

Systematic Approach for the Cooling System Optimization of a Battery Electric Sports-Car

Dipl.-Ing. Alexander U. Kayser, Dr.-Ing. Timo Kuthada, Dipl.-Ing. Nils Widdecke,
Prof. Dr.-Ing. Jochen Wiedemann

FKFS / IVK, University of Stuttgart, Germany

Summary

For a high performance BEV a large number of cooling topologies exist to arrange its cooling components. To find an optimal topology, an evolutionary algorithm is utilized. In combination with a Fast Calculation Model more than 1.8 million solutions are found, leading to 2.797 different topologies.

The simulation of the best evaluated topology in a coupled thermal system simulation shows an improvement of 4 % faster lap times for a high load case and a reduction of energy consumption of up to 10 % for the standard driving cycles WLTC, NEDC and CADC.

Keywords: BEV (battery electric vehicle), optimization, simulation, thermal management

1 Introduction

Battery electric vehicles (BEV) have in common, that they are facing a conflict between cruising range and energy for cooling or heating of their components and passenger compartment [1]. Sports cars have essentially higher requirements for cooling, especially on racetracks in hot countries, compared to being driven in driving cycles like WLTC, NEDC or CADC. But still the total amount of waste heat in BEVs is lower than in conventional internal combustion engine cars.

The vehicle, which is considered within the joint research project e-volution is designed as a high performance BEV. The project is funded by the Bundesministerium für Bildung und Forschung within the framework of the cluster of excellence Elektromobilität süd-west. Project partners under the lead of Dr.-Ing. h.c. F. Porsche AG pursue the approach of researching a BEV combining innovative technologies to create a high performance sports car. Special attention was paid to the powertrain, energy management, thermal management and charging infrastructure. The Research Institute of Automotive Engineering and Vehicle Engines Stuttgart (FKFS) is contributing to the sub-projects electric and integrated thermal management [2].

The vehicle is equipped with four-wheel drive consisting of two gearboxes, electric motors and power electronics. The power for the components is delivered by the traction battery. At peak power, more than 350 kW are provided, which lead to a heat loss of about 7 kW at the battery cells. This heat must be dissipated for continuous safe operation of the battery. To ensure a sufficient cooling at all times, the vehicle features two radiators in the front bumper which dissipate heat from the coolant to the air.

Most of the components are liquid cooled and therefore require a connection with coolant tubes. The layout of those cooling connections is of importance for the cooling performance. This layout is called *cooling topology* in the following. The number and variety of different components makes it difficult to arrange them in an optimal cooling topology. The presented approach in this paper is a systematic optimization process. An evolutionary algorithm, combined with a Fast Calculation Model, is used to investigate all

possible topology variants. After identifying the best result, a coupled thermal system simulation is used to confirm the cooling topology and the methodical approach.

2 Thermal Vehicle Simulation

In order to optimize the cooling system of the vehicle holistically, a coupled thermal simulation of the BEV has been adapted and enhanced within the project e-volution. The simulation environment “Thermal Vehicle Model Stuttgart” (TheFaMoS) developed at IVK/FKFS consists of two parts [3-6]. One part is implemented in Matlab™/Simulink™ and calculates based on the vehicle driving resistances the resulting power from the velocity profile and determines the drive train efficiency [7]. By the modelled wheels, the velocity-profile is transformed into a driving power. This power defines the required power output of motors, power electronics and battery (see Figure 1) and their respective heat losses. The heat losses are transferred from the components to the coolant. In the simulation this heat transfer is implemented in the second part of the calculation model, which is created with the help of KULI™ [8].

In the thermal-hydraulic model, two coolant circuits are modelled. The first coolant circuit includes the power electronics, electric motors, gearboxes and radiators. The other coolant circuit contains the traction battery, voltage converter and a chiller for heat dissipation to the refrigerant circuit, which is integrated as a characteristic map in the Simulink model.

The system simulation model is used to simulate the BEV in defined driving cycles under a set of ambient conditions. In the driving cycles NEDC, WLTC, CADC and Racetrack the potential of the optimizations is quantified. The Racetrack driving cycle is a high performance test. The velocity profile is based on a track-like round course. The lap time is approximately two minutes with a maximum speed of 200 km/h and an average of about 120 km/h [9].

