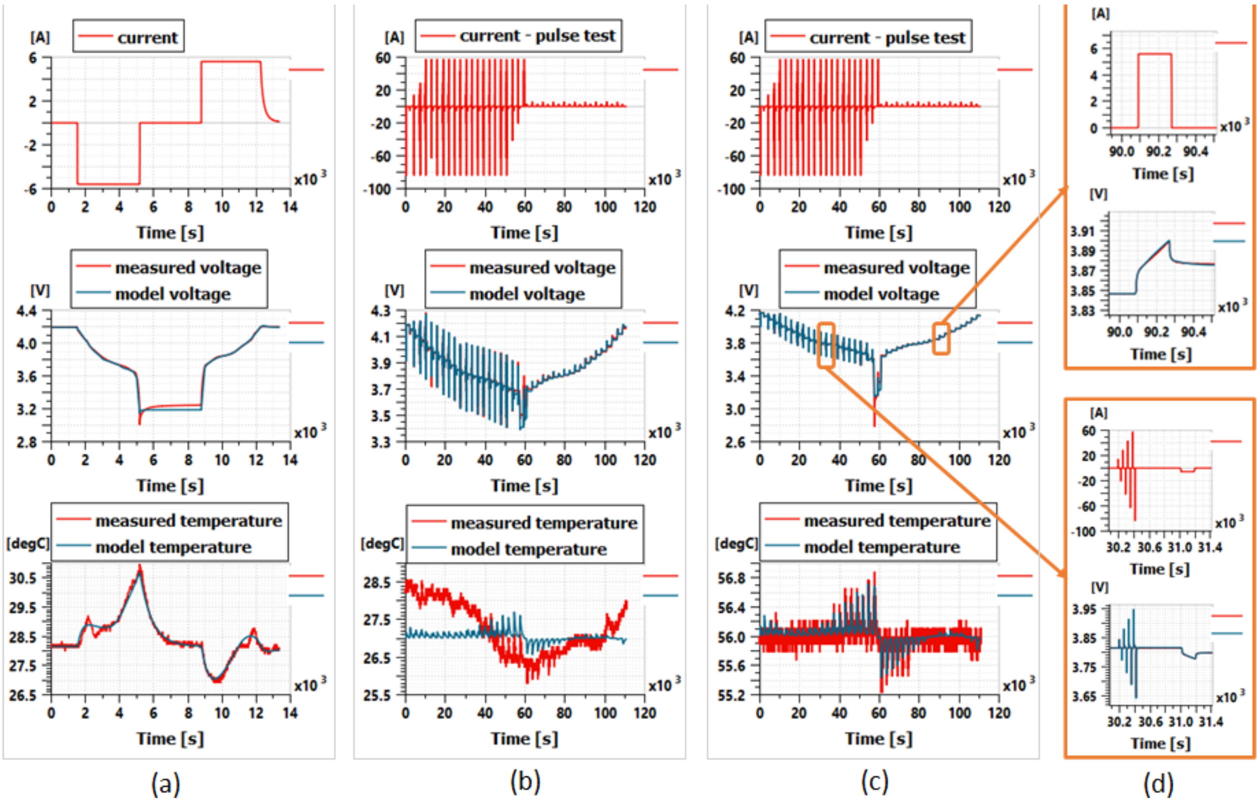
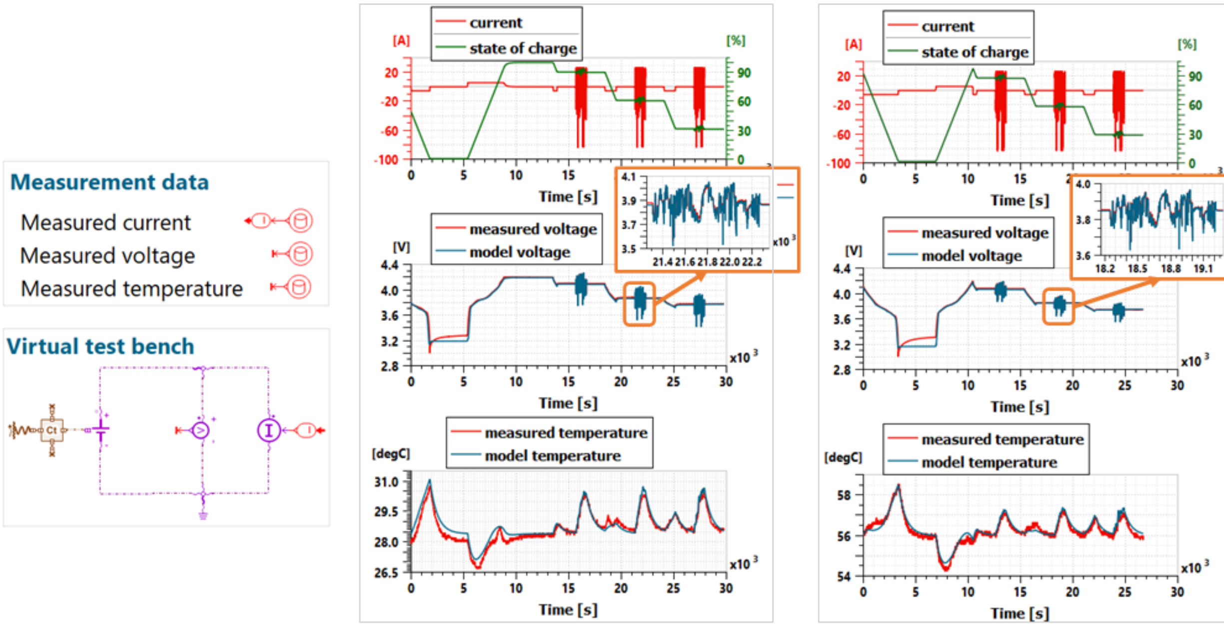


