Holistic System Design and Efficient Optimization of a Liquid Cooled Battery Module through 1D- and 3D-Simulations

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Abstract. This publication extends on a holistic system design approach by implementing an efficient simulation methodology to design a robust cooling system for a liquid cooled battery module. After gaining insight into the functionality of the system and its components, the most promising parts for redesign were selected using a method called Extended Target Weighing Approach (ETWA). Because of this redesign, the cell mount was reduced in height and the cooling system topology parallelized to lower pressure losses. The design of the new cooling system geometry is explored. The parameter optimization is carried out with a simplified 1D fluid dynamics model. To verify and validate the 1D-simulation, a more detailed 3D-simulation is used at bespoke crucial times during development. The main boundary conditions were keeping the pressure losses at or below its reference level from the module's predecessor, while designing a robust system in terms of flow rate distribution in the parallel channels. The result was a system behaving almost indifferent to changes in temperature or total flow rate with the channels individually changing less than 5% of total flow rate and all channels staying in the range between 20% to 32% of total flow rate at all times. The overall system pressure drop could be brought down to half of its reference value. The two simulations were achieving similar results, eventually deviating less than 5% relative to each other in simulated flow rates and pressure losses.

Keywords: Battery · Functional lightweight design · ETWA · CFD · Simulation · Parameter optimization · Steady state

1 Introduction

The generation of system knowledge and the evaluation of initial concepts in early phases of product development is a central building block of product development. One method that can be used to generate knowledge in the context of battery system development is the CFD simulation.

With 3D-simulation programs becoming more and more sophisticated and computing power more expendable, developers might lean towards using the most advanced methods on hand independently of what the problem calls for. While 3D-simulations seem superior to their 1D little siblings, they come with their own drawbacks. The developer needs to be able to use them correctly and interpret the results accordingly, which requires a certain expertise and experience. Additionally, especially for the field of fluid dynamics, simulation times still easily exceed hours or days on big computation clusters. Often this approach is not affordable for SMEs (Small and Medium sized Enterprises). Therefore, this paper investigates a more efficient approach: to use higher dimension simulations only to verify and validate 1D-simulations, which can be executed much quicker, are more straightforward to troubleshoot and interpret and can therefore keep the solution space wide and the initial system design holistic.

1.1 Motivation

With the number of electric vehicles increasing, the competition in every sector of development naturally also becomes more competitive as the market grows. Subsystems of these vehicles, such as traction batteries, not only need to become cheaper, more efficient and more energy and/or power dense, also the process of developing these products needs to adjust to the changing market conditions.

One interesting market is the refitting of special conventional vehicles with an electric drivetrain. These vehicles call for a modular, spatially distributed and lightweight solution with a high temperature control performance.

One module for this particular use case is investigated in [1] and in this paper. The module assembly is depicted in Fig. 1 and consists out of a cell mount, housing and two lids. The coolant flows through the fluid channels, resulting in a temperature gradient between the cells. Round type 18650 cells are mounted in the cell mount.

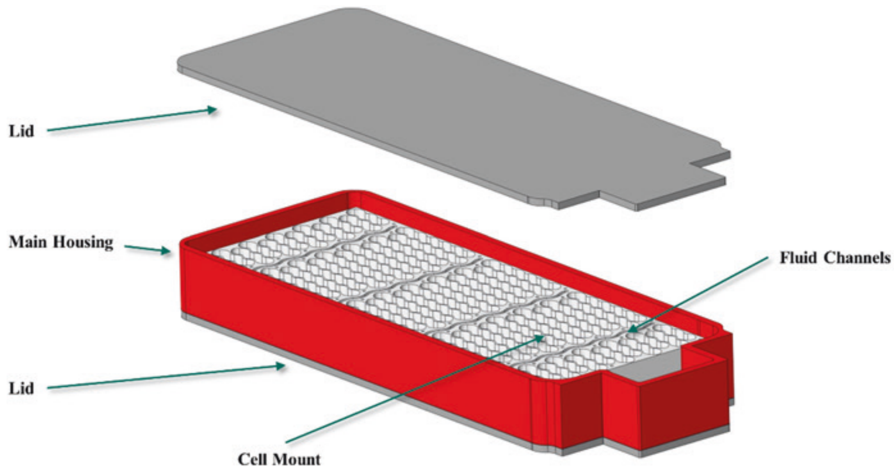

Fig. 1. Simplified battery module assembly [1]

1.2 State of the Art

Krotlin and Reinhart [2] show the importance of simulations in the early phases of product development for the design and evaluation of concepts. They focus in particular on CFD simulations.