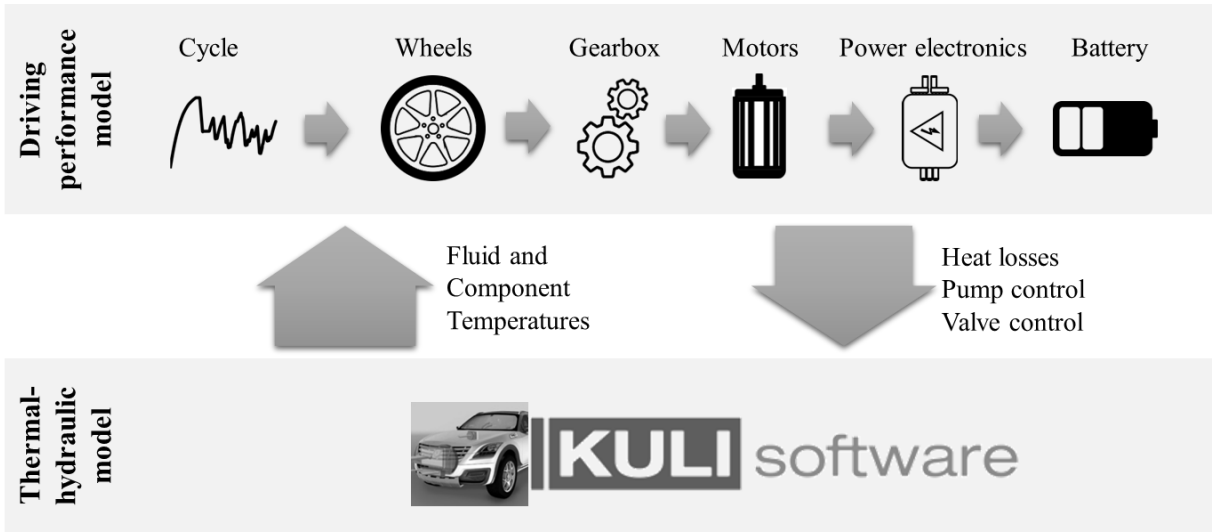


Figure 1: Structure of the system simulation in TheFaMoS

The results presented in the following are not based on a single driving cycle run as criterion for evaluation but on load cases. A load case consists of two variables: One of the four driving cycles and one of three ambient temperatures. The vehicle starts at a battery state of charge (SOC) of 95 %, defined as fully charged battery (see Figure 2). The driving cycle is repeated for several times until a SOC of 5 % reached, the drive is then stopped by the control process.

After this first drive, the battery is fast charged as a relevant part of the load case: the charging power is 300 kW and causes losses in the battery which are a challenge for thermal management and will be an essential criterion for BEVs in future [10]. Since there is no flow around or through the vehicle standing still, the required air flow through the heat exchangers must be driven by fans. When the battery is fully charged again, the second drive starts. The load case finishes after the battery reaches a SOC of 5 % again.

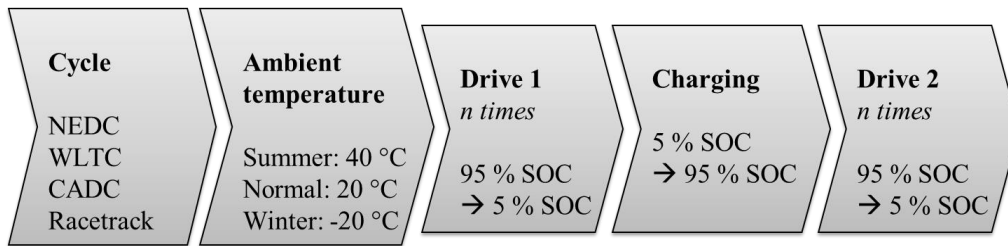


Figure 2: Composition of a load case by definition of a driving cycle and an ambient temperature for successive execution of driving, fast charging and driving

The heating and cooling performance of the components changes with their different arrangement within one cooling circuit. Depending on the load case, an optimal cooling circuit topology can be found with minimized power consumption for cooling or maximized cooling performance of the components. Since a large amount of different variants can result from the relevant 11 components, a new approach for searching the optimized topology has to be utilized, which will be introduced in the next chapter.

3 Optimization Process

At ambient temperatures of up to 40 °C, cooling of the battery or the passenger compartment cannot be achieved by direct air cooling or with a coolant circuit only. For these ambient conditions a refrigerant circuit is required. Therefore, a low temperature coolant circuit (LTC), which cools the battery, is connected to the refrigerant circuit with a chiller (Figure 3). The refrigerant circuit is operated with a compressor and dissipates the heat via two condensers to the ambient air. The condensers are placed in the vehicle front, ahead of the radiators. For the operation of the medium temperature circuit (MTC), pumps operating at 12 V are required. To transform the traction battery voltage level to 12 V, a DC/DC converter is installed, which also requires cooling.