Figure 3: Experimental test data and model estimations from the Battery Electro-thermal Identification Tool in Simcenter Amesim: (a) constant discharge and standard CC/CV charge test (b) pulse test at 25 °C (c) pulse test at 55 °C (d) zoom of pulse test at 55 °C

To validate the cell electrical and thermal models, a validation profile has been applied to the cell via the test bench at different ambient temperatures. The validation profile includes a fast charge phase from about 0% State of Charge (SoC) and several dynamic driving cycles at different SoCs as shown in Figure 4 (b) and (c). A battery cell simulation sketch in Simcenter Amesim as Figure 4 (a) is used to compare the model voltage and temperature estimations to the experimental data. Figure 4 (b) and (c) show the comparison results for respectively 25 and 55 °C. A minor temperature difference can be seen at the beginning of the test at 25 °C, which is due to the ambient temperature variation in the climatic chamber like the test at 25 °C in Figure 3 (b). At very low states of charge (<5% SoC), the battery electrical behavior becomes very nonlinear which cannot be accurately represented by the equivalent circuit model. Otherwise, the identified models give accurate estimation of the battery volage and temperature behavior at these two temperatures. The identified cell electrical and thermal models are then validated.



(a) (b) (c)

Figure 4: (a) cell model validation in Simcenter Amesim (b) comparison between model estimation and experimental data.

3 System simulation model

Based on the model of the single cell, that was electrically and thermally characterized as described in the previous section, the model of a cell stack consisting of several cells is built. To this end and according to the 12s2p stack configuration in the race car described in Section 2, in the system simulation environment 24 instances of the cell model are electrically linked with each other to form a stack. It is noteworthy that building the stack model using any pre-calibrated cell is possible even before the cell characterization. In this case, the cell parameters of the pre-calibrated cell would be improved accordingly once the cell characterization is complete. This process of parallelization may be useful in the view of a reduced project time.

In terms of a modular and efficient model construction, in Simcenter Amesim a cell pair of 1s2p configuration is first created as a so-called supercomponent, as portrayed in Figure Figure 5. As suggested by the name, a supercomponent comprises several components combined into one and this way facilitates the re-use of model parts sharing the same setup. By means of exposed parameters and exposed variables, relevant "inner" quantities are defined as accessible outside the supercomponent. In this way, the supercomponents consisting of several individual components, such as the 1s2p cell configuration, simplify the visual appearance and ease the parametrization of complex models [9].

Figure 5Figure 5 shows the supercomponent created and the electrical parallel connection of two single cells, which deliver their potential voltage through the electrical ports 1 and 3. The voltage of the cell pair can be extracted with the signal output of the voltmeter and processed further if needed. The thermal ports of both cells are connected to a node that enables the data exchange via the common thermal port 2. In this way, the heat flow rates due to the power losses generated in the cells are added and the simplifying assumption is that both cells have the same temperature, as two cells in parallel are thermally connected in this case.

