EVS30 Symposium
Stuttgart, Germany, October 9 - 11, 2017

Validation of a Cooling System for Temperature Conditioning of Cylindrical Battery Cells

M. Eisele[1], K. Kohler[1], F. Prinz[1], S.Ott[1]

[1]IPEK - Institute of Product Engineering at Karlsruhe Institute of Technology (KIT), Kaiserstr. 10, 76131 Karlsruhe, Germany, martin.eisele@kit.edu; sascha.ott@kit.edu

---

Abstract

One of the major customer requirements on electric vehicles is fast-charging capability. Considering thermal load, fast charging is a crucial load condition that makes battery-cooling necessary. Common direct cooling systems for cylindrical battery cells mostly use air, but have small heat dissipation. The validation process for a direct liquid cooling system for 18650 cells is described in this paper. An appropriate CFD model is described and gained systems understanding is used to develop a test setup according the IPEK X-in-the-Loop-approach in order to investigate selected cooling concepts.

Keywords: battery, cooling, fast charge, testing processes, thermal management

---

1 Introduction

Lithium ion batteries as used in common electric and hybrid vehicles offer high energy density but are temperature sensitive. Most lithium ion chemistries operate optimal in temperatures between 20°C and 40°C [7]. Because of changing ambient temperatures and high electrical loads, heating up the battery cells, a temperature-conditioning unit for a battery system is necessary in electric cars to provide optimal thermal conditions. By temperature conditioning of a battery system driving range, charging rate and lifetime can be influenced to fulfil customer needs. Charging batteries with high current at low temperatures leads to irreversible chemical reactions and decreasing battery capacity. Heating up batteries at low environmental temperatures enables recuperation and therefore increases the driving range. At high temperatures internal resistance of batteries decreases, but in the same way aging processes accelerate. Temperature-dependent aging processes can be approximated with the Arrhenius equation, thus higher temperatures lead to an exponential loss of capacity [3]. Besides high environmental temperatures, high power charging or discharging rises battery temperature. Especially high charging currents over longer periods rise battery temperature. This is a typical and the most crucial load condition for electric vehicles considering battery aging [8, 14]. To meet customer requirements of fast-charge capable battery systems with high energy density in electric vehicle, a powerful cooling system with space efficient design is necessary.

Active battery cooling systems used in today's mobility applications are air cooling, refrigerant cooling and liquid cooling systems. First-mentioned is lightweight and has low heat dissipation capacity due to the use of air as cooling fluid. It is the simplest way of cooling but occupies more constructive space than the other principles. Refrigerant cooling is efficient, using enthalpy of vaporization. A disadvantage is the need of a separate heating system for every battery module. Whereas liquid cooling enables cooling and heating with the same fluid. Heat dissipation is good but battery weight rises due to the use of a liquid.

Cooling designs of battery systems not only differ in cooling principles, the used cell format and the application have also impact on the design. For instance, cylindrical cells in consumer batteries like laptops and e-bikes have no active cooling. Whereas cylindrical cells of automotive mobility applications, have complex cooling systems, using different cooling principles, such as liquid and air-cooling. This paper focuses on the design of liquid cooling system for battery cells type 18650 for mobility applications.

2 State of the Art

2.1 Direct Cooling Systems

Common direct cooling systems for cylindrical battery cells mostly use air as cooling fluid [17, 18]. One advantage of air-cooling is that sealing between cooling fluid and electrical parts such as electric wiring or battery cell are not necessary. Air cooling systems involve disadvantages due to the ambient air flowing through the battery system, such as moisture and dust from the ambient air get inside the battery system. Although it is a lightweight cooling system big voids are needed to duct air between cells, therefore energy density is smaller in comparison to liquid cooling. The poor heat capacity of air also limits the heat dissipation of the cooling system. Liquid or refrigerant cooling systems provide better heat dissipation but are more complex. Cooling pipes or plates are separated from battery cells by the means of electrical insulation materials with low thermal conductivity. Small contact areas and poor heat transfer between fluid and battery cell housing lead to a reduced heat dissipation and inhomogeneous temperature distribution inside battery modules.

However, direct liquid cooling of battery cells devoid of thick insulation material between fluid and battery cell housing offers better heat dissipation. Heat transfer resistances are reduced to a minimum and the contact area for convective heat dissipation can be increased. The approach of direct liquid cooling of cylindrical cells is subject of research, only the company Kreisel Electric uses this cooling principle in their battery systems [11]. Missing experience are the reason why, validation processes are unknown for this cooling type considering new design parameters. In common works air cooling systems for cylindrical cells are investigated via CFD [17, 18]. These models are validated by investigating the electro thermal behavior of single cells in physical test setups under defined thermal conditions. Additional approaches for developing physical test setups on module level are not provided. Besides the homogeneous and efficient cooling of the battery, especially in mobility applications, an efficient use of available space is one of the major objectives. Due to simulations and physical investigations, the conflict of objectives can be solved, designing a powerful cooling system that occupies minimum of space. This paper describes the validation of liquid direct cooling system for cylindrical (type 18650) cells in a battery module for mobility applications with high packing density and maximum heat dissipation.

2.2 Validation Methods

There are three different validation methods that are applied in product engineering: Virtual, physical and physical-virtual mixed validation. By the right use of these methods, validation processes can be designed efficiently, offering a fast growing systems understanding.