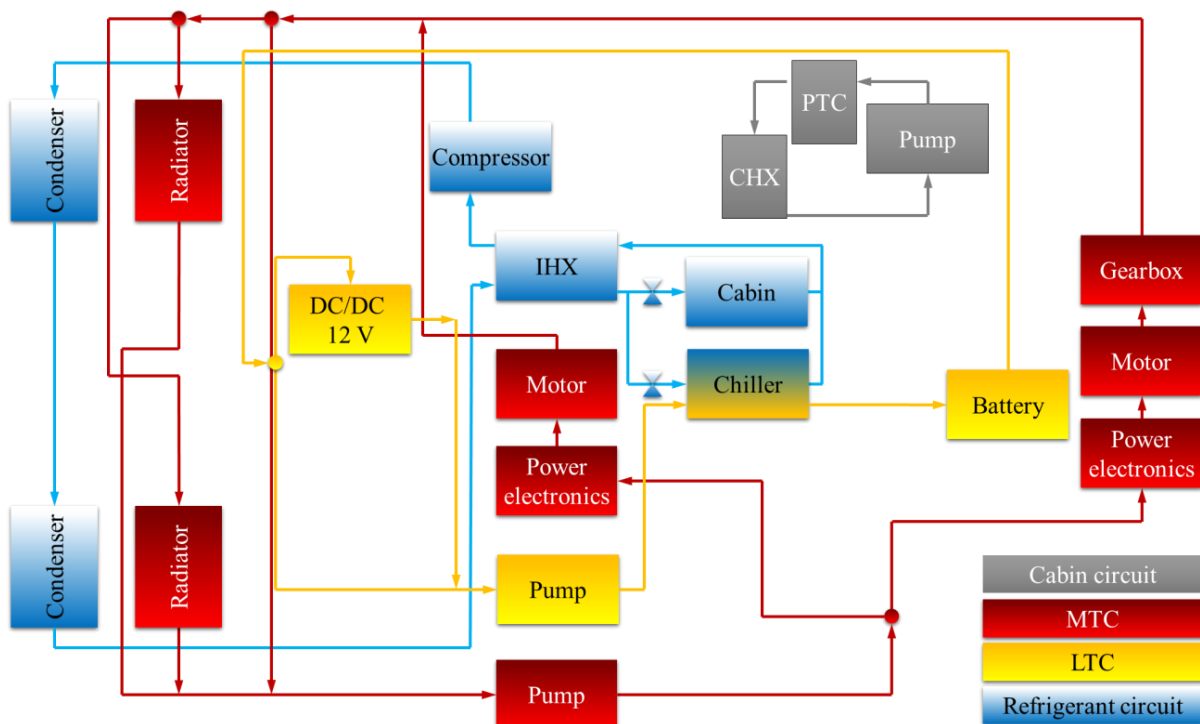


Figure 3: Baseline cooling topology of the regarded BEV with Internal Heat Exchanger (IHX) and Cabin Heat Exchanger (CHX)

In total, the investigated vehicle contains 11 components to be cooled, located in the coolant and refrigerant circuits. In addition pumps, compressor, expansion tanks, valves, collectors and dryer are also necessary for operation.

To determine to the best suited cooling topology, called *ideal*, it would require simulating all possible system variations. A complete variation of all components leads to a large design space. An appropriate procedure to find a better, an *optimal* topology, is a systematically stepwise approach [11]. After the explanation of this approach, the required Fast Calculation Model (FCM) is explained.

3.1 Systematically Stepwise Approach

Siebertz introduces a model, consisting of three process steps for systematic optimization [12]. The first step is the *description of the system*. The model is described based on equations and characteristic maps in program code. The second step is called *screening of the factors*, the entire solution space is investigated in a comparatively coarse resolution. *Good* and *bad solutions* are found to the problem. Good solutions are well suited to the optimization goal. For example, if the component temperature shall be minimized as an optimization goal, a better solution is the identified design, featuring a lower temperature. This calculated temperature represents a local minimum and thus the local optimum solution. In the final process step, the *detailed investigation*, an algorithm determines additional process variable sets which are expected to result in a further improvement. If such a setting is identified, the calculation is performed, resulting eventually in an improved result, a new optimum. Several different algorithms can be used in this step; the algorithm used in this work is an evolutionary algorithm.

Evolutionary algorithms are based on the Darwinian Theory of The Origin of Species by Means of Natural Selection: A population produces offspring that fight for their survival. Well-adapted individuals inherit their properties from previous generations (parents), thereby optimizing the overall population to the environment. In this study, the initial population is defined by the baseline cooling topology and one derivative. Crossings of designs create new ones (children), which are calculated.

As in Darwin's theory the best-adapted individuals are crossed. The selection of the parents is achieved by analyzing their quality and setting up a Pareto Front. The Pareto Front consists of all designs where no optimization of a factor is possible without reducing other factors to the same degree [12].

After the selection of good parents, the creation of the children generation is computed. As already mentioned, this is mainly achieved by crossing. The offspring is a combination of the parents' parameters. Besides, another important mechanism of evolutionary algorithms is the random mutation. It modifies the child's information in a way that not only combinations of the parent's information are generated. As a result, the optimizer does not remain in a local optimum, but randomly jumps to new locations in the design space. This so-called *exploratory character* is a decisive reason for the selection of such algorithms for the described large optimization problem (according to Deb et al. [13]).

3.2 Fast Calculation Model

The program modeFRONTIER™ is used for automated calculation of the optimization. For the optimization of the cooling system topology, the predefined parents are the described topology and its derivative. *True topologies* define realistic cooling topologies in consequence of the interconnection of all components. Thus, illogical and even impossible designs are producible by the quasi-random adjustment of process variables: As shown in Figure 4 every input and output of each component is connected to a memory. It is interpretable as a coolant reservoir, from which the component is supplied, or into which it releases the coolant.

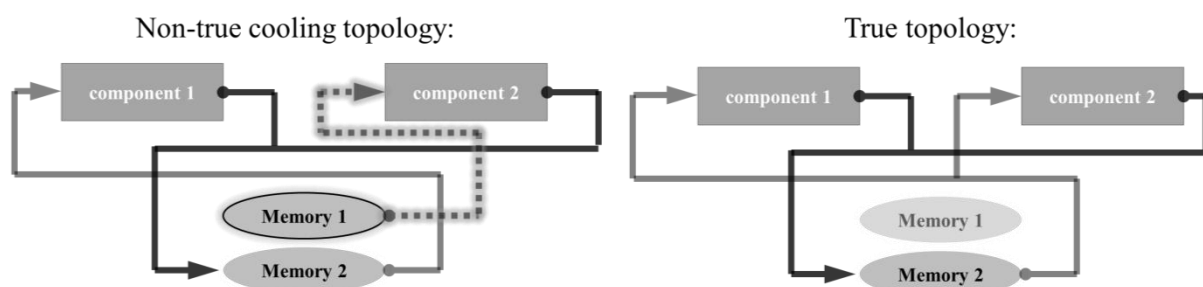


Figure 4: Exemplary connection of the components, analogous to topology 15 (left) and 16 (right) from Table 1

The address to the individual memory is defined by a process variable for the respective port. Table 1 describes the possible combinations for two components and two memory addresses, including the two topologies 15 and 16 shown in Figure 4.