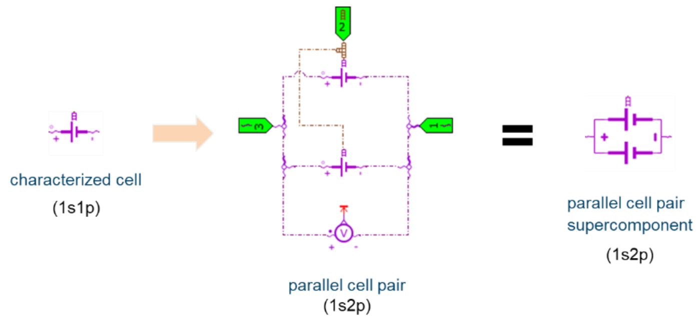


Figure 5: Supercomponent representing 1s2p cell pair

The electrical stack configuration 12s2p is implemented by interconnecting 12 of the cell pairs (or 12 instances of the supercomponent) in series as it is shown in the bottom part of Figure 6. The current going through the stack is consequently divided between the two cells and combined accordingly at the nodes connecting the 1s2p elements. Thermal adapters are connected to the thermal ports of the cell pairs to enable the exchange of temperature as input and heat flow as output at the signal level. This exchange applies to each pair of cells and is ultimately used for co-simulation with the CFD model.

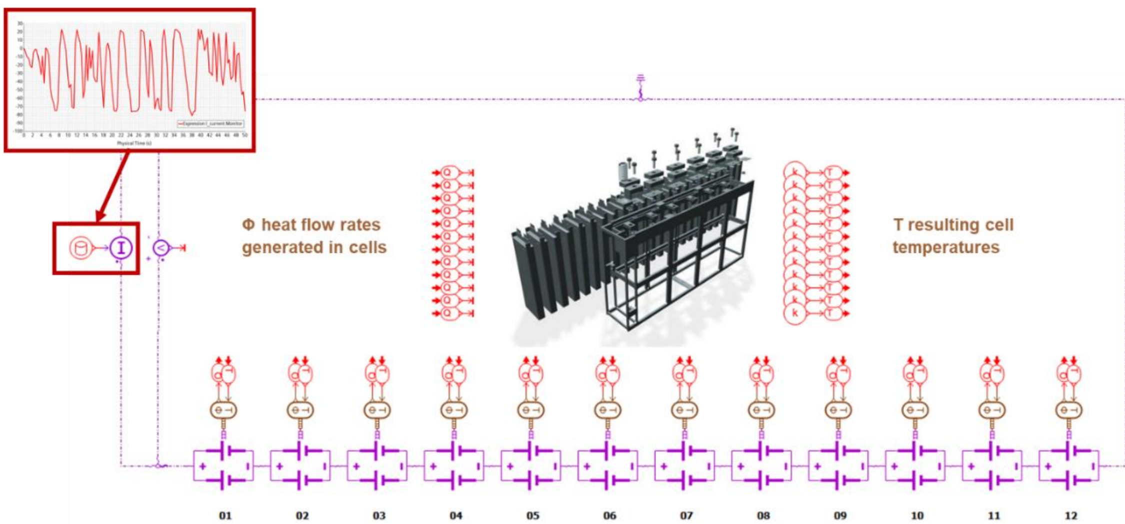


Figure 6: System simulation battery stack model

To account for different situations, i.e., different current loads, and to ensure the re-usability of the model, the current profile is applied by means of a component (a current source) that points to a table file. To simulate different scenarios the user only needs to swap the table file. This procedure is also applied to validate the SYS model: current profiles from measurements are used to assess and verify the voltage response during charging and discharging, read from the voltage sensor connected in parallel with the current source. At this stage, the model is used in an open-loop fashion meaning that it is not accounting for changing temperatures due to power losses in the cells, but rather prescribing constant cell temperatures. Once the model is validated, it can then be embedded in the CFD simulation as described in the following.

Whereas the system simulation reflects the electrical setup of the stack, the thermal interconnections between the cells and thus their orientations to each other as well as their thermal properties are modelled in CFD. Figure 7 shows the basic idea of the co-simulation between the electrical system simulation model and the thermal CFD model. Between the models, the temperatures are passed from the thermal model to the electrical model and, vice versa, the heat flow rates from the electrical to the thermal. The so-called *watch parameters* and *watch variables* are defined within the system simulation model, to possibly change system simulation model parameters and also to access result variables from the CFD model.