2.2.1 IPEK XiL

The IPEK X-in-the-Loop-approach (IPEK XiL) provides a methodical basic for a continuous validation during the engineering process. The IPEK XiL was originally developed to validate drive systems of vehicles. In general, the X stands for the System in Development (SID). This can be carried out from the active surface pair via subsystems of different levels up to the complete vehicle on different system detailing levels and is supplemented by the remaining subsystems of the vehicle. Thus, it can be examined and experienced in real-life driving maneuvers and test cases, taking into account the super system - driver, vehicle and environment. The special feature of the IPEK XiL idea is that all systems can be integrated physically, virtually or combined physically virtual. The approach thus makes an efficient contribution to the design and construction as well as the selection, application and documentation of validation environments. [1, 10]

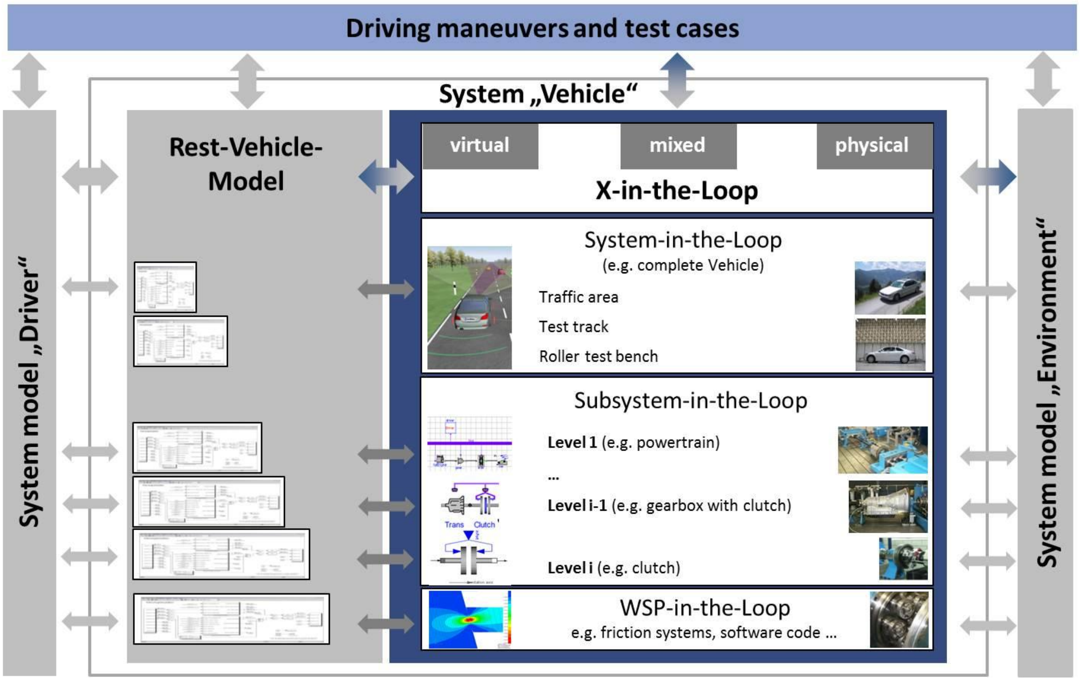

Figure 1: IPEK-X-in-the-Loop-Framework corresponding to [10]

The three mentioned methods virtual, physical and physical-virtual mixed validation are described below.

2.2.2 Virtual Validation

Virtual validation is especially suitable for building up systems understanding in the early phase of product engineering. The complexity of modelling subsystems of cooling systems differs according to the objective of validation. This applies particular for modelling battery cells.

YANG uses a 2D conjugate heat transfer model coupled with 1D electrochemical model to investigate the performance of cylindrical battery cells under forced air-cooling. Regarding the requirements, an appropriated solution for the minimal distances between cells in aligned and staggered arrangements are obtained. The applied thermoelectric battery cell model is precise but complex. This method is suitable to validate a cooling system considering the electrical characteristics of one special battery cell, whereas cooling effect in the third dimension are neglected. [18]

On the contrary LI uses a third degree polynomial to describe the temperature dependence of the internal resistance of each battery cell in its 2D CFD model to investigate temperature distribution in a battery module under different stream velocities. Temperature distribution inside the battery cell and electrical effects such as the variation of the cell voltage under load are not considered. [9]

WANG investigates temperature non-uniformity between cooled cells in a 3D CFD model. Battery cells are modeled as homogeneous cylinders with a uniform heat generation. Using this method, different design parameters of the cooling system were change and investigated, getting detailed information about the temperature distribution inside the battery module. [17]

The challenge of virtual validation is the development of suitable models. To investigate a system entirely in detail makes a model complex. That leads to long modelling and computation time. To use physical-virtual mixed or physical validation methods can be more efficient when modelling complexity rises. Last-mentioned method is described here after.