Table 1: Possible address variables for two components and two memory addresses

Definition	Component 1 IN	Component 1 OUT	Component 2 IN	Component 2 OUT
Topology 1	M1	M1	M1	M1
Topology 2	M1	M1	M1	M2
...
Topology 15	M2	M2	M1	M2
Topology 16	M2	M2	M2	M2

Topology 15 shows a negative example of a variation. Information about the coolant is sourced from memory 1 as an input for component 2, but no information is fed into memory 1. This is comparable with a coolant reservoir, from which coolant is taken, but nothing returned. Topology 16 creates a true one because both components write to a memory address and obtain information from it.

The logic that prohibits such interconnections is also integrated in the FCM. It is implemented in Matlab™ and receives the address specifications of the component interconnection as process variables from modeFRONTIER™.

This work focusses on the approach of a systematic interconnection variation of the components present in the cooling system. As shown in Figure 5, for this purpose the model is divided in sub models for valve positions, components, coolant and cooling air. As input, the valve positions and component order are transmitted into the simulation. With this information, the stepwise simulation is performed within the FCM. As output, it provides information on the temperatures of the components and fluids.

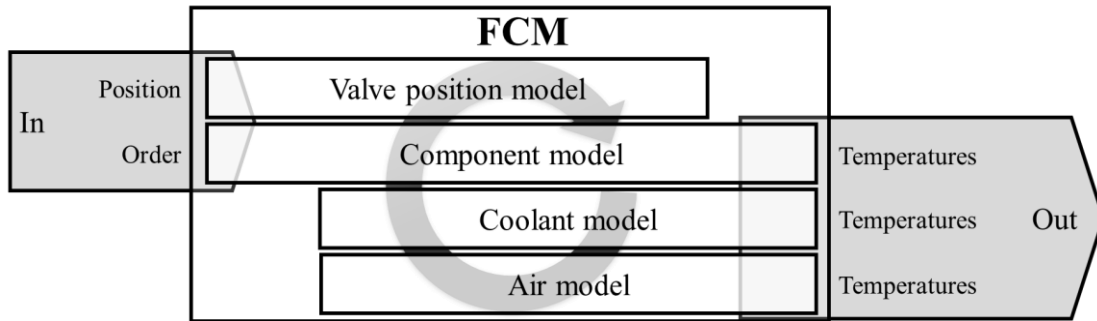


Figure 5: Basic structure of the FCM with four sub models, input and output

The change of component temperature is calculated as consequence of energy losses, mass and heat capacity according to the first law of thermodynamics (Equation (1) [14]):

$$\Delta T = \frac{\int \dot{Q} dt}{m \cdot c_p} \quad (1)$$

The driving cycle is implemented as loop instruction of discrete time steps in the program code. The variable topology simulation is realized by separating the calculation of the coolant model from the calculation of the component model. The temperatures of the components as well as the respective coolant temperatures are written into a short-term memory. Depending on the heat transfer coefficient, the area and the temperature gradient between component and coolant, heat is transferred to the coolant (Equation (2)):

$$\dot{Q} = \alpha \cdot A \cdot \Delta T \quad (2)$$

In the model the change in mass flow rate resulting from dividing the coolant into different branches is taken into account as well as the different possible heat transfer combinations between coolant, refrigerant and ambient air. In addition, an air model is used to calculate the heat transferred by the condensers and

radiators. The condenser is positioned ahead of the radiators in the air path and reduces therefore the effective temperature difference.

In addition to the air, coolant and component model, the valve model is important. For every parallel component connection, the valve position needs to be defined. Since there are 11 components in the cooling system, there could be up to 11 parallel coolant branches. They can be regulated with 10 valves. Every valve can be adjusted in 10 % steps but is fixed within one FCM simulation, which is an important simplification to minimize the calculation time.

The two initial topologies form the first two results of the FCM and enable the comparison to the more detailed simulation with TheFaMoS. They show an average deviation of less than 5 K for the component temperatures. The focus in this approach is the methodology and the speed of the calculation, which is 0.3 seconds per topology. To confirm the results of the optimization process, the coupled simulation in TheFaMoS is used to evaluate the identified optimum topology.

Starting from these two topologies, the evolutionary algorithm successively changes the process variables for interconnection order and valve positions. The genetic algorithm NSGA-II has been proven to be well suited for this investigation. A comparison with two other evolutionary algorithms shows a more powerful identification of cooling topologies. Based on a calculation time of 0.3 seconds for one topology, 5,400 different topologies can be investigated within 30 minutes. While the other two algorithms identify in between 1-20 topologies during this period, the NSGA-II allows in the same time the identification of 1,000-1,500 solutions. This means that approximately 20 % of all calculated process variable combinations create true cooling system topologies. For all these true topologies, FCM returns component temperatures to modeFRONTIER™. Nevertheless temperatures exceeding the maximum tolerable component temperatures are possible. This could be due to a direct interconnection of the output port of a component to its own input port. Although this topology seems to be only of minor practical relevance, it indicates that the component does not require fresh coolant. In addition, this interconnection may lead the evolutionary algorithm to another, more successful cooling circuit in following design generations.