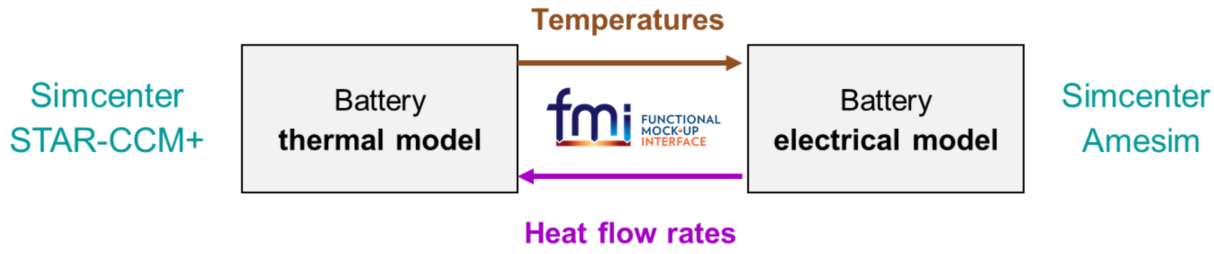


Figure 7: Co-simulation between battery thermal (CFD) and electrical (system simulation) model

The implementation of the co-simulation was made by means of the FMI standard [1] that allows to exchange models between different simulation tools, since both Simcenter Amesim and Simcenter STAR-CCM+ support this standard. Specifically, the FMI standard is used in the co-simulation protocol according to the FMI 2.0 standard. A Functional Mockup Unit (FMU) is generated in Simcenter Amesim with three steps: adding an interface block to the model (shown in Figure 6); removing the dummy signal components; connecting it to the current source and thermal adapter components. Eventually, the FMU is imported into Simcenter STAR-CCM+ with the complect electrical characterization that was conducted with experiments and SYS.

4 CHT Simulation

In this section, the setup of the three-dimensional CHT simulation is explained: The software used is Simcenter STAR-CCM+, version 2021.1 [10], a multi-physics CFD-focused platform, based on a Finite-Volume approach for the space discretization and a second-order temporal discretization of the transport equations, i.e., Navier-Stokes and energy equation.

Due to the constant air mass flow provided by the fans, the flow field can be seen as steady and changes only in reaction to the temperature effects via heat transfer from the surrounding solid regions, e.g., the cooling fins. Hence, in the present case study, a multi-time scale workflow is employed in which steady and transient solvers are combined. The transient behavior of the solid domains is calculated by using an algebraic multi-grid based iterative solver that is second order accurate in space and time. The fluid flow is captured by applying an eddy-viscosity based Reynolds Averaged Navier Stokes (RANS) solver in which a predictor-corrector approach is used for the velocity-pressure coupling, based on a Semi-Implicit Method for Pressure Linked Equation (SIMPLE) algorithm, with second-order accuracy in space. The κω-SST turbulence model [11] with a low-y^+ mesh approach is employed for an optimal modeling of wall turbulence.

The solid domains consist of the cooling fins, the printed circuit boards (PCBs), the cell tabs, the stack cages, and the battery cells as portrayed in Figure Figure 8. For each of this component was modelled with corresponding material values (e.g., thermal conductivity and density). The voids of the stack cages are modelled as solid regions (with air material properties) for solver stability and reduction of calculation time: separate investigations are conducted to assess that this choice has a marginal influence on the heat transfer but great computational advantages. The stacks of the active material layers of the pouch cells are modelled as a homogenized body with orthotropic thermal conductivity λ, assuming $\lambda_{\parallel} = 20$ W m^{-1} K^{-1} z-direction and $\lambda_{\perp} = 0.8$ W m^{-1} K^{-1} in in x- and y-direction (see Fig. Figure *8*). The battery cells are packed closely in the stack cages and are not in direct contact with the cooling fluid. Instead, the heat is conducted away through the cell tabs which are located at the top end of the cells and connected to the cooling fins.