Minovski et al. [3] coupled thermal 1D-simulations and steady state 3D-CFD-simulations to determine heat transfer in a general engine bay. The coupling is done by transferring the fluid temperature of the boundary cells and the heat transfer coefficients of the CFD-simulation to the 1D-simulation. A further approach for coupling a 3D- and a 1D-simulation is performed by Galindo et al. [4]. They couple a 1D finite difference method and a 3D-CFD-simulation based on the method of characteristics. Wagner [5] demonstrates the application of 1D-3D CFD coupling through the development of an intake manifold system.

The Target Weighing Approach based on Target Costing [6, 7] and Value Engineering [8] was developed by Albers et al. [9]. The aim of value engineering is to maximize a value previously ascribed to a certain function without generating additional costs [8, 10]. The approach enables the product developer to assign target values for costs, weight and volume and supports in the identification of lightweight potential [9].

Albers et al. [11] extended the TWA to the Extended Target Weighing Approach by taking the target value CO_2 into account. In addition, they considered uncertainties concerning new concepts [11].

Another method, which can be classified as functional lightweight design applies mass, mass distribution and moment of inertia as its functions and mass as its target value. It was introduced by Posner et al. [12].

2 Methodical Approach

This chapter describes the holistic approach used to reduce the battery modules weight and ensure cooling system performance and robustness. It consists out of an analysis step performed by using the Extended Target Weighing Approach (ETWA) to identify the most promising components for redesign from a functional lightweight design perspective, followed by a parameter optimization facilitating fast 1D-simulations and selectively used 3D-simulations at crucial steps.

2.1 System Analysis and Functional Lightweight Design

Choosing the cell mount for deeper consideration and optimization by extensive simulations was not an arbitrary choice. As laid out by Nöller et al. in [1] extensive research went into choosing the components with the greatest impact on the system's overall weight. To understand the groundwork for this publication, a very brief summary of this previous research is given in the following paragraph.

In order to optimize a system top-down, it needs to be fully understood first. Gathering all functions of the system and assigning the battery components carrying out these functions is a key step in this process. Facilitating the aforementioned ETWA approach, mapping of the so-called “efforts” (monetary, mass and/or CO_2; “effort” from here on denotes either of the three) onto the functions themselves by knowing the efforts of each component allows for the identification of functions with particularly high impact on efforts. By ranking all functions against each other in terms of their importance to the designer, it is possible to identify the components most suitable for redesign. Plotting the results (effort vs. relative importance) yields a visual representation of the process as seen in Fig. 4. Above a regression line, functions with too high effort compared to the rest of the functions are displayed. Tracing these functions back to their respective components unveils the most promising ones for redesign. These components possess a higher than average effort considering their contribution to function fulfillment.

2.2 Efficient Parameter Optimization

Changes made to a critical component such as the cell mount can have far reaching effects on the system overall. As the functions of each component have been explored in the previous chapter, the possible effects on cooling performance seemed most important. Other potential effects on the system, such as mechanical integrity, are not explored any further in this work.

While the benefits of optimizing the cell mount height from a thermal standpoint using a pareto-optimal solution for different use cases of the battery module were explored before [1], another concern was rising pressure losses due to the height reduction. As predicted by the empirical Darcy-Weisbach-equation, decreasing the cell mount height by half of its initial value almost quadruples the pressure losses in the cooling channels (the change in hydraulic diameter can be neglected in comparison for the given geometry).

One possible solution to counter this rise in pressure loss is parallelizing the coolant flow through the four cooling channels in the cell mount (see Fig. 3 for a visual representation of this parallelized design). As flow was routed sequentially so far, the distribution of the volumetric flow rates though the four channels and their sensitivity to changes of total volumetric flow rate and temperature level was to be investigated as well as the total pressure losses. The underlying goal was designing a system as insensitive as possible to changes in total volumetric flow rate and system temperature while keeping the pressure losses comparable to the original design. Not increasing or even decreasing system mass was considered as another goal.

As described in the motivation part, an efficient optimization strategy is a key factor, especially in the early stages of product development for SMEs, where there are many variations to be considered. To tackle this problem efficiently, an approach using a full factorial 1D- and singular validating 3D-CFD-simulations was developed.

Pressure losses of the initial design of the cooling channels for various heights were obtained in earlier simulations, therefore only the new design had to be modeled, simulated and evaluated.