After the calculation is finished, the first step in post-processing is to filter out the designs, which exceed the maximum component temperatures. The combination of all individual temperature criteria for the components leads to comparatively few topologies. These topologies are *global solutions*.

The FCM does not contain any control algorithms for the coolant pumps or the refrigerant system. As previously described, the valve positions are also designed as fixed values within one simulation. Accordingly, lower component temperatures mean better cooling performance at same load and ambient temperature. Based on the mean value of all single dimensionless component temperatures (Equation (3)), Figure 6 shows that the optimization process achieves a temperature reduction within the first 700,000 global solutions.

The dimensionless component temperature is a measure for the achieved temperature in comparison to its respective maximum temperature. The maximum value of $\Theta_C = 1$ occurs if the highest acceptable component temperature is reached, so the lowest possible values for Θ_C are striven for.

$$\Theta_C = \frac{T_C - T_{amb}}{T_{C_{max}} - T_{amb}} \quad (3)$$

with

T_C in K Component temperature
 $T_{C_{max}}$ in K Maximum component temperature
 T_{amb} in K Ambient temperature

After the calculation of design no. 700,000 the following 400,000 designs show no result in the diagram. All these solutions contain component temperatures that are not within the temperature limits and are therefore no global solution. Only after the 1.1-millionth design further solutions are achievable which, however show no further significant improvement.

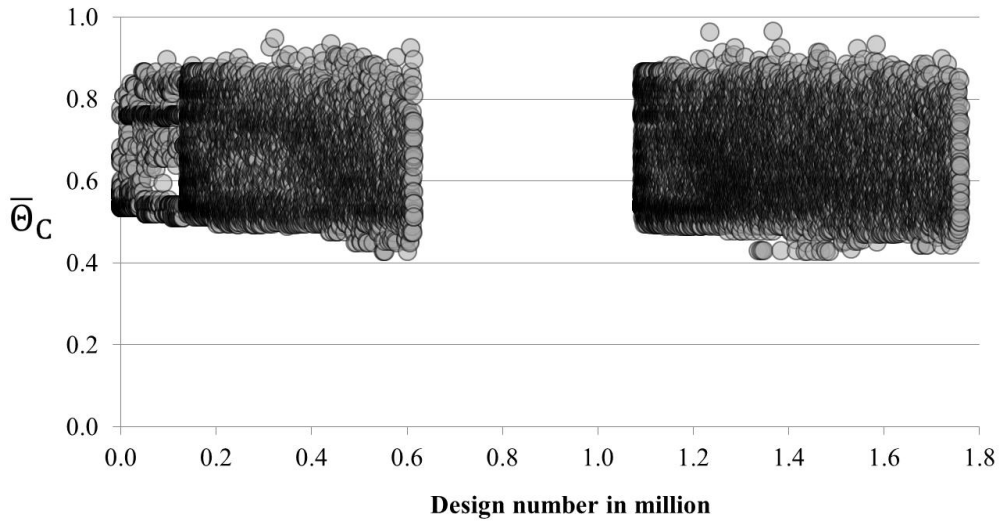


Figure 6: Calculated, true topologies, which do not contain exceeded maximum component temperatures by means of their average dimensionless component temperature

The analysis of the values for input and output process variables of almost 1.8 million designs reveals that nearly every possible valve position is investigated. Since in the final evaluation of the topologies, in TheFaMoS, the valves are controlled automatically, the valve position for the pre-selection does not constitute a distinction criterion for the designs. The check for redundant designs without the distinction by valve positions results in 2,797 different topologies. The ascending sorting, according to the arithmetic-mean dimensionless component temperature $\bar{\Theta}_C$, indicates 20 designs with almost identical evaluation criterion. The consideration of the individual dimensionless component temperatures, which lead to this average temperature, shows an insufficiency of this consideration: Designs with comparatively high component temperatures are also rated as “good” (see Figure 7).

