A method to find a thermal optimum cell size

Matthias Kerler*, Markus Lienkamp†
Technische Universität München
Institute of Automotive Technology
Email: *kerler@ftm.mw.tum.de, †lienkamp@ftm.mw.tum.de

***Abstract*—Today's battery electric vehicles (BEVs) use a broad variety of shapes and sizes of lithium-ion battery cells. One of the major concerns about a BEV battery pack is the process of aging, and the loss of driving range over the years of utilisation. The phenomenon of capacity loss of lithium-ion batteries has been under scientific investigation for many years. Meanwhile, it is commonly accepted that the influence of the temperature plays an important role in this context [1]–[3]. Due to this fact, the aim is to keep the battery pack and its cells within a perfect thermal window. Hence, too low, as well as too high of temperatures need to be avoided, but the thermal gradient in a battery cell also has to be kept low.**

Hence, the question is if a thermally optimized cell size can lead to a low-priced cooling system as well as to a thermal optimized aging behavior. Therefore, a tool is developed which utilities a thermal simulation and geometrical optimization in a loop. Focus shall be put on the different behavior of rather small consumer cells like the 18650 cylindrical shaped cells and larger cells like the BEV2 cells (60Ah) in accordance with the German VDA standard. Early results of this comparison will be presented. Hereafter, the next necessary steps are presented to improve the validity and fidelity of those results.

I. Introduction

In the early stage of the concept phase for a new BEV battery pack, an important part of the development is the decision for the correct battery cell (cell size, cell shape and chemistry). It has a major influence on many of the following decisions, like the cooling system or the internal interconnections, etc. However, the performance of the system also partly depends on the right choice of cells, as parallel interconnections within the battery, for example, lead to a more efficient energy utilization [4]. Looking more closely at today's BEV car market, a bright variety (shape and capacity) of cells installed in BEV's battery packs can be found. On the one hand, it is mainly larger OEMs which are using very big cells in accordance with the German VDA standard, with up to 60 - 66 Ah capacity. When such cells are used to reach a voltage level of 300 - 400 V, no parallel connection is necessary to get a sufficient battery capacity (e.g. BMW i3). On the other hand, Tesla Motors is using 18650 battery cells to build up packs under the use of a massively parallel connection. At this point, the questions emerge as to whether a rather simple battery pack layout with big cells is the best solution, or where the benefit is to Tesla Motors greater effort, with its utilization of a large quantity of small cells (7104 cells). To answer this question, the influence of the cell size on efficiency, safety aspects, weight, costs, thermal behavior and aging will be investigated. As a result, a method will emerge to define the optimum cell size.

In this paper the thermal behavior of lithium-ion cells and their influence on optimization results are investigated more into detail. The temperature (absolute and distribution) is a very crucial parameter for Lithium-ion-based batteries because, when operated outside their specified safe operation area (SOA) for temperature, this could lead to consequences which range from irreversible cell damage to thermal runaway and even cell burst [5], [6]. To keep the cells in their SOA, based on the battery pack design, a cooling system is necessary. Those systems can be roughly divided into passive and active ones, whereby active systems are rather costly and difficult to integrate. Therefore, one question is whether costs for the cooling system can be reduced and the efficiency raised by supporting the decision process on the right cell choice (because lesser power for cooling fans or pumps is necessary and no performance potential of the battery pack is wasted).

Hence the topic of this paper is, if a method can be determined to find a thermally optimized cell size, by utilizing the Finite Element Method and an optimization algorithm. A possible method will be tested on three different BEVs' battery cells.

In chapter II, important regarded aspects of thermal behavior will be presented. After that in chapter III, focus is put on the thermal modeling of lithium-ion cells. In chapter IV, the structure of the optimization tool is presented. After presenting early results in chapter VI, in VII and VIII, the results are evaluated and the next necessary steps are presented to improve the validity and fidelity of those results.

II. Thermal behavior of lithium-ion cells

During the charging and discharging process, a lot of chemical reactions and transport processes take place. Some of those reactions are exothermic and produce heat, which can accumulate inside the battery if the cooling or the heat transfer is not sufficient enough [7]. Important topics in this context are safety aspects because too much heat can lead to a so called thermal runaway [8]. The temperature influence on aging is another important point as well as a possible cooling system and its costs. All of those aspects, which will be presented in detail in the following, can be influenced by a thermally optimized cell size.

A. Safety aspects

Today's battery electric vehicles are using very large lithium-ion battery packs, whereas the layout can be very different. On the one hand, it is possible to build a battery pack using only a few, yet very large cells or, on the other hand, a large amount of rather small cells. Under the aspect of safety, the already introduced thermal runaway is a very critical event. In this context, J. Lamb et al. [9] investigated the failure propagation of small lithium-ion battery systems. Two different types of cells (18650 2200 mAh and pouch 3000 mAh) were examined. Those cells were assembled to a small battery pack:

- cylindrical cells (triangular cell arrangement)
  - 10S1P
  - 1S10P
- pouch (stacked cell arrangement)
  - 5S1P
  - 1S5P

Afterwards, in every battery pack configuration, one cell was nail penetrated. The result for the cylindrical cells were, that the penetrated cell went into thermal runaway in both electrical configurations, but only in the 1S10P configuration did the thermal runaway propagate through the whole battery pack [9]. In the case of the pouch cells, both configurations went into thermal runaway. Lamb assumes that in the case of the 1S10P configuration of cylindrical cells, maybe an internal short could be the reason for every surrounding cell also going into thermal runaway, as this could have created the necessary additional heat. In the case of the pouch cells, Lamb presumed that the good thermal heat transfer between the cells could be the reason why failure propagation was observed in both configurations.