The transient energy equation on the battery cell level can be written as:

$$\frac{\partial T_{cell}}{\partial t} = \frac{\lambda_{cell}}{\rho_{cell} c_{p,cell}} \nabla^2 T_{cell} + \dot{q}_{cell} \quad (1)$$

with $\dot{q}_{cell}$ being the heat source calculated by the electrical cell model in the FMU, depending on the SoC, the cell temperature T_{cell} and the current I at the respective time step.

The symmetric architecture of the battery system allows the simulation setup to be reduced to six cell stacks, representing half of the battery system: A symmetry boundary condition is therefore applied to the symmetry plane as displayed in Figure 8. On all other outer system boundaries apart from the inlet and the outlet, a convection boundary condition with a heat transfer coefficient of 6 W m^{-2} K^{-1} is applied, representing a natural convection in the battery container. The fans at the back of the battery container are modelled as a constant air mass flow of 0.0045 kg s^{-1}. The driving heat transfer modes inside the battery container are conduction and convection and, due to the limited expected temperature below 60 °C, the influence of radiation is considered negligible and therefore neglected. For the fluid region, i.e., the cooling channel, the mesh consists of around 12 Mio. cells while all solid regions together consist of around 11 Mio. cells.

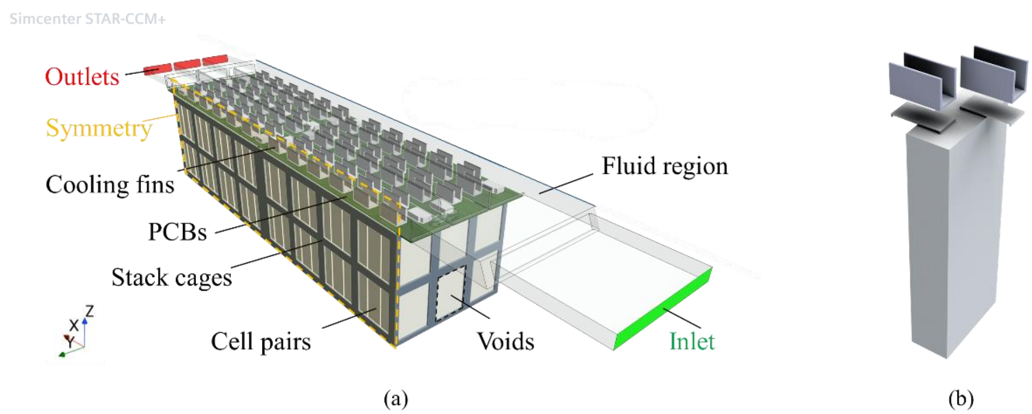


Figure 8: (a) Fluid and solid regions in the CFD model and (b) explode view of the cell, tabs and the cooling fins

The small impact of the temperature change on the fluid flow and the different time scales between the solid and fluid continua in terms of propagation of temperature allow for the utilization of a steady-state fluid solver that is updated periodically, mimicking a transient behavior. For the multi-time scale workflow, a time step of 0.1 s is employed for the implicit unsteady solver of the solid continua whilst the steady state solver of the fluid continua is updated every 60 s of simulation time by running 20 iterations until converged for the prevalent conditions of the solid continua. In the underlying case study, this multi-time scale workflow has proven to be computationally less expensive with a negligible deviation compared to the fully time dependent simulation.

As described in Section 3, the system simulation model represents a complete cell stack, incorporating 24 of the previously parameterized battery cell models, consisting of 2 cell pairs. The system simulation model is now exported as a *Standalone* FMU, allowing Simcenter STAR-CCM+ (that acts as the master tool for the coupled electro-thermal simulation of the battery system) to call the FMU for the co-simulation independently of the secondary controller tool (Simcenter Amesim). For a FMU to be called by the CFD simulation, it must be embedded in Simcenter STAR-CCM+, specifying the exchanged variables, the exchange time step and optional watch parameters to access electrical quantities in the CFD simulation. Since six cell stacks are necessary in the CFD setup, six time the same FMU is imported and the inputs ($\dot{q}_{cell}$) and outputs (T_{cell}) are linked to the three-dimensional volumes of the respective cell pairs, allowing for the models to exchange data in a closed loop. The latter, with an exchange interval of 0.1 s, consists of the following steps: the mean temperature of each cell pair is evaluated in the CHT simulation at each (solid continua) time step; then passed to the FMUs; the latter evaluates the corresponding generated heat (calculated by the underlying electrical model in the FMU itself); finally, this value is imposed as a volume heat source in the CFD calculation. The current profile applied in the CFD simulation is a recorded profile measured during an endurance race.

