SIMULATING THERMAL MANAGEMENT OF BATTERY MODULES FOR THE PROPULSION OF HYBRID VEHICLES

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Abstract

The coupling of 1D and 3D Tools is gaining constantly more applications in automotive development processes. This paper demonstrates the possibility to couple the 3D Computational Fluid Dynamics (CFD) tool FLUENT with the 1D Software KULI to simulate the thermal management of battery modules for the propulsion of hybrid vehicles. One of the most important aspects of hybrid vehicles is to ensure the cooling of the propulsive components (electric motor and converter) and the battery module. The durability of each cell of the battery module strongly depends on the temperature rise during the charging- and discharging process. Hence the behavior of the entire battery module was simulated and optimized prior the availability of hardware components using both 3D and 1D tools. The optimization process aimed at restricting the temperature range of each cell to a reasonable level.The Heat Transfer Coefficient (HTC) of the cells was calculated with FLUENT and used to simulate the transient behavior of the module with KULI. A transient charging and discharging cycle was used to simulate real driving conditions. The focus was laid on comparing different cooling strategies (air and water cooling) with respect to efficiency and feasibility. Moreover the heat-up of the cell itself was simulated and the results were compared with measurements, showing good agreement.

Keywords: CFD simulation, Hybrid vehicle, Battery cooling, Coupled simulation

Presenting Author's biography

Christian Kussmann received his master degree from the university of applied science in Graz, department automotive engineering in 2002. Directly after his study he entered Magna Steyr, where he was working in the field of CFD and 1D simulations. In 2006 he became the groupleader of the department "Thermal Simulations and Aerodynamics". His interests are complete vehicle simulation, coupled simulation techniques, the thermal management, hybrid systems and aerodynamics.

1 Introduction

The hybrid vehicle segment is a rapidly growing niche market. Apart from increasing the fun factor and producing 'emotional' vehicles, the main reason why OEMs are diving hybrid development is the current legislation. MAGNA STEYR has also responded to these trends by developing hybrid modules and hybrid vehicle control units within the framework of its hybrid program.

Hybrids efficiently combine an internal combustion engine with an electric motor. Energy which is normally wasted during coasting and braking is converted into electricity, which is stored in batteries before it is needed by the electric motor. The hybrid vehicle can be used in various different operation modes, such as running on the internal combustion engine only, just with the electric motors, in hybrid or regenerative mode [2]. The live time of the electric components strongly depends on the temperature range the cells undergo. Hence the need for an effective cooling system is crucial and jointly responsible for the customer satisfaction.

The current study reveals possibilities to realize the aforementioned cooling, using high-end simulation tools for both 3D and 1D aspects. This thermal simulation of the energy storage system is a key example of a virtual development process [2]. The coupling of FLUENT and KULI, employing the strength of both of them, leads to a global understanding of the influence of various parameters like cooling fluid mass flow, heat production of the cells or reaction of cyclic charging and discharging.

2 CFD Simulations

All CFD Simulations in the framework of these studies were performed with FLUENT. The goal of the simulation is to get an impression of the behavior of the cooling medium on the one-, and to calculate physical quantities like the pressure loss of the system on the other hand. Moreover simulations to investigate the transient cool down and heat up of the cells itself have been performed.

2.1 Validation of the simulation model

Despite the remarkable progress that has been made in numerical simulation technologies in recent years, the accurate calculation of heat transfer coefficients (HTC) is still no trivial task. In order to validate the meshing and solution approach for handling problems including convection, a simple test case was used and compared with theoretical models.

In order to ensure good results, the focus was shift on adequate wall treatment for all problems. As found in preliminary studies, the Enhanced Wall Treatment combined with y+ values close to one are the optimal choice for predicting the HTC.

2.1.1 Transient behavior of the cell

To investigate the behavior of the cells interior, heat up and cool down simulations of the cell itself have been performed and compared with measurements, showing good agreement. The battery systems use the powerful lithiumion chemistry since that type has a higher power density than the standard nickel-metalhydrid batteries [3].