He sums up that, in this case, the impact of the heat transfer between cells and modules overtops the impact of the electrical configuration. Nevertheless, he mentioned that a lot more experiments are necessary.

Kim et al. [10] developed a single cell abuse model to be able to predict the behavior of cells in critical thermal conditions. Afterwards, he made some basic investigations related to the behavior of different cell sizes. He sums up, that an acceptable abuse tolerance of smaller cells (approximately 3 Ah) can be reached by generous use of safety devices (such as shutdown separator, positive temperature coefficient (PTC), current interrupt, electronic, and pressure vent devices). Larger cells and the high power requirement prevent the use of such devices [10]. Furthermore, in the case of excessive heat generation, the cell size is not the crucial parameter, but the heat transfer area per unit volume A/V_{jr}. In the simulated oven tests, Kim could observe the following behavior: A large A/V_{jr} leads to a fast thermal runaway at high surrounding temperatures (160°C), but, heat rejection is large enough to balance with the heat generation at lower temperatures (140°C) [10].

Larger cells behave almost vice versa. Because of the greater mass, a higher surrounding temperature can be sustained for a while; but if an exothermic reaction starts within the cell, the heat generated cannot be rejected fast enough because of the smaller A/V_{jr}. A thermally optimized cell size could give an answer to the perfect A/V_{jr} ratio.

B. Thermal Aging

According to [1], [3], [11], [12] the temperature within a lithium-ion cell plays an important role for the aging process. Not only is the maximum occurring temperature of great interest, but also the temperature distribution within the cell. Especially with the increasing size of the cell, the emergence of a larger temperature difference can be observed.

Fleckenstein et al. [1] mentioned that, according to literature, the dependency of the degradation process can be described by the Arrhenius law of chemistry. Generally speaking, according to [13], an exponential correlation between the stress factor temperature and capacity decrease can be observed as well as an exponential increase of the inner resistance.

With regard to the aforementioned temperature gradient and the correlation between aging and temperature, it is possible that a cell degrades inhomogeneously. Simulation results of [1] reveal that this could lead to an alternating current distribution within a cell over time and, thus, to an uneven volumetric heat generation density. In the worst case scenario, the cooling system is not able to handle such a condition. Because of the unknown consequences (long-run behavior, safety), such a condition should be avoided.

C. Thermal Management System and Costs

To keep the temperature of the battery pack within a safe operation area (SOA), a thermal management system is necessary. As presented in [14], different types of battery cooling systems are possible:

- Air cooling
- Base/head cooling
- Cooling plates between cells
- Fluid-ducting cooling plates
- Conductor cooling

All mentioned system types are conceivable as passive or active ones. Active air cooling and Fluid-ducting systems are most common today. Generally speaking, the costs for the cooling system are proportional to the complexity. To estimate the overall costs for a battery pack, [15] developed a cost model. There, an air cooling system correlates with the baseline cooling system. The costs for such a system are independent of the pack size estimated at 120 $ (costs for the manufacturer) for a BEV battery pack. If the battery cooling system shall be coupled with the AC-System, the costs come up to 40 $ (costs for the manufacturer) per kW of cooling power . The costs for a heating system add up to 20 $ per kW of installed heating power [15].

Those data can be used as a basis for the thermal optimization of the cells in order to reduce the costs for the battery pack.

III. Thermal modeling of lithium-ion cells

According to [7], a thermal model of a lithium-ion cell simulates the temperature profile inside the battery while it is charged or discharged. A bright variety of models are available in literature, beginning with relatively simple, one-dimensional models that assume a simplified cell design and operation mode (constant current, isothermal, lumped thermodynamics or constant heat generation rates) all the way to highly sophisticated, three-dimensional models. However, when simulating normal conditions, simple models using heat generation and lumped properties are sufficient.

For the following examination, a three-dimensional heat generation model is used. Later in chapter VIII, the use of an electro-thermal model will be presented. There, the current will be calculated with an equivalent circuit model. With knowledge of the current, according to [7], the heat generation can be calculated with equation 1.

$$\dot{Q} = I \cdot \left[(E_{eq} - E) + T \frac{\mathrm{d}\, E_{eq}}{\mathrm{d}\, T} \right] \tag{1}$$

$\dot{Q}$	= overall heat generation rate (W)
I	= applied current (A)
E_{eq}	= cell equilibrium voltage (V)
E	= cell voltage on load (V)
T	= cell temperature (T)

Regardless of the model accuracy, the energy balance of the cell can be calculated with the following equations (equation 2 for Cartesian and equation 3 for the cylindrical solution).