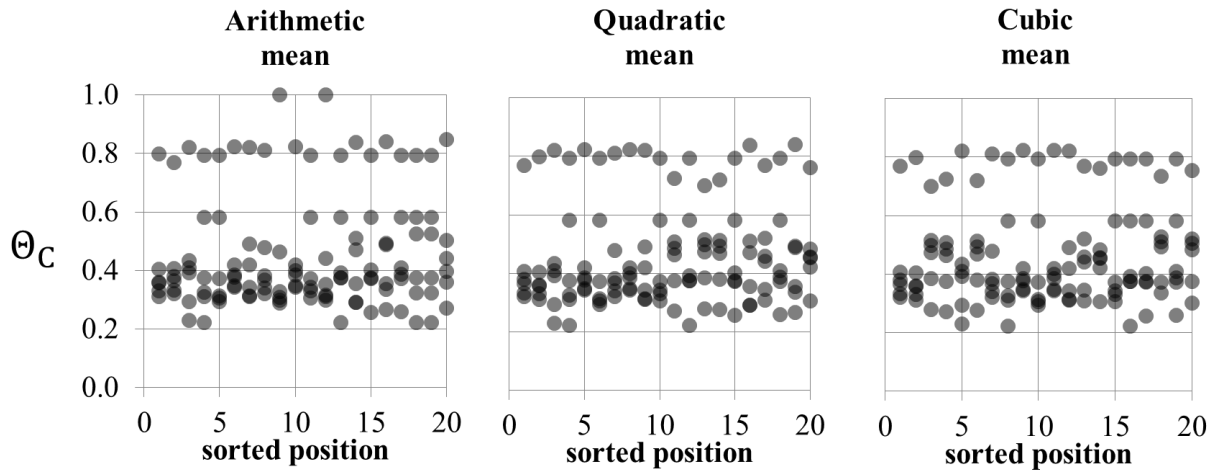


Figure 7: Representation of the individual component temperatures of the best 20 designs for sorting by arithmetic mean (left), quadratic mean (center) and cubic mean (right)

The formation of the quadratic mean value (Equation (4)) or of the cubic mean value (Equation (5)) leads to a different order of best designs. Their maximum occurring component temperatures are lower because of the higher influence of larger Θ_C values on the mean value $\bar{\Theta}_C$. For this reason, the cubic mean value has been chosen as sorting criterion for the results.

$$\bar{\Theta}_{C\text{Quadratic}} = \sqrt{\frac{1}{n} \cdot \sum_{C=1}^n \Theta_C^2} \quad (4)$$

$$\bar{\theta}_{C_{\text{cubic}}} = \sqrt[3]{\frac{1}{n} \cdot \sum_{C=1}^n \theta_C^3} \quad (5)$$

The topology with the lowest cubic mean temperature is shown in Figure 8. A major difference to the baseline topology is the separation of the medium temperature circuit into two circuits and the integration of the cabin heat exchanger into the medium temperature circuit. Each circuit contains a radiator.

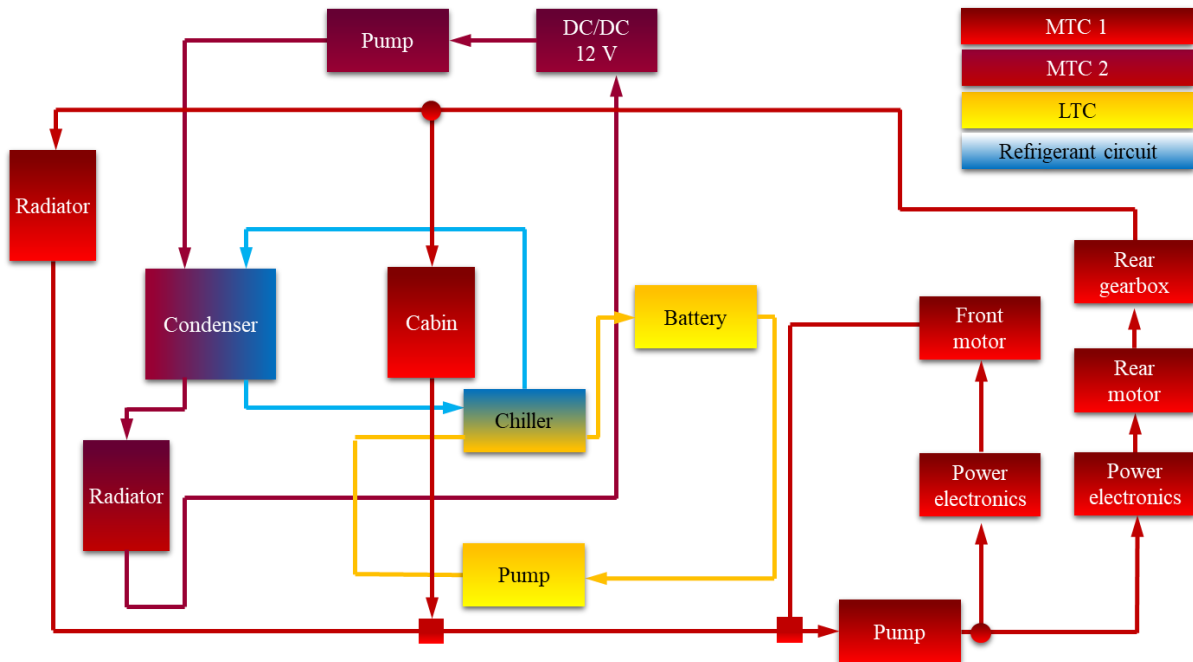


Figure 8: Schematic illustration of the cooling topology with the lowest cubic mean temperature

Another significant change is the direct feedback loop from the front axle power electronics and motor to the coolant pump. The results presented in the next chapter prove the functional scope of the automated topology optimization, which can result in new solutions.

4 Optimization Results

The integration of the new cooling topology in TheFaMoS finally shows the achieved degree of optimization. The calculation of the high-load driving cycle Racetrack at an ambient temperature of +40 °C shows after 10 repetitions in the first driving cycle and 10 more in the second a reduction of 4.1 % of the time needed for this distance in comparison to the baseline topology.