2.2.3 Physical Validation

Physical validation means, that all relevant subsystems for the validation are physical models. In comparison to virtual validation, measurement points are limited in physical setups, so that a certain degree of systems understanding is necessary to choose the right measurement equipment and use reasonable measurement points. These prototypes mostly include original battery cells, whereas other parts of the cooling system are modelled in different degrees of abstraction. KHATEEB for example investigates different modes of heat dissipation in battery modules using PCM. Therefore, real battery cells are used, measuring the cell temperature in the center of the battery module while charging and discharging the cells. [6] Due to the use of real battery cells, the electro thermal behavior of the cooling system can be characterized detailed for the use of one special battery cell. This often fulfils the expectations of a battery system validation, if only battery cells of one supplier are used in combination with the cooling system. However, to prove the sustainability of the cooling system for the use of future battery cells a physical-virtual mixed validation is more suitable, using cell dummies that can represent different battery cell characteristics. The IPEK-XiL-approach, enabling physical-virtual mixed validation, is described below.

2.2.4 Physical-Virtual Mixed Validation

The physical-virtual mixed validation is mostly used for modelling vehicles to validate subsystems of the drive system, like gearbox and the electric motor (Figure 2). In this paper, the IPEK XiL is used to validate a battery cooling system. The physical-virtual mixed modelling provides flexibility in validation due to simple variation of parameters in the virtual domain. Whereas subsystems with complex physical relations are modeled in the physical domain. In both domains, physical and virtual, appropriate models are used. In some cases, they are greatly simplified, but also original components of the drivetrain can be used in the physical domain. The so-called “Koppelsystem” or “Sensor-Actor-System” is the interface between virtual und physical models, enabling communication between the domains.

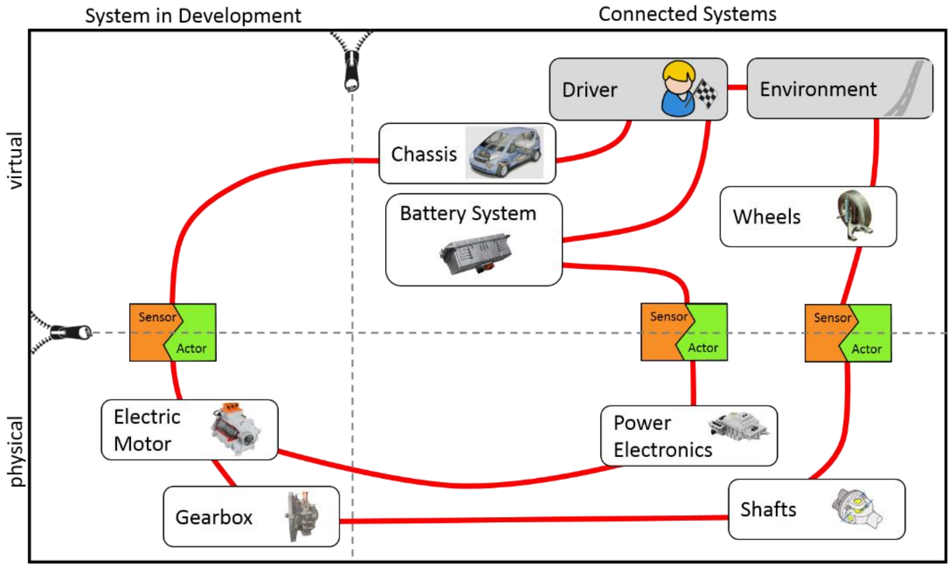

Figure 2: example of a physical-virtual mixed modelling of a hybrid car to validate a gearbox with an integrated electric motor corresponding to [10]

3 Validation Process for a Battery Cooling System

The task is to define a cooling system with high cooling efficiency using minimum of space, suitable for different 18650 cells. Modules consist of 96 battery cells, which are positioned at right angle to the liquid flow. Initially four different cell arrangements and two different module dimensions are investigated. To define the design of a first physical prototype of a battery module, solution space is reduce by several validation steps. Different cooling concepts are simulated with a simple CFD model to identify design parameters with high impact and to evaluate different cooling concepts. Via the gained knowledge and the IPEK X-in-the-Loop (IPEK-XiL)-Approach [10], a test setup is designed to test preselected cooling designs. Task of the setup is to validate the CFD model on one hand and to investigate new design parameters that are not simulated on the other hand, to define a design for a first physical prototype of the cooled battery module.