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} + \frac{\dot{\omega}}{\lambda} = \frac{1}{a} \frac{\partial T}{\partial t} \tag{2}$$

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2} + \frac{1}{r^2} \frac{\partial^2 T}{\partial \varphi^2} + \frac{\dot{\omega}}{\lambda} = \frac{1}{a} \frac{\partial T}{\partial t} \tag{3}$$

T	= Temperature in K
t	= Time in s
x, y, z	= cartesian coordinates
r, z, φ	= cylindrical coordinates
$\dot{\omega}$	= heat source density in $\frac{W}{m^3}$
λ	= thermal diffusivity in $\frac{W}{mK}$
a	= thermal diffusivity in $\frac{m^2}{s}$

IV. Structure of the Optimization Tool

To overcome the aforementioned problems, the idea is to optimize the geometrical parameters of the battery cells in order to minimize the maximum temperature and the maximum temperature gradient within the cell. The developed tool consists of two parts. The first part is a parametric Finite Element Model of the cell which was realized in Ansys 15 Classic. The second part is an optimization algorithm and a calculator for the simulation parameters, both realized in MatLab R2013b. In the following, the Finite element model will be presented. Afterwards, the MatLab component is explained and finally all necessary assumptions and simplifications are presented.

A. Finite Element Model

To be able to calculate the heat distribution inside the cell and in respect to the results to be achieved, a three dimensional Finite Element Model is necessary. To investigate all common cell formats, three parametric models in Ansys Classic were created (figure 1, 2 and 3).
The cylindrical cell can be altered in height and radius. The prismatic cell can be altered in all three spacial directions and the pouch cell can be altered in length and width.
In the case of the cylindrical cell, the jelly role was also

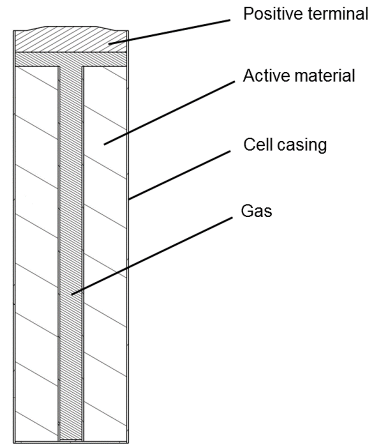

Fig. 1. cut through the three-dimensional thermal parametric model of the cylindrical cell

TABLE I. HEAT TRANSFER COEFFICIENTS ACCORDING TO [17]

Type of convection	medium	heat transfer coefficient in $\frac{W}{m^2K}$	used heat transfer coefficient
free convection	air water	3 – 10 100 – 600	10 –
forced convection	air water	10 – 100 500 – 10000	100 500 – 1000

modeled in good approximation as a cylinder with a hole in the middle. The structure is based on literature [16] and on our own disassembly results.
The prismatic cell was designed according to [1] with four separate jelly roles inside the casing, which are connected into parallel. Two tabs on each side are connected with the terminals on top of the cell.
The Pouch cells' active material is surrounded by a thin foil and its two terminals are mounted on one side.

The implementation of the cooling is independently of the cell shape realized by Newton's Law of Cooling (equation 4). Different types of cooling methods in the simulation are realized by different values for the heat transfer coefficient α. Thru the data structure (chapter IV-C) the according values (table I) are applied to the different surfaces of the cell. For example, by setting the value for the heat transfer coefficient to zero an adiabatic boundary can be simulated. By tuning the heat transfer coefficients, a consideration of the spatial arrangements of the cells is also possible.

$$\dot{q} = \frac{\dot{Q}}{A} = \alpha(T_{surface} - T_{ambient}) \tag{4}$$

$\dot{q}$	= heat flux in $\frac{W}{m^2}$
$\dot{Q}$	= overall heat generation rate (W)
A	= Area in m^2
α	= heat transfer coefficient in $\frac{W}{m^2K}$
T	= Temperature in K

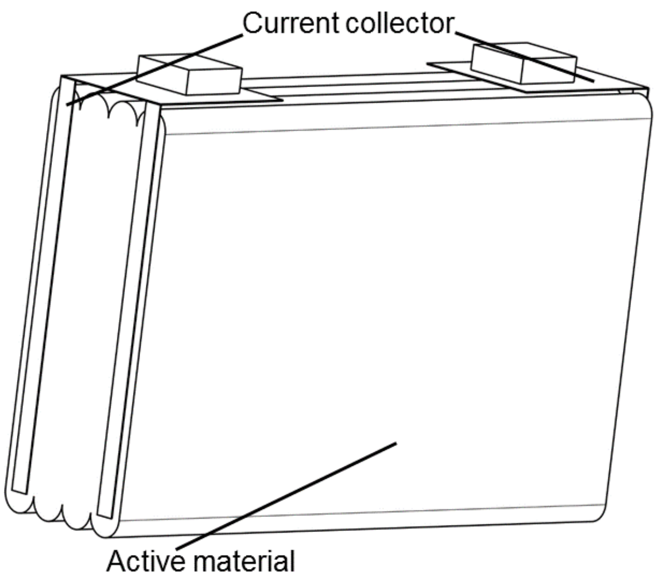

Fig. 2. three-dimensional thermal parametric model of the prismatic cell (shown without casing)