In addition, this optimized cooling topology also demonstrates an improved efficiency. Therefore, the energy consumption of the BEV is taken into account. Equation (6) shows the definition of the energy consumption B_E for a fixed reference distance. The distance results from a number of repetitions of the driving cycle after starting and a further number of repetitions after fast charging.

$$B_E = \frac{E - E_{\text{ref}}}{E_{\text{ref}}} \quad (6)$$

with

E consumed energy of the battery when driving the predetermined reference distance

E_{Ref} consumed reference energy of the battery in WLTC at +20 °C with baseline cooling topology

Figure 9 shows the results from TheFaMoS of the baseline cooling topology in comparison to the optimized cooling topology for the three driving cycles. These results confirm the developed approach.

Depending on the velocity profile of the driving cycle, higher or lower specific energy consumption results. The tendency for the optimized topology however is quite similar and shows an overall reduction of B_E . In winter load case at $-20\text{ }^\circ\text{C}$, the energy consumption is lowered by up to 10 %. For summer load case, a reduction of approx. 2 % is achieved.

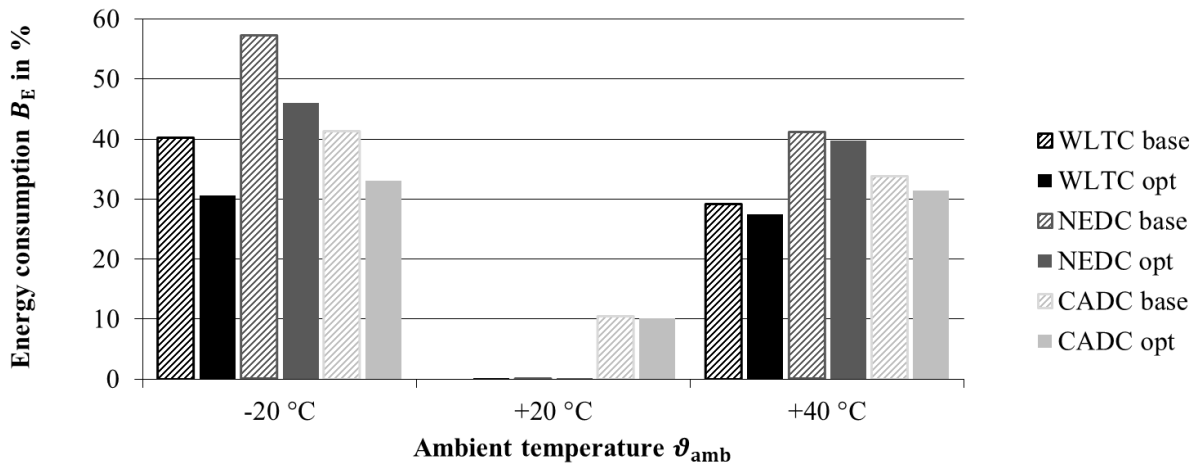


Figure 9: Comparison between the baseline topology and the optimized cooling topology for the three standard driving cycles

The impact resulting from ambient temperature is for the NEDC more significant than for the CADC. The higher average velocity in CADC leads to faster discharge of the vehicle in CADC, shorter driving time and thus to minor extent in which the thermal management base load affects the energy consumption.

Figure 10 shows the distribution of energy in a Sankey Diagram for the WLTC at $40\text{ }^\circ\text{C}$ ambient air temperature. The high losses due to the load on the DC/DC converter and high power requirement from the compressor can be seen.

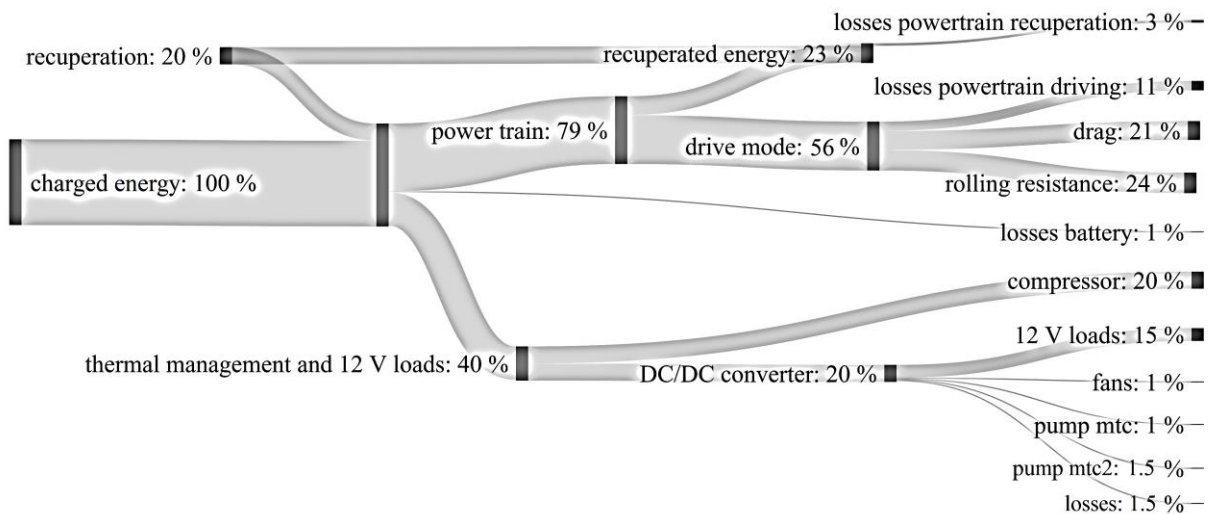


Figure 10: Breakdown of energy consumption during WLTC at $40\text{ }^\circ\text{C}$ ambient air temperature

5 Conclusions

While BEVs are facing generally a conflict between cruising range and energy for cooling or heating, battery electric sports car require in addition a powerful cooling. This is especially a severe requirement on racetracks in hot countries, in comparison to driving in driving cycles like WLTC, NEDC or CADC.