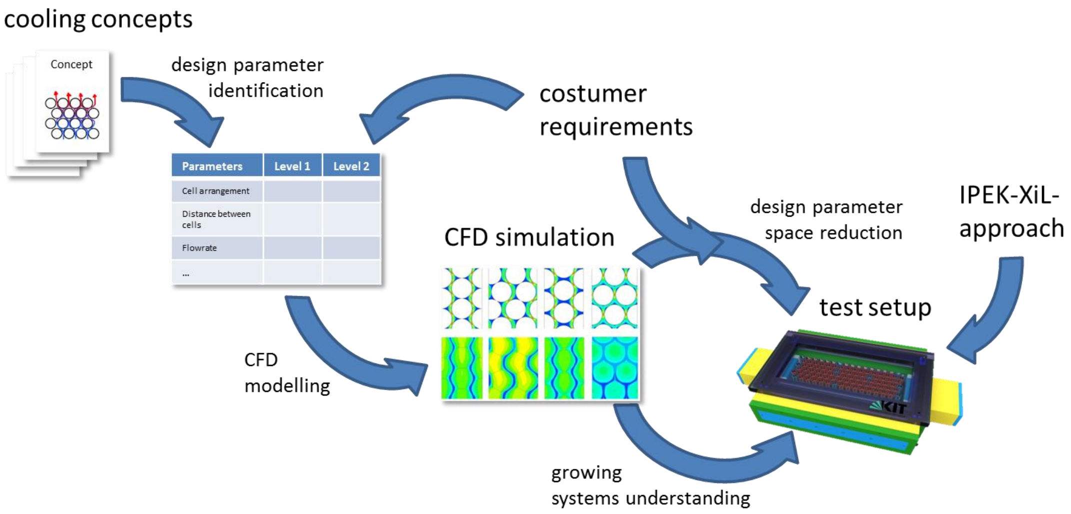

Figure 3: Validation process for a battery cooling system

3.1 Parameter Identification

As already mentioned, fast charging is a crucial load condition for battery cooling and one of the major customer requirements for electric vehicles [14]. Battery cells should remain in the temperature range between 20°C and 40 °C [7] also during the constant current charge phase. To prove if the cooling system is suitable for fast charging an equivalent load condition is defined. The thermal load on battery cells should be equal in battery systems to guarantee a homogenous electrical load distribution and therefore exhaust the maximum battery capacity. A temperature difference of 5 K between battery cells should not be exceeded [7]. In addition, temperature gradients inside the battery cell are a criterion to evaluate a cooling system.

To fulfil the requirement of high cooling efficiency design parameters with a high impact on heat dissipation are identified by using an empirical computation method [15]. The battery module is modelled as a tube bundle that is positioned right angle to the cooling flow. Due to the convergence behavior of the iterative method, only a section of the battery module is investigated with the assumption, all cells having the same temperature. The following design parameters are varied in a design of experiments study regarding the heat dissipation:

- five cell arrangements
- three cooling fluids
- two different gaps between cells
- two flowrates of cooling fluid
- two module sizes
- two temperature levels of the cooling fluid

Figure 4 shows the standardized effects of the design parameters for one exemplary cell arrangement.

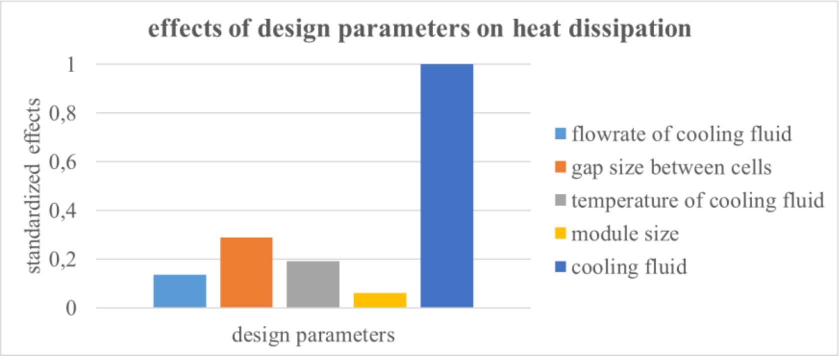

Figure 4: effects of parameter variation on heat dissipation for one cell arrangement

Due to different heat capacities, thermal conductivities and viscosities, changing the cooling fluid has the most significant influence on the heat dissipation. Therefore, the fluid leading to better cooling performance was chosen for further investigations using CFD. The variation of the gap size between the cells has the second largest impact. Computations indicated that smaller gaps lead to a higher heat dissipation in a certain range. The comparison of the five cell arrangements demonstrated different cooling efficiencies and differences in space efficiency. Therefore, one of the arrangements was excluded for further investigations.

Despite the simplifications in this calculation, the major impact factors could be identified and parameter space was reduced to enable an efficient use of CFD in the next validation step.

3.2 CFD - Simulation

Based on the cooling concepts and the previous calculations, a 2D CFD model is build up to gain more information about the systems characteristics. Due to higher model quality in comparison to the previous used computation, CFD enables to validate more customer requirements, such as temperature homogeneity of the module and of single cells and robustness considering thermal abuse of a battery cell. Therefore, beside the fast charging load condition, cooling concepts are assessed concerning safety in case of an internal short circuit of a battery cell. The cooling system should prevent an excessive heat up of the battery cell and impede a thermal runaway. In this abuse case, a good heat transfer between cells would lead to a chain reaction heating up surrounded cells crucially. This leads to another conflict of objectives, on one-hand battery cells should be thermally isolated against each other and on the other hand, a homogeneous temperature distribution between battery cells is positive, regarding performance and lifetime of the battery system.

To reduce complexity and computing time, three rows of battery cells positioned parallel to the fluid flow along the entire module are modeled in 2D. Flow guiding geometries at the inlet or behind the cell bundle are not investigated in CFD. A 3D model was build up first to indicate that the walls at the top and bottom of the cells have only little influence on the fluid flow. Considering increased thermal conductivity in axial direction, non-uniform heat dissipation along the cell axis can be neglected. The cells are considered as lumped solids with homogeneous thermal properties, a uniform heat generation, simulating a constant current charge phase. Differences in radial and tangential thermal conductivity inside the cells are not taken into account. Due to the simulated small conductivity according to UPTMOOR equal to the radial thermal conductivity of a LiFePO4 battery cell leads to higher temperature gradients in tangential direction, than in reality [2].