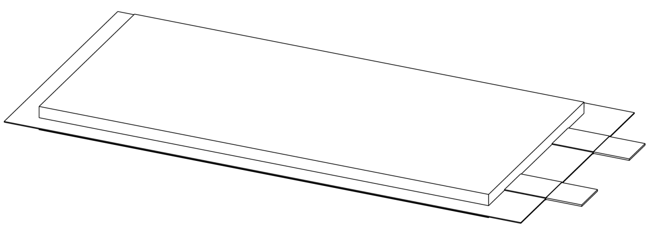

Fig. 3. three-dimensional thermal parametric model of the pouch cell

B. MatLab

The whole optimization tool is based on a MatLab script. The two tasks of this script are firstly, to build an interface to the user and to process his input and, secondly, to submit the necessary data to Ansys by building input files for an APDL script (Ansys Parametric Design Language).
The user can interface with the tool by a MatLab data structure. There, all necessary data is stored, like the material data, cooling data of the cylindrical, prismatic or pouch cell, temporary and necessary data for the optimization, such as an initial geometrical data set, the driving cycle and other vital settings.
To solve the optimization problem, because of the

- nonlinear, differential objective function
- continual objective function with a simple solution space
- limited objective function
- nonlinear, none differentiable constraint function
- small quantity of function calls

the *patternsearch* optimization algorithm is chosen to optimize the geometrical parameters of the cell. For the optimization,

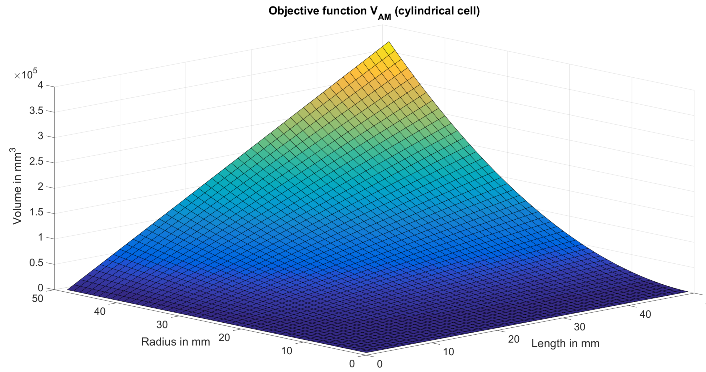

Fig. 4. objective function of the cylindrical cell

those time steps of the simulation results are evaluated, with the maximum temperature and maximum temperature difference within the cell.

The objective function represents (equation 5) the actual volume of the active material which shall be maximized (cylindrical cell: $f(x) = -V_{AM}(\text{radius,length})$; prismatic and pouch cell: $f(x) = -V_{AM}(\text{length,width,height})$). Figure 4 shows an example of the objective function of a cylindrical cell. Only one global maximum exists (it is the same with the objective function of the prismatic and pouch cell). The thermal simulation (chapter III) in Ansys acts as the constraint function and calculates the before mentioned maximum temperature and maximum temperature difference within the active material.

$$\begin{aligned} &\min_x f(x) \\ &b(x) \leq 0 \end{aligned} \tag{5}$$

C. Data structure

The whole tool can be controlled with a data structure in the MatLab Workspace (figure 5). There, the type of cell, the cell chemistry (LFP, LCO, LMO), initial size of the cell, type of cooling, initial conditions and the cooled areas of the cell can be defined. Furthermore, temporary data is stored in this structure, as well as the current pattern.

D. Assumptions and scenarios

An important input parameter of the optimization tool is the driving cycle. Combined with the specifications of the car and its battery configuration, it is possible to calculate the current for each time step. This is done by a longitudinal dynamic calculation combined with a model of the car and its components, like the engine or the power electronics. Of course, the results of the optimization depend on the type of driving cycle or on the currents, respectively. In the following, concepts that exist on the market shall be investigated.

- Tesla Model S P85
- BMW i3
- VW eGolf

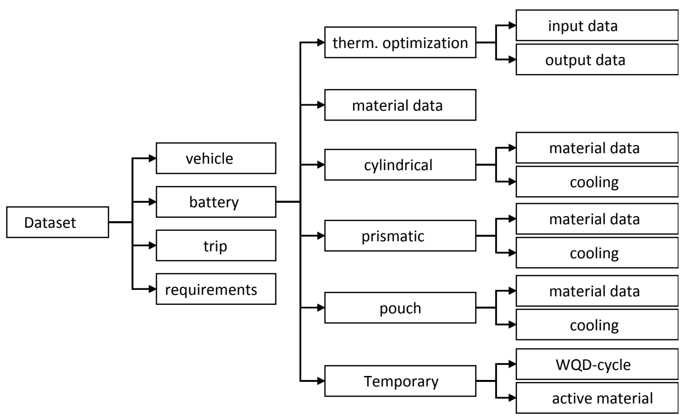

Fig. 5. Data structure of the optimization tool

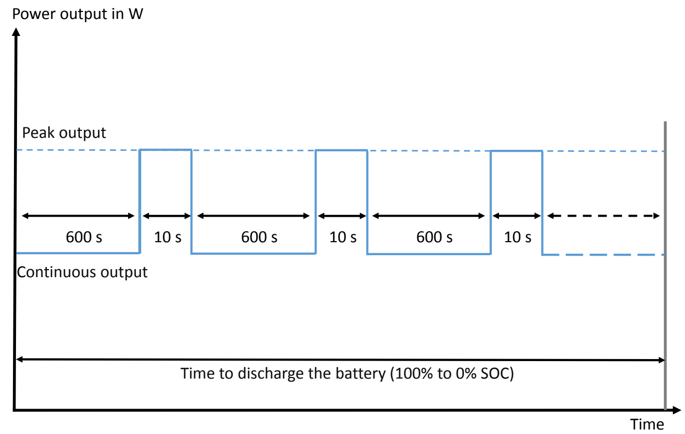

Fig. 6. Discharging power pattern

In some cases, only little is known about the exact parameters of the cells. Therefore, reasonable assumptions are made based on literature and our own measurements of comparable cells. The thermal management concept of those cars will be evaluated regarding the optimization results.