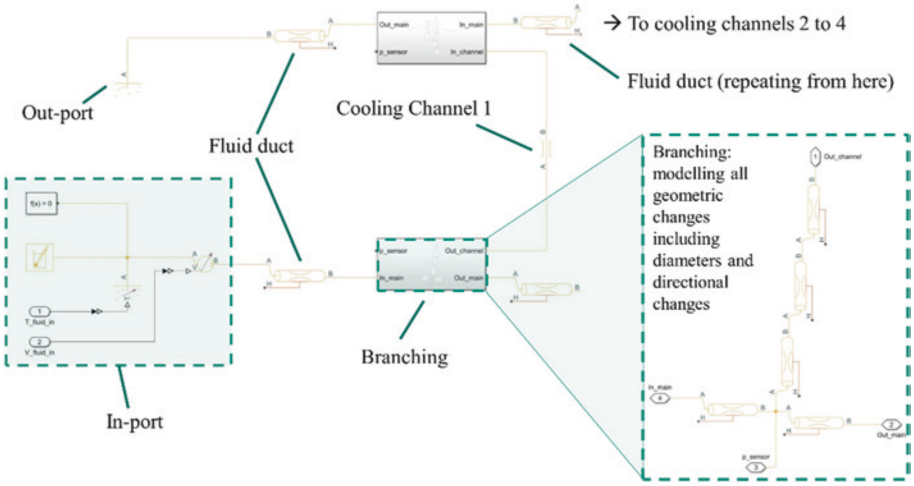

Fig. 2. Overview of 1D-simulation

The 1D-simulations were carried out in Matlab/Simulink using the SimScape physical "Thermal Liquid" library, which, among others, includes the dependency of density and viscosity on temperature and pressure. Figure 2 gives an overview of the simulation setup. The fluid parameters relevant to this simulation (density and viscosity) were exchanged with the 3D-simulation to set up a common reference. The design problem was twofold and therefore was optimized in two stages.

First, a parameter optimization with given increments and upper and lower boundaries was performed to set the geometric diameters of the fluid guiding segments. To facilitate an easier manufacturing process, one boundary condition was to use the same fluid duct diameters for the ducts between the channels and also the same diameters for all the sections branching off the main line into the cell mount. Therefore, two parameters were to be optimized for a predefined and fixed reference case of total volumetric flow rate and temperature level. The simulations did not include any heat flow, as the temperature rise of the cooling fluid from the in-port to the outflowing port due to incoming heat flow from the power losses in the battery cells rarely exceeds 1-2K, which has negligible effects on the fluid parameters. This simulation eventually yields sets of diameters suitable for the set conditions. Naturally, for a lightweight system design, the set with the smallest diameters is preferred.

After obtaining the most promising set of diameters, the second simulation now keeps those diameters fixed and performs a variation of the system's temperature level and total volumetric flow rate in order to evaluate the system's sensitivity to changes in these parameters. To catch worst-case scenarios, the system temperature was varied from −40 °C up to 60 °C, which has a substantial effect on the fluid's viscosity. The distribution of coolant fluid flowing through each channel needed to stay similar as to not starve one module segment from cooling or heating. Again, due to low simulation times, a full factorial simulation was carried out to evaluate the system's robustness against changes in total flow rate and temperature.

The 3D-simulations were deployed to assist in two critical stages: Verification of the 1D-simulation implementation and secondly validation of the simulation results. Therefore, the initial guess for geometry parameters was modelled in 3D, meshed, preprocessed and simulated in order to check, if the two simulation approaches show similar results for a range of temperatures and total volumetric flow rates. After successful verification, the two staged 1D-simulations were performed and, having obtained the set of geometric parameters, the geometry was implemented in 3D again to validate the results. Figure 3 shows one of the 3D-models used for the simulation based on the EU-patented cell mount design by Rainer and Oliver Puls [13].