Via design of experiments different combinations of the mentioned design parameters flowrate, distance between cells, cell arrangement and module size are simulated. By means of simulation results, four cell arrangements are evaluated considering the criteria:

- temperature gradient inside the module
- temperature gradient inside the battery cell
- cooling sensitivity for varying distances between cells
- temperature distribution in case of an internal short circuit of one cell

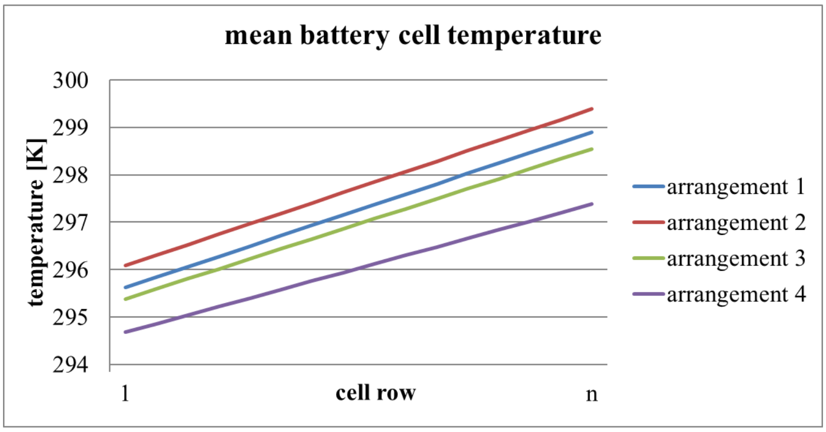

Figure 5: temperature rise of battery cells along the cooling flow for different cell arrangements corresponding to [5]

Figure 5 shows the mean cell temperatures along the cooling flow for different cell arrangements. Cell temperatures are averaged over the flow rates and the two different gaps between the cells. All lines have the same gradients except arrangement 4. This can be explained by different flows near the inlet zones caused by the cell arrangement. This leads to varying heat dissipation in the first cell rows. Apart from that, mean temperatures differ between the four arrangements being cooled with the same fluent temperature. It can therefore be concluded that arrangement 4 has the best cooling efficiency, whereas the temperature level of cells in arrangement 2 is about 1.5 K higher.

Temperature differences inside the cells are smaller than 2 K in all investigated cell arrangements. So all arrangements fulfil the requirement of temperature gradients less than 5 K inside the cell considering the implemented thermal conductivity.

One of the lessons learned is the positive effect of long module sizes, that leads to a smaller flow area and therefore to higher fluent velocity. Smaller gaps between the cells have the same effect, improving the heat dissipation. Without regarding pump performance, rising up the mass flow in the same extent has a higher impact on the cooling efficiency on long module sizes than on modules with a wide inflow. This can be explained by the transition of a laminar to turbulent flow. In addition, space efficiency of lean module is better. As a result, lean modules meet customer requirements of high space and cooling efficiency. Therefore, they are chosen for further investigations using a physical test setup.

In case of an internal short circuit, the cooling system has to prevent a thermal runaway due to exceeding heat up of the cell or surrounded cells. To prove this a maximum heat generation of 105 W for one cell was implemented releasing 19.4 kJ of heat energy. This is the maximum heat, generated by a cell with 2.6 Ah capacity during a thermal runaway [5]. The results of this simulation reflect the determined cooling efficiencies of the arrangements. The cell with the short circuits heats up about 70 K in case of arrangement 4 whereas in arrangement 2 the hottest cell heats up about 80 K. The temperature rise of surrounded cells is more significant. Downstream cells in arrangement 2 heat up about 55 K, making a chain reaction realistic. However, in arrangement 4 the second hottest cell of the battery module only heats up about 5 K due to the heat of the cell with the short circuit. In conclusion, arrangement 4 solves the conflict of objectives of an efficient cooling with a uniform temperature inside the module and a thermal insulation in of damaged hot cells.

The four arrangements were evaluated in a benefit analysis regarding the packaging efficiency and the mentioned thermal objectives. As result, two concepts are evaluated best and selected for further tests in an IPEK XiL-setup.

3.3 Test Setup According the IPEK XiL Approach

Similar to the simulations, temperature distribution inside a battery module shall be investigated in a test setup. Moreover, additional design parameters that are not taken into account in the CFD model to keep the simulation as simple as possible are considered in the test setup. For example, the inflow of the battery module in the CFD simulation is homogeneous whereas in the test setup different nozzle positions and geometries can be investigated. To ensure reproductive and time-independent test results the IPEK-XiL approach is used to design the test setup.