V. Simulation Settings

As mentioned before, three different, yet important BEVs' battery concepts available on the German market shall be investigated and evaluated regarding thermal dimensioning.

- Tesla Model S P85
  - Cells: 7104 (96S74P), 3.4 Ah
  - Cell type: cylindrical, 18650
  - Power: 310 kW (peak) / 70 kW[1] (rated)
  - Cooling system: AC coupled liquid cooling system
- BMW i3
  - Cells: 96 (96S), 60 Ah
  - Cell type: prismatic (BEV2)
  - Power: 125 kW (peak) / 75 kW (rated)
  - Cooling system: AC coupled liquid cooling system
- VW eGolf
  - Cells: 204 (102S2P), 25Ah
  - Cell type: prismatic (PHEV2)
  - Power: 85 kW (peak) / 50 kW (rated)
  - Cooling: No active cooling system

For the first investigations in this paper, no recorded driving cycle will be utilized. The assumption is that the battery will be completely discharged (from 100% SOC to 0% SOC) with the cars rated maximum continuous output. Every 600 seconds, there is a peak with the maximum rated power for a duration of 10 seconds. The current per cell will be calculated before the simulation by a conversion from the BEV power specification to the current per cell (approximated with the nominal cell voltage, and knowledge of the internal battery pack interconnection). This displays a rough utilization of the battery and demands the thermal management of the battery.

With the assumption that the battery is the power bottleneck in a BEV drivetrain, the current will be scaled up or down with the capacity, which is calculated by the optimization algorithm. According to [18], the resistance of a cell is a function of its capacity.

$$R_{cell} \cdot Ah = constant = C_R \quad (6)$$

R_{cell} = internal resistance of a battery cell
Ah = capacity of a battery cell
C_R = normalized resistance

With the knowledge of this correlation , it is possible to scale the cell size (assuming the cell design is not influenced by the cell alternation) up or down with regard to its thermal loss. In the Tesla Model S and in the BMW i3 high capacity cells are installed. Therefore, $C_R = 0.116$ is used (based on our own measurements on a Panasonic NCR18650PF). In the eGolf, where high power cells are utilized, the assumption is, therefore, that the inner resistance is smaller by half ($C_R = 0.058$).

Main goal of the algorithm is to maximize the cell capacity. Thus, when the temperature limits are undercut, cell size will be increased and vice versa.

VI. Results

The following restrictions were set for the optimization (ΔT based on the demand for a low temperature difference [7], and in situ measurements of a 18650 cell of Zhang et al. [19] and T_{max} based on the requirement of a slow aging process):

- $T_{max} = 35°C$
- $\Delta T_{max} = 2°C$
- $T_{ambient} = 20°C$
- initial temperature $20°C$

We found that different temperature restrictions can lead to different results, for example a larger ΔT_{max} can lead to larger cell dimensions, as well as a larger T_{max} does.

The ambient temperature displays the temperature of the surrounding cooling medium according to equation 4.

[1]nominal power estimation based on top speed of 210 km/h

TABLE II. RESULTS OF THE OPTIMIZATION OF THE TESLA BATTERY CELL

	Initial cell	Optimized cell
size	9 mm radius 65mm length	15.25 mm radius 497mm lenth
crucial optimization parameter		ΔT
Temperature ΔT	$21.9°C$ $1.1°C$	$22.7°C$ $1.9°C$

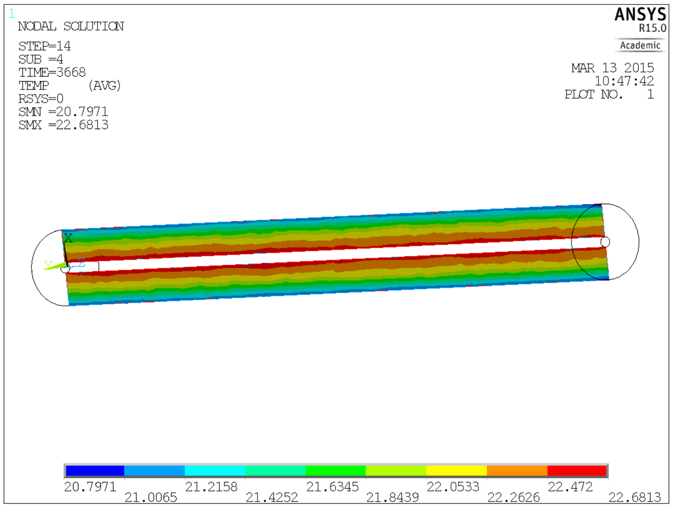

Fig. 7. Tesla P85: Result of the thermal optimization; temperature distribution within the jelly role

The computational time took, depending on the cell shape and the amount of necessary iterations of the optimization algorithm 12 hours to 4 days on a Intel Xeon(R) CPU E5-1620 3.6Ghz, with 64 GByte RAM (cylindrical cell: approximately 5000 nodes, 20000 elements; prismatic cell: 22000 nodes, 118000 elements; pouch cell: 43000 nodes, 179000 elements).