The cell is build up in the following way: The liquid electrolyte core is wrapped with positive and negative electrode layers which are disconnected by a separator. The electric components are placed in a aluminum casing, see Figure 1. The simulation model aims to reproduce the physical properties of the cells as realistic as possible. The electrode layers are modeled as solid media with different thermal conductivity coefficients λ in axial and radial direction to account for the anisotropic material.

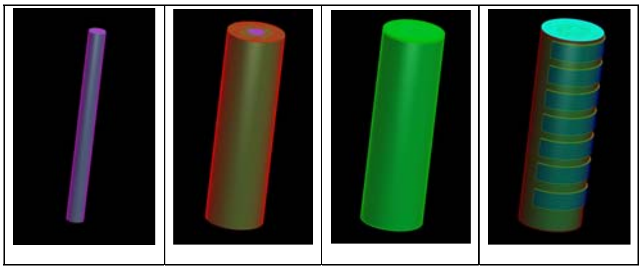


Fig. 1 Build up of the Lithium-Ion Battery simulation model including the electrolyte core, the wrapped electrode layers and the aluminum casing.

The validation of the used model was performed by measuring the heat up of the cell when exposed to a constant heat introduction without cooling. Therefore a resistance wire is wrapped around the cell which is placed in an isolated box to avoid cooling from the ambient air, see Figure 2. The resistance wire introduces a co The validation of the used model was performed by measuring the heat up of the cell when exposed to a constant heat introduction without cooling. Therefore a resistance wire is wrapped around the cell which is placed in an isolated box to avoid cooling from the ambient air, see Figure 2. The resistance wire introduces a constant heat flow volume, the heat up of the cell is measured at different locations on the aluminum casing. Measurements are performed for two cell configurations, one with the original, working battery and one with an opened cell where the electrolyte fluid has been removed.

The results of the validation can be seen in the following figure. Changes made in the simulation model - the radial thermal conductivity coefficient was varied - lead to small variations of the final temperature.

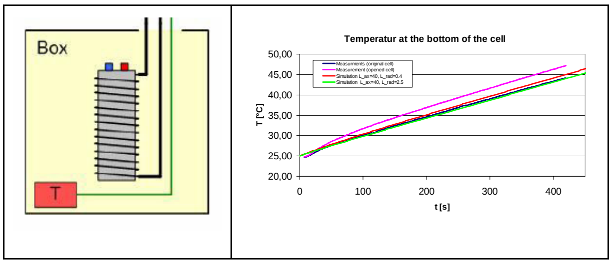
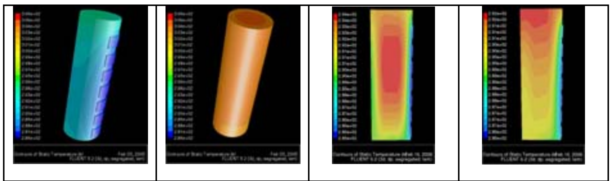


Fig. 2 Measurement set up (left), Results of the measurements/simulation for a heat flow volume of 18W (right). The simulations correlate with the measurements, especially the comparison with the original cell is good.

2.2 Preliminary study of different cooling strategies: Bottom vs. side cooling

The following simulations aimed to compare different cooling strategies. Due to the an-isotropic material properties of the cell, it is not clear if cooling of the bottom of the cell, or cooling of the side walls is more efficient. Therefore simulations have been performed to compare the state of stability for both strategies when a heat amount of 10 W is introduced in the cell and a convective wall boundary condition with a given HTC and a free stream temperature of the cooling fluid is applied. The results show that side cooling is the better choice, since the resulting average cell temperature is lower, and the temperature range is less as well. The results of the simulation can be seen in Figure 3.



Side cooling	Bottom cooling	Side cooling	Bottom cooling

Fig. 3 State of stability temperatures for side and bottom cooling strategy. The resulting temperatures are better for side cooling.

The side cooling approach is further investigated if different cooling fluid mass flows are applied which leads to varying heat transfer coefficients. Therefore a transient cycle (US06, Pavg=580mW) of heat introduced in the cell is set as volume boundary condition. The convective wall boundary condition with different HTC values, calculated from different cooling fluid mass flows, is set at the side wall of the cells. The temperature of the cooling fluid is 303 K. Moreover a simulation without cooling, and a simulation with optimal cooling, where a wall boundary condition with 303 K is applied, is performed. From the results it can be concluded that the cooling for a realistic cooling fluid mass flow is close to the optimal condition. The results for different HTC values do not differ dramatically, hence a sufficient cooling of the cells can be assured for less mass flows as well. Detailed results of these simulations can be seen in Figure 4 and Figure 5.