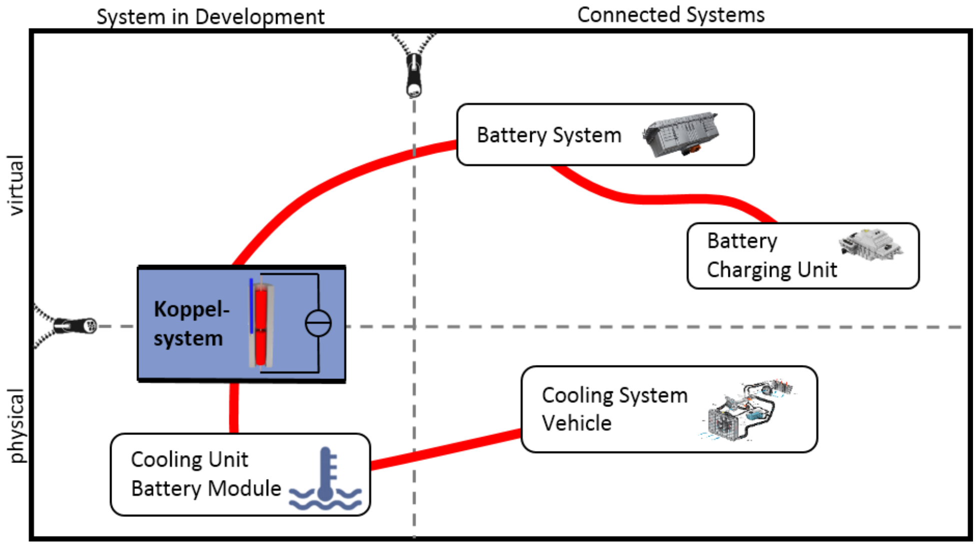

Figure 6: IPEK XiL modelling to validate cooling concepts

With the use of real battery cells with different, unknown and SOC dependent internal resistances, the reproducibility of tests could be negatively influenced. Moreover, heat generation is limited due to the use of real battery cells and a cell independent evaluation of the cooling system would be difficult. For this reason, cell dummies connected to a power source to control the heat generation inside the module are used in the test setup. The cell dummies and the controllable power source form the "Koppelsystem". The cell dummies are made from steel tubes with resistors inside to get a similar thermal conductivity in axial and tangential direction to real battery cells [2]**.** Temperature gradients inside the battery dummy in radial direction are not investigated, because the thermal conductivity of steel is too high in comparison to the thermal conductivity of the layered cell winding structure. The differing heat capacity of steal has no effect on the validation, because static load conditions such as constant current phase during charge are investigated. Due to the resistors that are wired in series, generated heat can be defined by adjusting the current. Temperature dependent changes of the internal resistance of the battery cells that would lead to inhomogeneous heat generation inside the battery module can be neglected because of the small temperature differences within the battery module. According to the equation of LI [9], in the investigated temperature range of 2 K, the internal resistances vary less than 3.5 %. Due to the use of cell dummies, cell temperature can be easily measured by thermocouples that stuck in bores 0.3 mm distanced from the outside surface. Therefore, temperature near the heat transfer surface can be measured without influencing the coolant flow behavior.

Another task of the test setup is to validate parts of the CFD simulation. Due to different thermal modeling of battery cells in the CFD model and the virtual physical mixed model, temperature distribution inside battery cells cannot be compared. Inlet geometries as well as the shell of the physical setup influence the flow and therefore the local heat dissipation. In case of lean modules with a long cooling flow, the temperature gradient between cells that are located in the middle of the module should be equal to the simulated temperature distribution in CFD.

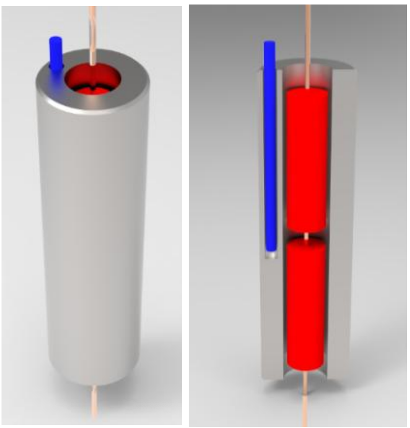

Figure 7: cell dummy with two sealed resistors (red) connected in series and one thermocouple (blue) [4]

When the final cooling configuration is defined, dummies can be replaced by real battery cells. Similar to the CFD-validation, thermal behavior of the cooling system using real battery cells can be used to validate the investigations where dummy cells were applied. Now it is possible to investigate dynamic load cases to validate the cooling system. Using real battery cells the “Koppelsystem” changes to a controllable power source and electrical load to charge and discharge the battery. In addition, the connected system has to be adjusted. Beside the charging unit the vehicle, the driver and the environment have to be modeled for a holistic validation of a battery cooling system for a special battery cell, simulating load cases during driving cycles. To measure the temperature of the cell cases, thermocouples should be placed in back water areas, to have little influence on the fluent flow. Temperature differences between real cells can be compared with the temperature differences between the cell dummies. Due to differing thermal properties of real cells and cell dummies as well as the different positions of thermocouples, absolute measured temperatures cannot be compared.

Finally, the gained systems understanding can be used to build up a first cooling prototype of the battery module, with realistic dimensions.

4 Application on Other Cell Formats

The described methodical approach to validate direct battery cooling system is used for battery module with cylindrical cells. However, particularly in mobility applications like electrical or hybrid cars also large battery formats are used. Therefore, it has to be proved in further works, if the method is suitable for prismatic cells and pouch cells.

Adjustments and outstanding issues for the application of the validation approach on cooling systems for large-size battery cells are described in the following:

Due to the small size of cylindrical battery cells especially of the format 18650, the heat conduction path inside the cells is small and heat generation of the layered cell winding structure is uniform. Therefore modelling physical cell dummies to validate a cooling system is relatively easy. Many parallel circuits of cylindrical cells in one module make the electrical performance of a battery system sensitive for temperature differences inside the modules. Validation of cooling systems for small sized battery cells hence aims on a homogenous temperature distribution inside the module and an efficient heat dissipation.