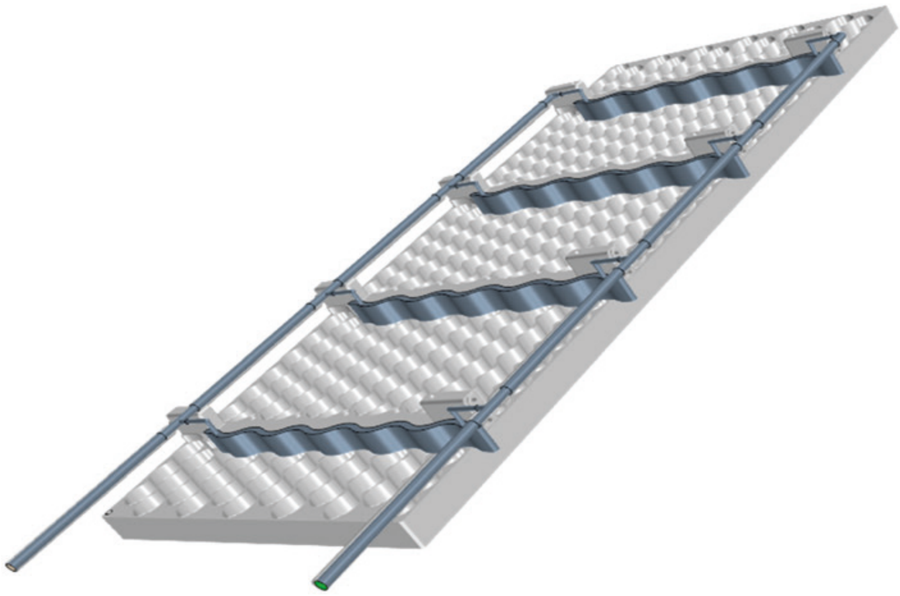

Fig. 3. Cell mount – 3D-geometry and fluid volume overlay

This approach can lead to a substantial reduction in simulation times and cut down on computation costs and, more importantly, on the laborious process of setting up 3D-simulation models for geometry variation.

3 Results

In the following, results of the development steps are presented and discussed. The main parameters for the simulations are mentioned and findings and drawn conclusions are laid out.

3.1 System Analysis and Functional Lightweight Design

The system analysis task using the ETWA method and the results are discussed in more detail in [1]. The three main function groups with high effort (Fig. 4) were:

- Battery cell cooling
- Sealing against the environment and sealing against coolant leakage
- System mounting and protection against external forces/moments

As the cell mount is the main contributor to the first function group while also being one of the heaviest parts itself, focusing on it extensively was the most reasonable choice. The other subsystems responsible for the function groups two and three are evaluated in detail in [1] and therefore not presented in this particular research.

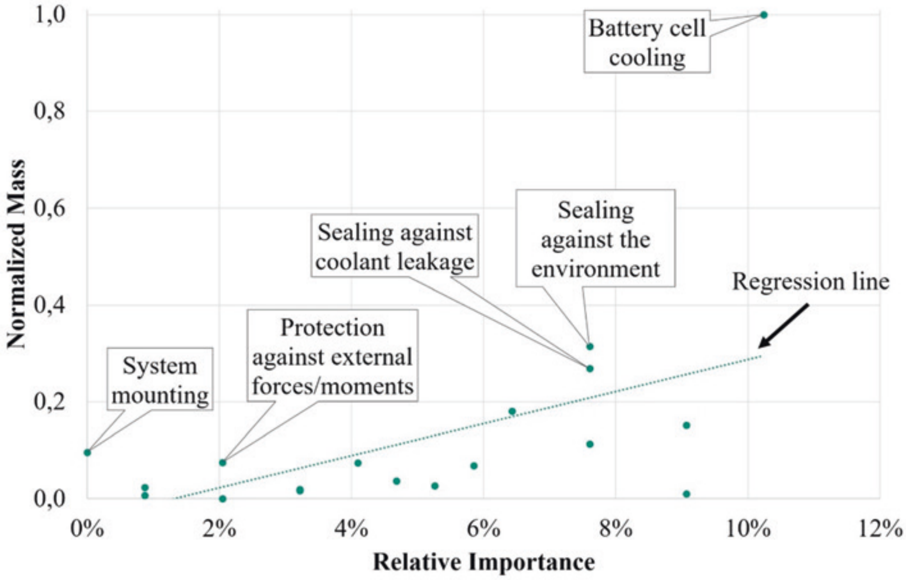

Fig. 4. Evaluation of functions using the ETWA: Mass vs. Relative Importance [1]

3.2 Efficient Parameter Optimization

The 1D-simulations were performed using a water-glycol mixture (50–50 mass fraction) with the parameters for atmospheric pressure conditions shown in table 1. The simulations were performed in steady state.

The initial verification of the 1D-model by 3D-simulation yielded very close similarity between the two simulations in terms of volumetric flow distribution with less than 5% relative error.

Given the simplified nature of the 1D-model with approximated geometry, these results were reasonably precise. The pressure losses of the system on the other hand deviated by almost 50% from the 3D results, revealing the geometry modelling as too simplified for good pressure loss estimation. The 1D-model was therefore reworked and extended to resemble the real geometry more closely and relative error dropped down to less than 5% as well. Figure 2 shows this revised model. With these good results, the two-staged 1D-simulations were carried out.