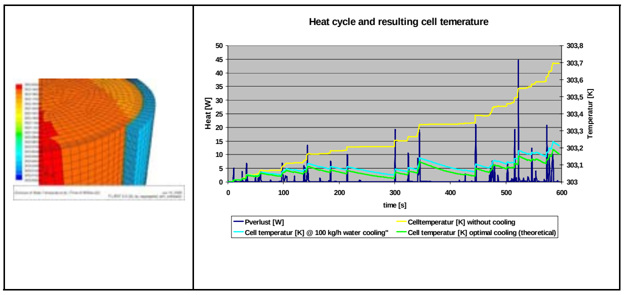


Fig. 4 Surface temperatures at the end of the cycle (left). Comparison of cell temperature for a case without cooling, with a realistic HTC and a cooling fluid temperature of 303 K and a case with the theoretical, optimal cooling (wall temperature 303K).

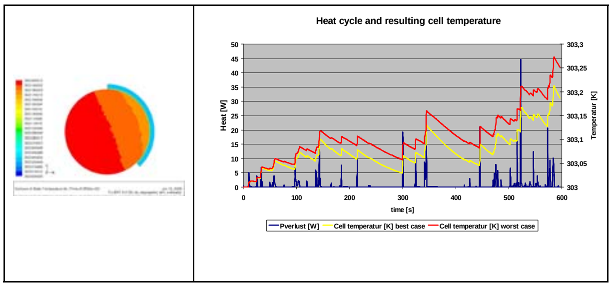


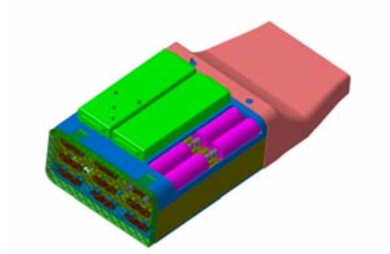
Fig. 5 Temperature in a plane cut Transient cell temperature for two different cooling fluid mass flows (right).

2.3 Realization of side cooling strategies

Since the side cooling strategy was found to be more efficient, various possibilities to realize this battery cooling approach in a hybrid electrical vehicle have been developed and evaluated. In the following section, one representative solution will be presented, starting with principle investigations using CFD. Furthermore the need for the coupling with KULI and the outcomes of this studies will be presented.

The geometry including the cells can be seen in the following figure. The cooling air is taken from the interior of the car to provide a constant temperature and ensure a quick cooling down of the air if the vehicle is exposed to high temperatures.

For the meshing process, the MAGNA STEYR tool SPIDER is used. SPIDER enables the engineer to create high qualitative hybrid meshes in a minimum of time. The robustness against low-quality CAD data yields to an effective and fast meshing process.



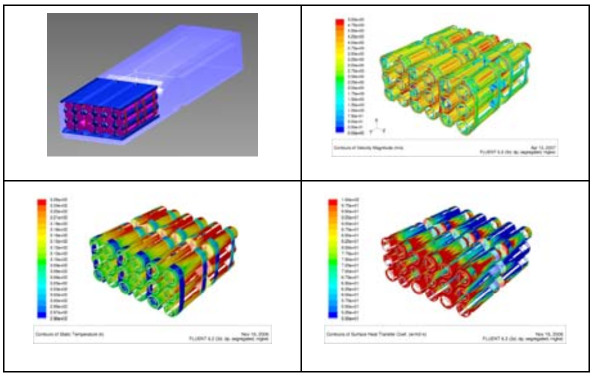
Fig, 1 The geometry consists of a channel, including brackets which secure the cells (pink) and nozzle with guiding vanes to route the cooling air to the outlet.

To calculate the pressure loss of the system, respectively the heating of the cooling air, simulations with four different cooling air volume flows (110, 82,5 55 and 27,5 m³/h) and two different heat flow volumes from the 36 cells (8W/cell respectively 10W/cell) have been performed. The air guidance through the system aims to ensure uniform flow velocities on the cells in order to provide equal cooling of the cells and avoid internal variations in temperature.