The temperature of the battery pack and the velocity field inside the cooling channels at the end of the endurance race simulation can be seen in Figure 9 (a). The development of the average temperature, the voltage and the SoC over time in a selected cell pair (S1P12 = stack 1, cell pair 12) are shown in Figure 9 (b-d). In general, the results show the expected behaviour for the electrical and thermal quantities for the applied current profile of the endurance race. The plateau that can be seen in electrical and thermal values from 725 s – 975 s corresponds to the driver change phase in which the car is stands still and the current load is zero. Furthermore, the simulation results fit well with the target values that have been defined during the battery development. For an initial temperature of air and solids of 30 °C (which represents a canonical weather condition at Hockenheim in summer) the hottest cell of the battery pack reaches a maximum temperature of 59.2 °C at the end of the endurance race which is slightly below the temperature limit defined by the competition rules [13]. The temperature spread inside the selected cell pair amounts to 7.9 °C and is below the limit of 10 °C that is linked to an accelerated aging in a battery cell. According to the simulation, the car reaches the end of the endurance race with a remaining state of charge of 7% which shows that the battery pack provides enough energy, but it also points to a possible improvement of the energy management strategy.

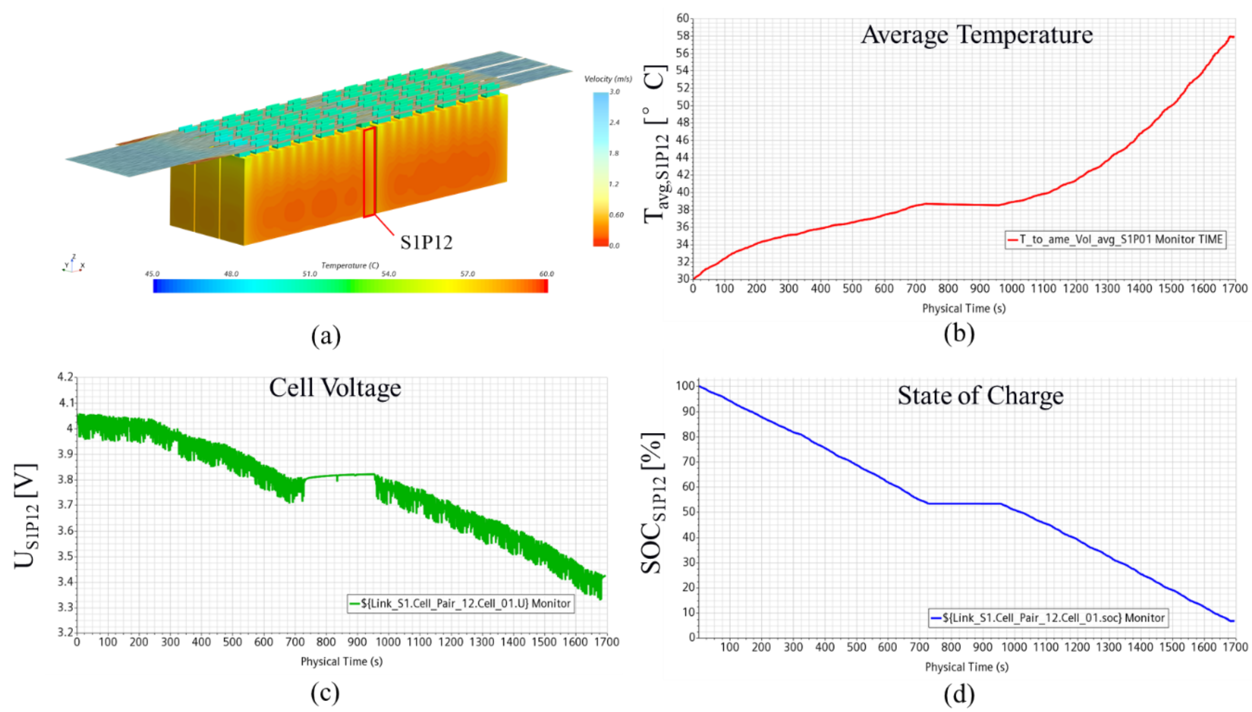


Figure 9: velocity field of air region (a); cell pair temperature (b), SoC (c) and voltage (d) over time for one selected cell pair.