Dependent on the cooling concept of large-size battery cells, such as prismatic or pouch cells, heat transfer paths can be long, causing large temperature gradients inside the cell. The uniformity of heat generation inside the batter cell also effects the temperature distribution. Especially pouch cells differ in the distribution of heat generation, as shown in Figure 8. The cell on the left side heats up excessively near the electrical taps, whereas the hot spot of the cell on the right side is located in the middle of the cell.

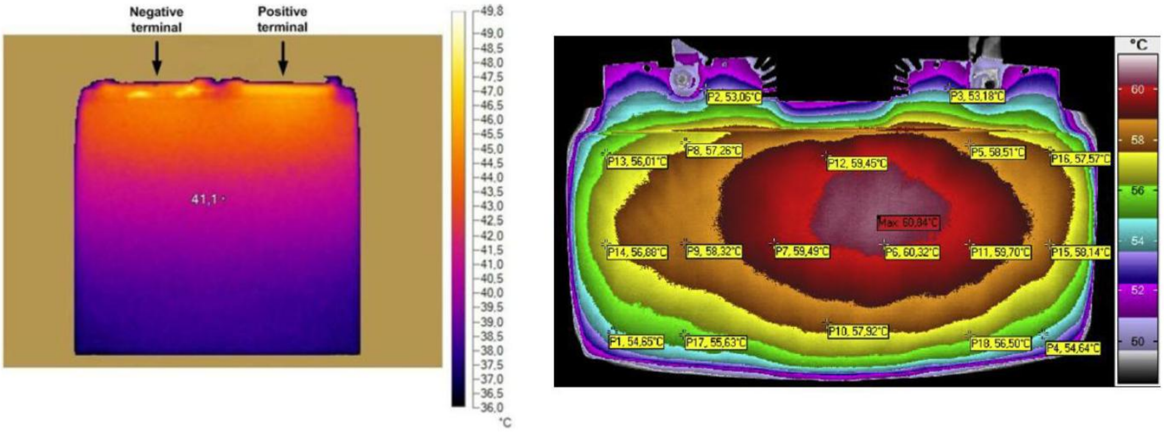

Figure 8: temperature distribution in different battery pouch cells [12, 16]

High electrical capacities of these cells reduce the needed parallel circuits. Modules contain only a few cells, sometimes cells are only wired in series like in BMW i3. That makes it easier to control the temperature distribution between the battery cells in one module, than to control the temperature gradients inside the cells.

In sum, the application of the methodical approach on large-size battery cells efforts an adjustment in the thermal modelling of battery cells, to validate the cooling system.

According to the distribution of heat generation and thermal conductivity of large-size battery cells, a cooling concept has to be defined to meet customer requirements. Rough calculations help to identify design parameters and to estimate their impact on the validation tasks. Further studies are necessary to prove rough calculation methods for various cooling concepts for large-size battery formats.

To simulate fluent flow of cooling systems for large-size battery formats via CFD, heat generation distribution of the battery cell must be implemented. Thermoelectric simulations of a single cell that are verified by physical experiments can do this [13, 19]. The correct anisotropic heat conductivity of the battery cell model is important to simulate realistic temperature distribution. Therefore, 3D simulations can be necessary.

Summarizing, the effort and complexity of CFD simulation of cooling systems rises by using large-size battery cells such as prismatic cells or pouch cells. Using other cooling fluids such as phase change material or other cooling mechanisms, leads to an adjustment of modelling the cooling fluid or cooling mechanism.

Similar to the CFD simulation, the challenge in designing a physical setup according the IPEK-XiL approach is the correct design of a battery cell model. There exist two ways of modelling the heat generation of a battery cell. According to the cell dummy presented in this paper, thermal characteristics can be implemented physically, e.g. due to a fix circuity of several heat sources, in this case resistors. On the other hand, distribution of heat generation inside the battery cell could be variable by implementing thermal characteristic of a cell in the virtual domain. It means that a cell dummy includes multiple heat sources, controlled individually by a virtual battery model. One advantage of the last mentioned model is the possibility to investigate the robustness of the cooling system by changing the distribution of heat generation of the cell dummies to simulate battery cell characteristics of different cell customers. For steady state simulations like simulating heat dissipation while constant current phase, charging the battery system, heat capacity of the cell dummy does not matter. Whereas thermal conductivity is important for the temperature distribution of the battery cell. It depends on the cooling concept and the shape of the battery cell if an anisotropic modelling of the cell is necessary. To validate cooling systems for large-size cells, further works are necessary how to design appropriate battery cell dummies. If the cooling system is designed for a battery system that uses only cells of one customer, the effort of designing cell dummies should be evaluated against using real battery cells for the physical test setup.

5 Summary and Outlook

The validation process for a direct liquid cooling system is described to evaluate fast charge capability of a battery module for cylindrical battery cells. Due to the use of a 2D CFD model, design parameter space can be reduced quickly by examination different cooling concepts. Gained systems understanding is used to develop a test setup according the IPEK-XiL approach to investigate selected cooling concepts considering additional design parameters that are neglected in the CFD model. The setup enables a high flexibility in parameter variation and a validation independent from battery cell manufacturers by using cell dummies. Task of the physical-virtual mixed validation is to define the design of a first battery module prototype. When the cooling design is discrete, real battery cells can be used in the test setup. Furthermore, results of the physical investigations could be used to improve the validity of the CFD model, by implementing additional design parameters with high effect on cooling characteristics.