The algorithm calculated the following cell sizes for the three different BEVs' battery cells:

A. Tesla Models S P85

The results (Table II and figure 7) show that the cells' radius can be increased to approximately $15mm$. Because of the cooled lateral surface (forced liquid cooling), there seems to be no limitation in length of the cell because the cooled surface increases with increasing length. Hence, the optimization algorithm almost reached the limit of the maximum length target. The radius was limited by the target of the maximum temperature difference within the cell.

Simulation setting (heat transfer coefficients to represent the afore mentioned conditions):

- lateral surface: $500\frac{W}{m^2K}$ (because of the not entirely cooled lateral cell surface in the Tesla Models S the value was set to $500\frac{W}{m^2}$)
- cell terminals: $10\frac{W}{m^2K}$ (simulation of heat transfer thru thin bonding wires)

TABLE III. RESULTS OF THE OPTIMIZATION OF THE I3 BATTERY CELL

	Initial cell	Optimized cell
size	width 45.00mm length 173.00mm height 115.00 mm	width 43.50mm length 20.00mm height 20.00 mm
crucial optimization parameter		ΔT
Temperature ΔT	$40.6°C$ $11.5°C$	$29.48°C$ $2.00°C$

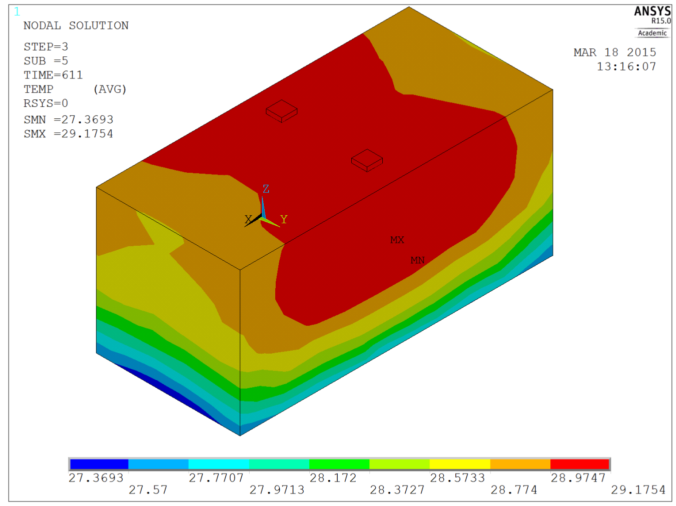

Fig. 8. BMW i3: Result of the thermal optimization; flat prismatic cell

B. BMW i3

The size of battery cell of the BMW i3 was dramatically reduced by the optimization algorithm (Table III and figure 8). The height limitation results from the liquid cooled bottom surface of the cell. Because of the anisotropic heat conductivity of the active material there seems also to be a limitation in width. Simulation setting (heat transfer coefficients to represent the afore mentioned conditions):

- bottom surface of the cell: $1000\frac{W}{m^2K}$ (to represent an effective cooled bottom surface)
- remaining surfaces $20\frac{W}{m^2K}$ (simulation of heat transfer between neighboring cells)
- cell terminals $75\frac{W}{m^2K}$ (simulation of heat transfer to the current collectors)

C. VW eGolf

The battery pack of the Volkswagen eGolf does not have any active cooling system. The only heat sink is the passive cooling of the battery pack casing. It is assumed that the airstream at top velocity acts like a cooling system at the bottom of the battery pack (forced convection). This leads to a cell size that is very low in height (figure 9, table IV). Simulation setting (heat transfer coefficients to represent the afore mentioned conditions):

- bottom surface of the cell: $100\frac{W}{m^2K}$
- remaining surfaces $20\frac{W}{m^2K}$ (simulation of heat transfer between neighboring cells)

TABLE IV. RESULTS OF THE OPTIMIZATION OF THE EGOLF BATTERY CELL

	Initial cell	Optimized cell
size	width 26.50mm length 148.00mm height 91.00 mm	width 111.00mm length 239.00mm height 15.00 mm
crucial optimization parameter		ΔT
Temperature ΔT	$43.8°C$ $4.17°C$	$31.12°C$ $1.97°C$

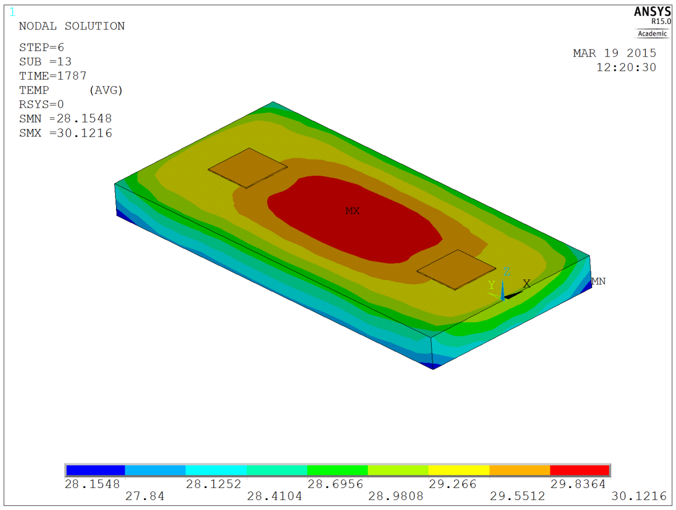

Fig. 9. Volkswagen eGolf: Result of the thermal optimization; flat prismatic cell