The high performance BEV considered in this investigation is equipped with four-wheel drive with more than 350 kW peak power. In total, the vehicle contains 11 relevant components, located in the coolant and refrigerant circuits. For the investigated BEV several thousand feasible cooling topologies exist.

To find an *optimal* topology, an evolutionary algorithm is utilized. On the basis of selection and mutation, new designs are developed. Each design has to be calculated in the vehicle simulation to quantify the impact. The suitability of a full system simulation for this large number of variants is restricted. The introduced Fast Calculation Model describes the behavior of the vehicle components sufficiently accurate. In comparison to a fully coupled system simulation, the calculation can be carried out with a 1,400-times higher speed.

The optimization process determines 1.8 million solutions, leading to 2,797 different topologies. The evaluation enables the identification of an optimal topology. The simulation of this topology in TheFaMoS confirms the improved cooling performance. For a high load case 4 % faster lap times, compared to the basic cooling topology, are achievable. The simulation of the driving cycles WLTC, NEDC and CADC show a reduction in energy consumption of up to 10 %.

In terms of the currently available computing performance, the FCM offers an efficient way to find an optimal cooling system topology. Also in the near future, calculating all possible variations for a number of components as presented in this work will still be unrealistic. A further approach therefore would be the limitation of the design space by excluding unrealistic variants. However, this would require an intensive preparation of the models and limits the unconfined approach. A benefit of future increasing computational performance can be the integration of more complex features like valve control.

Acknowledgments

This work was carried out as part of the project “e-volution” within the framework of the cluster of excellence “Electro mobility South-West” and was funded by the Federal Ministry of Education and Research (BMBF).



Bundesministerium
für Bildung
und Forschung

References

- [1] Karras, N.: *Optimierung der Wärmeabfuhr eines Fahrzeug-Elektromotors und Auswirkungen auf den Gesamtkühlkreislauf*, ISBN: 978-3-658-17803-1, University of Stuttgart, Dissertation, 2017.
- [2] Elektromobilität Süd-West: *e-volution - Integration innovativer Konzepte für ein effizienteres und leistungsfähigeres E-Fahrzeug*, homepage prompted on July 24th 2017: <http://www.emobil-sw.de/de/aktivitaeten/aktuelle-projekte/projektetails/new-content-5.html>.
- [3] Genger, M.; Weinrich, M.: *Optimiertes Thermomanagement*, FVV Vorhaben Nr. 068540, FVV Frankfurt, 2006.
- [4] Stegmann, B.; Stotz, I.: *Prognose Thermomanagement*, FVV Vorhaben Nr. 939 und 1004, FVV Frankfurt, 2010.
- [5] Karras, N.; Kuthada, T.; Wiedemann, J.: *Simulation of a Complete Battery Electric Vehicle*, conference proceedings International KULI User Meeting 2013.
- [6] Auer, M.: *Ein Beitrag zur Erhöhung der Reichweite eines batterieelektrischen Fahrzeugs durch prädiktives Thermomanagement*, Universität Stuttgart, Dissertation, 2015.
- [7] Wiedemann, J.: Skript zur Vorlesung „*Kraftfahrzeuge*“, Institut für Verbrennungsmotoren und Kraftfahrtwesen, Universität of Stuttgart, 2015.
- [8] Manual KULI advanced, MAGNA, Engineering Center Steyr, Version 10.1, 20.03.2015.
- [9] Kayser, A.; Kuthada, T.; Widdecke, N.; Wiedemann, J.: *Thermal Management of a Battery Electric High Performance Sports Car*, International Stuttgart Symposium 2017, Stuttgart.
- [10] Steiner, M.: *Schneller laden, länger fahren*. ATZ 01/2017.
- [11] Yu, H.; Janiga, G.; Thévenin, D.: *Computational Fluid Dynamics-Based Design Optimization Method for Archimedes Screw Blood Pumps*. Laboratory of Fluid Dynamics & Technical Flows, University of Magdeburg “Otto von Guericke,” Magdeburg, Germany. At International Center for Artificial Organs and Transplantation and Wiley Periodicals, Inc., 2015.
- [12] Siebertz, K.; van Bebber, D.; Hochkirchen, T.: *Statistische Versuchsplanung – Design of Experiments (DoE)*. Springer-Verlag, ISBN: 978-3-642-05492-1, 2010.
- [13] Deb, K.; Agrawal, S.; Pratap, A.; Meyarivan, T.: *A Fast Elitist Non-Dominated Sorting Genetic Algorithm for Multi-Objective Optimization: NSGA II*, KanGAL Report No. 200001, Indian Institute of Technology Kanpur, India, 2007.
- [14] Langeheinicke, K.; Jany, P.; Thieleke, G.: *Thermodynamik für Ingenieure - Ein Lehr- und Arbeitsbuch für das Studium*. 6th Edition, Vieweg Verlag 2006, ISBN: 978-3-8348-0103-6.

Author



2006-2013: Diploma, Mechanical Engineering, University of Stuttgart

Since 2014: Research Assistant at FKFS / IVK University of Stuttgart