In further works, cooling concepts that were investigated in CFD have to be validated by varying described design parameters, using the test setup. Then the validity of the CFD can be proved and a final cooling design must be defined. The described validation process is transferable on other cylindrical cell formats. To use it for large-size cell formats such as pouch or prismatic cells, inhomogeneous heat generation inside the battery cells must be regarded in CFD modelling as well as in the physical test setup. The application of the approach on large-size battery cell formats has to be proved in separate studies.

References

[1] A. Albers, K. Matros, M. Behrendt, H. Jetzinger. 2015. Das Pull-Prinzip der Validierung – Ein Referenzmodell Das Pull-Prinzip der Validierung - Ein Referenzmodell zur effizienten Integration von Validierungsaktivitäten in den Produktentstehungsprozess. *Konstruktion*, 74–81.

[2] Felix Uptmoor. 2011. *Modellbildung und Simulation von Batterien in der Elektromobilität*. Master Thesis, HAW Hamburg.

[3] Frieder Herb. 2010. *Alterungsmechanismen in Lithium-Ionen-Batterien und PEM-Brennstoffzellen und deren Einfluss auf die Eigenschaften von daraus bestehenden Hybrid-Systemen*. Dissertation, Universität Ulm.

[4] Friedrich Prinz. 2017. *Entwicklung eines Prüfaufbaus zur Validierung eines Kühlsystems für Lithium-Ionen-Batteriesystemen*. Bachelorthesis, KIT.

[5] Karina Kohler. 2017. *Analyse einer Batteriekühlung mittels numerischer Strömungsmechanik*. Masterthesis, KIT.

[6] Khateeb, S. A., Amiruddin, S., Farid, M., Selman, J. R., and Al-Hallaj, S. 2005. Thermal management of Li-ion battery with phase change material for electric scooters. Experimental validation. *Journal of Power Sources* 142, 1-2, 345–353.

[7] Korthauer, R. 2013. *Handbuch Lithium-Ionen-Batterien*. SpringerLink : Bücher. Springer Vieweg, Berlin, Heidelberg.

[8] Leng, F., Tan, C. M., and Pecht, M. 2015. Effect of Temperature on the Aging rate of Li Ion Battery Operating above Room Temperature. *Scientific reports* 5, 12967.

[9] Li, X., He, F., and Ma, L. 2013. Thermal management of cylindrical batteries investigated using wind tunnel testing and computational fluid dynamics simulation. *Journal of Power Sources* 238, 395–402.

[10] Lindemann, U. 2016. *Handbuch Produktentwicklung*. Carl Hanser Verlag, München.

[11] Markus Kreisel. 2015. *Neue Kreisel Traktionsbatterien – noch leichter und sicherer*.

[12] Murashko, K., Pyrhonen, J., and Laurila, L. 2013. Three-Dimensional Thermal Model of a Lithium Ion Battery for Hybrid Mobile Working Machines. Determination of the Model Parameters in a Pouch Cell. *IEEE Trans. Energy Convers.* 28, 2, 335–343.

[13] Rizzo, G., Christen, R., and Stöck, M. Prüfstand zur thermischen Charakterisierung von Batteriezellen und Validierung geplanter Kühlkonzepte. In *Hochschule München 2016 – 23. Design & Elektronik-Entwicklerforum*.

[14] Tataria, H. S. *USABC Goals for Advanced Batteries for EVs - CY 2020 Commercialization*. http://www.uscar.org/guest/article_view.php?articles_id=85. Accessed 19 January 2017.

[15] 2013. *VDI-Wärmeatlas. Mit 320 Tabellen*. Springer Vieweg, Berlin.

[16] Veth, C., Dragicevic, D., and Merten, C. 2014. Thermal characterizations of a large-format lithium ion cell focused on high current discharges. *Journal of Power Sources* 267, 760–769.

[17] Wang, T., Tseng, K. J., Zhao, J., and Wei, Z. 2014. Thermal investigation of lithium-ion battery module with different cell arrangement structures and forced air-cooling strategies. *Applied Energy* 134, 229–238.

[18] Yang, N., Zhang, X., Li, G., and Hua, D. 2015. Assessment of the forced air-cooling performance for cylindrical lithium-ion battery packs. A comparative analysis between aligned and staggered cell arrangements. *Applied Thermal Engineering* 80, 55–65.

[19] Yu, K., Yang, X., Cheng, Y., and Li, C. 2014. Thermal analysis and two-directional air flow thermal management for lithium-ion battery pack. *Journal of Power Sources* 270, 193–200.

Authors

Martin Eisele

Martin Eisele, M.Sc. is scientific assistant in research group drive systems of the Institute of Product Development at the Karlsruhe Institut of Technology. The research group focusses on Systems, methods and processes in the development and validation of conventional and electrified drive systems.

Sascha Ott

Dipl.-Ing. Sascha Ott is managing director of the Institute of Product Development at the Karlsruhe Institut of Technology and responsible chief engineer for the research fields drive systems and tribology systems.