- cell terminals $75\frac{W}{m^2K}$ (simulation of heat transfer to the current collectors)

VII. DISCUSSION

The result of the optimized Tesla Cell in chapter VI-A showed that there only seems to be a limitation on the radius of the cell. At this point, it must be mentioned that, in the parametric model, it is assumed, the whole lateral surface of the cell can be cooled, which represents a rather theoretical scenario. In reality, this is hardly possible. Hence, there is a design limitation, determined by the construction of the cooling system, which limits the length of the cylindrical cell. Furthermore, the installation position also limits the length of the cell. In the Tesla Model S, an underfloor solution for the battery pack is chosen where the cells are installed vertically. Because cells with more length affect the height of the battery pack, a higher pack itself affects the whole package of the car.
Moreover a larger cell in this case would lead to fewer parallel connections within the battery pack. This can lead to more thermal losses at the cell connectors or the internal wiring [4]. Hence, later the results have to be reevaluated as a whole again. Since the initial cell was smaller (18650 consumer cell form factor), it seems there is, however, some potential to reduce costs by using fewer, yet larger cells.
Results of the BMW i3 (chapter VI-B) show that the cells have to deal with a great temperature difference within the cells. According to [1] this does not have to necessarily be a problem. With the restriction of a $2°C$ maximum temperature difference within the cells, the algorithm reduces the cell height. Thus, the distance between the cooled bottom surface and the top part of the active material is reduced. Such a cell would also alter the battery pack concept, since BMW intentionally uses only a serial interconnection with very large cells.
In the case of the eGolf battery (chapter VI-C), no exact data was available about the passive cooling system. With the assumption that the air stream at high velocity cools the battery packs bottom, the optimized result was a very flat prismatic cell. Such a flat prismatic cell would not make sense under the aspects of production and weight. Therefore, a completely different battery pack concept with pouch cells, or cylindrical cells would be more efficient.
Generally speaking, large prismatic cells with only one cooled surface, seem to have a problem with a larger temperature difference within the cells. Therefore, further investigations should concentrate on the consequences of such a gradient on the long time behavior (especially safety and aging) of the cell.

The presented method to find a thermally optimized cell size basically works. However because of the combination of the computational effort of the constraint function and the unknown amount of iterations of the patternsearch algorithm, one does not know how much time the optimization takes. Therefore the next reasonable step would be to bring surrogate models (response surface models, metamodels) into use. Those models can be build with a predefined number of sampling points. The following optimization could then run very fast.

VIII. OUTLOOK

A. Electro-thermal Model

To increase the accuracy of the thermal results, the model will be altered to an electro-thermal model. Therefore, small geometrical changes of the parametric models are necessary. Furthermore, an electrical modeling of the resistance of the jelly role will be necessary. This can be done with results from literature as well as from measurements. With an equivalent circuit model, it is possible to calculate the response of the cell based on the state of charge (SOC). Hence, it is also possible to assess the influence of the SOC on the thermal loss. Especially low SOC conditions are critical because of the higher emerging currents.
This modification will lead to more accurate heat distribution within the cell. Based on this, it will be possible to more accurately evaluate the effects of the right or wrong cooling system or the right or wrong cooled area of the cell, respectively.

B. Discrete aging model

After the implementation of the electro-thermal model the next step will be to link an aging simulation to the electro-thermal simulation. An aging model already implemented in MatLab will be discretized and coupled. Hereby, it is possible to not only optimize thermal parameters, but also the aging behavior of the cells. Therefore, a combination of a Performance-based Model and an Equivalent Circuit Model will be utilized [13]. The thermal and electrical information of every FE-Element will be routed through the aging model, which calculates a state-of-health for every element. Thereby, an aging matrix can be built up and restrictions can be set.

TABLE V. SIMULATION PARAMETERS [20]

Material	Density $\frac{kg}{m^3}$	Heat capacity $\frac{J}{kgK}$	Thermal conductivity $\frac{W}{mK}$
steel	7900.00	875.00	14.6
Active material			
graphite	1347.33	1437.4	1.04
polypropylene	1008.98	1978.16	0.3344
aluminum	2702.00	903.00	238.00
copper	8933.00	385.00	398.00
$LiCoO_2$	2328.50	1269.21	1.58
Total	2453.22	1009.75	$\lambda_0 = 54.91$ $\lambda_{90} = 1.14$

Hence, it will be possible to restrict the ΔSOH and minimize the total average SOH after every cycle. To minimize the calculation effort, it is also conceivable to lower the resolution of the SOH matrix, but further investigation will be necessary. Furthermore, it is possible to recalculate the new resistance of the FE-elements after every cycle. Inhomogeneous aging will especially lead to different resistances within the active material and, thus, to an inhomogeneous current distribution and heat generation. Maybe a swinging effect of the SOH distribution within the cell can be observed over time.