Conclusion

In this paper a novel, multi-disciplinary approach is presented to characterize and simulate the BTM (Battery Thermal Management) of a battery pack for a race car, leveraging and combining experiments, systems simulation, and computational fluid dynamics. First, a single cell is experimentally investigated to identify the equivalent circuit model under different temperatures. By using the identified cell model, a system level battery stack model is set up and is then exported into a FMU by means of the FMI standard to ensure the scalability, re-usability, and portability of the model. Finally, the FMU is embedded in a CFD simulation where the cooling of the battery pack is simulated. This procedure allows a detailed CFD fluid-solid simulation that embeds experimental characterization as well as the functional interconnection of cells at system level. The same procedure can also be applied to model and simulate battery packs with different types of cooling strategies, e.g., with liquid or emersion cooling.

There are several possible enhancements of this work and we briefly mention two of them. The first is a so-called Multi-disciplinary Design Optimization, employed with the objective of optimizing the performance of the cooling system. Focusing for example on possible design changes (such as number of fans – represented in the model by the value of the inlet mass flow, the shape of the air channel and cooling tabs, etc.), the SHERPA algorithm [14] can be employed to efficiently search for design optima. One possible optimization strategy could be to maximize the heat transfer between fluid and solid, i.e., increasing the cooling performance of the system, while trying to minimize the mass flow. This would allow for the reduction of the number of fans, reducing the weight of the car and the requirement for the electrical system. The two opposite optimization goals, i.e., increasing the heat transfer and reducing the mass flow, can be efficiently handled by the SHERPA algorithms within Simcenter HEEDS, providing an optimal compromise between the optimization goals and discovering the most efficient design parameter combinations (a so-called Pareto front). The second possible enhancement of the model is its utilization for the real-time controlling of the battery cooling system. Simcenter Amesim provides the possibility to export the described model for real-time targets such as dSPACE devices [15], i.e., controller units that are often used as vehicle control units. By replacing the CFD-generated temperature values with *instantaneously* measured cell temperatures during the race, the presented model could improve an existing vehicle model with a detailed online battery model. This would enable, for example, a predictive race strategy, which can utilize the knowledge of the *instantaneous* thermal behavior to adjust the operating limits of the car.

Acknowledgments

Ecurie Aix and Siemens Digital Industries Software kindly acknowledge the Institute for Power Electronics and Electrical Drives of the RWTH Aachen University for providing support to perform the tests in their laboratories in the framework of an ongoing and proficient cooperation between the team and the institute. Simulations were performed with computing resources granted by the RWTH Aachen University under project 0213.

References

[1] T. Blochwitz *et al.*, The Functional Mockup Interface for Tool independent Exchange of Simulation Models, in *Proceedings of the 8th International Modelica Conference*, Mar. 2011, pp. 105–114.

[2] Ecurie Aix Formula Student Team RWTH Aachen e.V., *eace08,* www.ecurie-aix.de/eace08 (2021)

[3] M. Doyle, T. F. Fuller, and J. Newman, Modeling of Galvanostatic Charge and Discharge of the Lithium/Polymer/Insertion Cell, *J. Electrochem. Soc.*, vol. 140, no. 6, p. 1526, Jun. 1993, doi: 10.1149/1.2221597.

[4] M. Petit, E. Calas, and J. Bernard, A simplified electrochemical model for modelling Li-ion batteries comprising blend and bidispersed electrodes for high power applications, *Journal of Power Sources*, vol. 479, p. 228766, Dec. 2020, doi: 10.1016/j.jpowsour.2020.228766.

[5] C. Edouard, M. Petit, C. Forgez, J. Bernard, and R. Revel, Parameter sensitivity analysis of a simplified electrochemical and thermal model for Li-ion batteries aging, *Journal of Power Sources*, vol. 325, pp. 482–494, Sep. 2016, doi: 10.1016/j.jpowsour.2016.06.030.

[6] A. Li, M. Ponchant, J. Sturm, and A. Jossen, Reduced-Order Electro-Thermal Battery Model Ready for Software-in-the-Loop and Hardware-in-the-Loop BMS Evaluation for an Electric Vehicle, *World Electric Vehicle Journal*, vol. 11, no. 4, Art. no. 4, Dec. 2020, doi: 10.3390/wevj11040075.