Table 1. Selection of fluid parameters for atmospheric pressure

Temperature in °C	Density in kg/m^3	Kin. Viscosity in mm^2/s
−30	1084.98	43.62
0	1074.59	7.63
20	1064.9	3.54
40	1053.4	2.02

Unsurprisingly, the results of the simulations revealed the benefit of bigger diameters in countering pressure losses. To keep the flow rates in the channels similar to each other, large fluid duct diameters and small branching off diameters were favored. This is easily understandable, since a high pressure loss in the parallel channels renders the losses in the ducts less influential overall and therefore evens out the distribution.

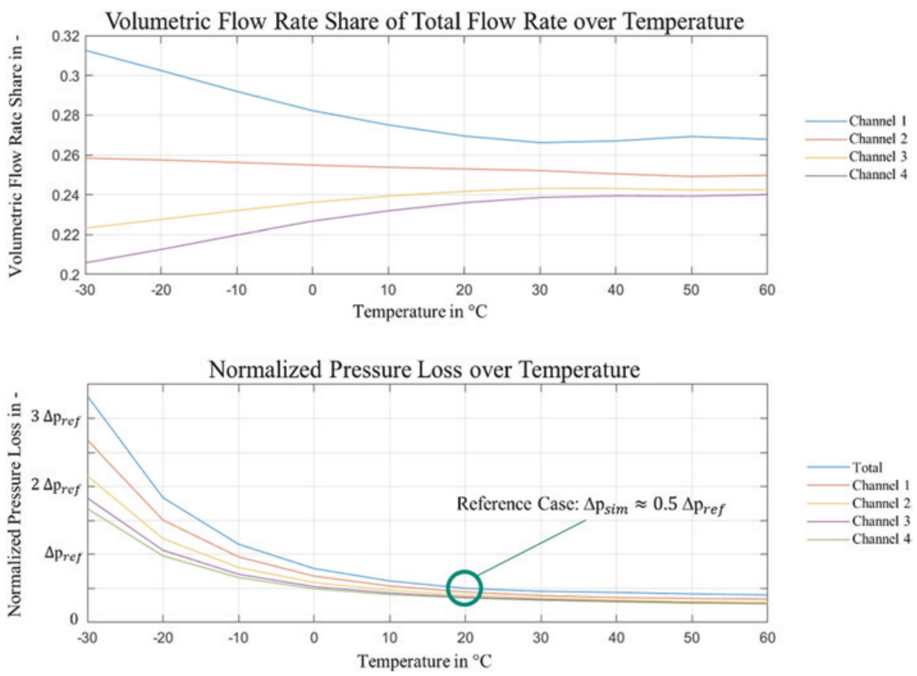

Fig. 5. 1D-simulation result for the final geometry at reference flow rate

Another interesting find was the overall robustness of the system's volumetric flow distribution over the full range of temperatures and total flow rates. With the final chosen geometry parameters, the volumetric flow rate changed by no more than 5% of total flow rate and all channels were staying in the range between 20% and 32% of total flow rate, with the first one (in the direction of flow) always having the highest flow rate. The results are shown in Fig. 5 for the reference volumetric flow rate.

Pressure losses were naturally more sensitive to changes in temperature and total flow rate, rising significantly for low temperatures and/or high flow rates.

From all of these observations, the rules for design for this case could be derived: The duct diameter needs to be as large as possible to minimize pressure loss and prevent distribution imbalance. The upper boundary is given by available design space, light-weight design principles and a diminishing return on increasing the diameter beyond a certain point. The branching off diameters should be chosen as small as possible without increasing the overall pressure loss to critical levels. Finally, the ratio between the two diameters needs to allow for even flow distribution between all channels.

Eventually, the final validation with a 3D-simulation again showed excellent comparability between 1D and 3D with less than 5% relative error for pressure losses.

4 Conclusion

The performed research clearly highlights the advantages of simplified simulations to perform full factorial case studies. For the given problem, an error due to simplification is to be expected. Nevertheless, use of an initially verifying and finally validating more precise simulation renders the whole approach feasible and allows for good prediction of the system behavior while taking advantage of low simulation times.

In this particular research, there was no direct coupling between the 1D- and 3D-simulation, therefore, parameters needed to be exchanged manually and models needed to be created from scratch for every geometry. More extensive case studies would therefore benefit from a directly coupled simulation, where modelling is automated and the iterations are triggering each other, when certain criteria are met. This leaves room for improvement of the methodology for future research.

Overall, the discussed approach underlines the importance of early verification and validation in the design process to narrow down the solution space to the most promising solutions quickly. On the other hand, as described with the failed first verification of the 1D-model, constant evaluation of simplification steps is of major importance as to not base the whole development on wrongly or hastily drawn conclusions or invalid simplifications.

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