IX. CONCLUSION

In this paper a method is presented for how to define an optimum thermal cell size. This method was realized with a tool based on Ansys and MatLab. With a few known parameters, it is possible to calculate or optimize, respectively, a, optimum cell size for an aimed cooling system.
The other way around it is also possible by defining aimed costs for a cooling system. A low-cost solution would lead to an air-cooling system, an expensive solution would lead to an AC coupled liquid cooling system [15]. With the thermal optimization of a cell, it is possible to achieve the best performance under given framework conditions.

ACKNOWLEDGEMENTS

This article contains results of term papers, Bachelors and Masters theses from Constantin Paschold, Ralf Köhler and Christian Karl and the authors would like to thank them for their contributions. Again, the authors would like to thank them for the support. The project was independently funded by the Institute of Automotive Technology at the Technische Universität München.

REFERENCES

[1] M. Fleckenstein, O. Bohlen, and B. Bäker, “Aging effect of temperature gradients in li-ion cells experimental and simulative investigations and the consequences on thermal battery management,” in *Electric Vehicle Symposium 26*, 2012.

[2] N. Omar, M. A. Monem, Y. Firouz, J. Salminen, J. Smekens, O. Hegazy, H. Gaulous, G. Mulder, P. Van den Bossche, T. Coosemans, and J. van Mierlo, “Lithium iron phosphate based battery Assessment of the aging parameters and development of cycle life model,” in *Applied Energy*, 2013.

[3] M. Broussely, P. Biensan, F. Bonhomme, P. Blanchard, S. Herreyre, K. Nechev, and R. J. Staniewicz, “Main aging mechanisms in li ion batteries,” in *Journal of Power Sources*, 2005.

[4] M. Kerler, P. Burda, M. Baumann, and M. Lienkamp, “A Concept of a High-Energy, Low-Voltage EV Battery Pack.” IEEE, International electric vehicle conference, 2014.

[5] C. Mikolajczak, M. Kahn, K. White, and R. T. Long, *Lithium-Ion Batteries Hazard and Use Assessment - Final Report*. The Fire Protection Research Foundation, 2011.

[6] G. P. Beauregard, “Report of investigation: Hybrids plus plug in hybrid electric vehicles,” ETEC, Tech. Rep., 2008.

[7] S. Al Hallaj, H. Maleki, J. S. Hong, and J. R. Selman, “Thermal modeling and design considerations of lithium-ion batteries,” in *Journal of Power Sources*, 1999.

[8] Q. Wang, P. Ping, X. Zhao, G. Chu, J. Sun, and C. Chen, “Thermal runaway caused fire and explosion of lithium ion battery,” in *Journal of Power Sources*, 2012.

[9] J. Lamb, C. J. Orendorff, L. A. Steele, and S. Spangler, “Failure propagation in multi-cell lithium ion batteries,” in *Journal of Power Sources*, 2014.

[10] G.-H. Kim, A. Pesaran, and R. Spotnitz, “A three-dimensional thermal abuse model for lithium-ion cells,” in *Journal of Power Sources*, 2007.

[11] M. Ecker, J. B. Gerschler, J. Vogel, S. Kbitz, F. Hust, P. Dechent, and D. U. Sauer, “Development of a lifetime prediction model for lithium-ion batteries based on extended accelerated aging test data,” in *Journal of Power Sources*, 2012, p. 248257.

[12] F. Herb, “Alterungsmechanismen in Lithium-Ionen-Batterien und PEM-Brennstoffzellen und deren Einfluss auf die Eigenschaften von daraus bestehenden Hybrid-Systemen,” Ph.D. dissertation, Universitt Ulm, 2010.

[13] C. Meis, S. Müller, S. Rohr, M. Kerler, and M. Lienkamp, “Guide for the Focused Utilization of Aging Models for Lithium-Ion Batteries an Automotive Perspective,” in *SAE 2015 World Congress*, 2015.

[14] “BEHR AG: Thermal Management for hybrid vehicles,” Techn. Ber. 2009.

[15] P. Nelson, K. Gallagher, and I. Bloom, Eds., *BatPaC - Battery Performance and Cost model*, http://www.cse.anl.gov/batpac/, 2012.

[16] Eric Darcy, Frank Davies, Pranav Patel, Brad Strangways, Tim Nelson, “Cell PTC Device Characterization,” *NASA Aerospace Battery Workshop*, 2008.

[17] P. Häupl, M. Homann, C. Kölzow, O. Riese, A. Maas, G. Höfker, and C. Nocke, *Lehrbuch der Bauphysik Schall - Wärme - Feuchte - Licht - Brand - Klima*, W. M. Willems, Ed. Springer Vieweg, 2013.

[18] G. Pistoia, *Lithium-Ion Batteries: Advances and Applications*. Elsevier, 2014.

[19] G. Zhang, L. Cao, S. Ge, C.-Y. Wang, C. E. Shaffer, and C. D. Rahn, “In Situ Measurement of Radial Temperature Distributions in Cylindrical Li-Ion Cells,” *Journal of the Electrochemical Society*, vol. 161, no. 10, pp. A1499–A1507, 2014.

[20] S. C. Chen, C. C. Wan, and Y. Y. Wang, “Thermal analysis of lithium-ion batteries,” in *Journal of Power Sources*, 2005, pp. 111–124.