[7] M.-K. Tran *et al.*, A comprehensive equivalent circuit model for lithium-ion batteries, incorporating the effects of state of health, state of charge, and temperature on model parameters, *Journal of Energy Storage*, vol. 43, p. 103252, Nov. 2021, doi: 10.1016/j.est.2021.103252.

[8] F. Lacressonnière, A. Varais, X. Roboam, E. Bru, and T. Mullins, Scale electro-thermal model of a lithium-ion battery for time-accelerated experiments in a hardware in the loop process, *Journal of Energy Storage*, vol. 39, p. 102576, Jul. 2021, doi: 10.1016/j.est.2021.102576.

[9] Siemens Digital Industries Software, Inc., *Simcenter Amesim User Guide*, Version 2021.2, 2021

[10] Siemens Digital Industries Software, Inc., *Simcenter STAR-CCM+ Documentation*, Version 2021.1, 2021

[11] F. R. Menter, Two-Equation Eddy-Viscosity Turbulence Models for Engineering Applications, *AIAA Journal*, vol. 32, no. 8, pp. 1598–1605, 1994, doi: 10.2514/3.12149

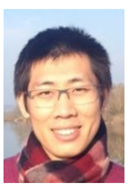
[12] D. Bernardi, E. Pawilkowski, J. Newman, A General Energy Balance for Battery Systems, *J. Electrochem. Soc.*, vol. 132, p. 5, 1985, doi: 10.1149/1.2113792

[13] Formula Student Germany rules 2022. https://www.formulastudent.de/fsg/rules/

[14] N. Chase, M. Rademacher and E. Goodman, A Benchmark Study of Optimization Search Algorithms, *BMK-3022*, pp. 1-15, 2016

[15] M. Ponchant, A. Li, C. Beckers, and M. Paroha, Battery Management System Evaluation within a Complete Electric Vehicle Model with Software-in-the-Loop and Hardware-in-the-Loop Approaches, in 2021 23rd European Conference on Power Electronics and Applications (EPE'21 ECCE Europe), Sep. 2021, p. P.1-P.10.

Authors

	Dr. Claudio Santarelli is a Business Developer for Academia at Siemens Digital Industries Software for the DACH region and is co-responsible for developing the Siemens academic strategy, being the main point of contact for several top-ranked universities in Germany. After receiving his master's degree in Aeronautical Engineering at La Sapienza University (Rome, Italy) and a PhD in Computational Fluid Dynamics at the TU Dresden (Germany), he joined Siemens Digital Industries Software in 2017 as a PreSales Solution Consultant with focus on simulation software, working with commercial customers and with student competition teams.
	Dr. An Li received the master's degree (*diplôme d'ingénieur*) in electrical engineering from Institut National des Sciences Appliquées Lyon (INSA-Lyon) in 2009, and the PhD degree in electrical engineering from the Lyon 1 University in 2013. Since 2017, he joins Siemens as technical product manager and then application specialist for battery modelling in the product management team for Simcenter Amesim. His work focuses on modelling, characterisation, aging and security of the electrical storage system with batteries and ultra-capacitors.
	Christopher Helbig works as a PreSales Solutions Consultant at Siemens Digital Industries Software since 2018. In this role, he supports customers in the field of multi-physical system simulation and acts as an interface between the sales team and product management. Christopher holds a Master of Science in Energy Engineering from the Technical University of Hamburg.
	Fabian Böhm joined the Formula Student Team Ecurie Aix in 2017 and worked as Head of the Electrical Powertrain group in the 2018/19 season. He did PCB Design, system commissioning and testing, as well as cell characterization and module commissioning for the high voltage accumulator. He holds a B. Sc. degree in Electrical Engineering and is currently pursuing an M. Sc. degree in Electrical Engineering, both at RWTH Aachen University. In his student assistant jobs he worked with fast switching power electronics and is currently focussed on the analysis of battery cell ageing.
	Thomas Nyhues was part of the Formula Student Team Ecurie Aix from 2017 to 2020 where he was responsible for numerical simulations in the department of aerodynamics and battery thermal management. He holds a Master of Science in Mechanical Engineering from the RWTH Aachen University and is currently working on his PhD thesis in the battery systems department at MAHLE where he focuses on electro-thermal battery simulations and thermal management systems for automotive applications.