As already stated above, the RNG k-epsilon model and enhanced wall treatment in combination with a very fine mesh resolution is the best choice to calculate heat transfer. The y+ values for the boundary layer need to be close to one for this purpose.

For the calculation of the heat transfer coefficient, the reference temperature was set to the mean air temperature of the domain around the cells. Due to the heating of the air, the HTC is not constant for the cells. Therefore the mean HTC is used for the 1D simulations with KULI, where the behavior of the complete battery system, when a varying heat flow volume is radiated by the cells, can be simulated.

The following figures give an impression of the flow though the system. The surface velocities are uniform, a constant cooling of the cells, without dramatic differences between adjacent cells can be assured.



Fig, 2 Impressions of the flow and the heat up for 110 m³/h air volume flow and 10W/cell heat input

The following tables compare the theoretically calculated results for the heating of the cooling fluid with the results obtained with CFD. The temperature T1 is the averaged temperature on a surface behind the cells.

Summary		CFD		Theory	
		8 watt/ cell	10 watt/ cell	8 watt/ cell	10 watt/ cell
Volume flow [m³/h]	Pressure loss [Pa] from CFD	T_{avg} °C	T_{avg} °C	T_{avg} °C	T_{avg} °C
110	170,8	32,2	34,6	30,6	32,6
82,5	111,6			33,2	35,7
55	63,4	41,7	46,4	38,3	42,1
27,5	25,6			53,6	61,2

Table 1 Calculated pressure losses and warming of the cooling air

3 Coupling 3D CFD with 1D KULI

Since the performance of transient CFD Simulations for a cycle is not feasible, the CFD simulations are coupled with KULI, a 1D software tool for vehicle thermal management optimization to calculate transient cell surface temperatures. Therefore a certain number of iterations between FLUENT and KULI is needed to obtain satisfying results. The average surface HTC is calculated with CFD for different cooling fluid mass flows and various quantities of heat, produced by charging and discharging of the cells.

The 1D simulation on the other hand provide the time dependent cell surface temperatures that can be used as input for the next 3D CFD run to update the heat transfer coefficient. After a few iterative cycles, this leads to results with appropriate accuracy. In comparison to an unsteady CFD simulation of the complete module, the described approach substantially reduces simulation time.

To validate the KULI model, the cell temperatures for a defined charging and discharging cycle, which is run several times, are compared to CFD results. In KULI, the cell itself is represented by two point masses that are connected with a thermal conductivity component.

On the one hand this allows heat conduction in both directions and on the other hand the cell's thermal lag is also modeled appropriately. The final 1D simulation model of the entire battery module consists of the individual cells, piping and tubing, heat exchanger and coolant pump [2]. The results of this validation process are presented in the following figure:.

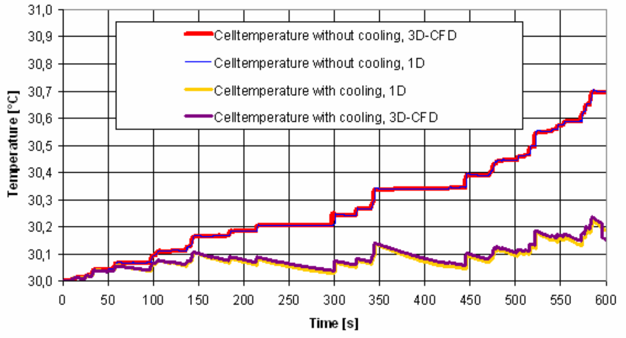


Fig. 8 Comparison of 1D and 3D Simulation. Both cases, one with and one without cooling, reveal that the use of 1D KULI to complement CFD simulations leads to excellent results

As already stated, each individual cells service life depends to a great extent on the temperature level during operation [2]. The cells should be operated in a temperature range which is below 45°C. If the temperature is between 45°C and 60°C, the operation of the cells reduces the lifetime, an operation above cell temperatures of 60°C is not recommendable.

Figure 9 shows the cell response during heating up and cooling down for different initial conditions (30°C and 65°C). The orange line represents the cooling down if the cells are inactive.

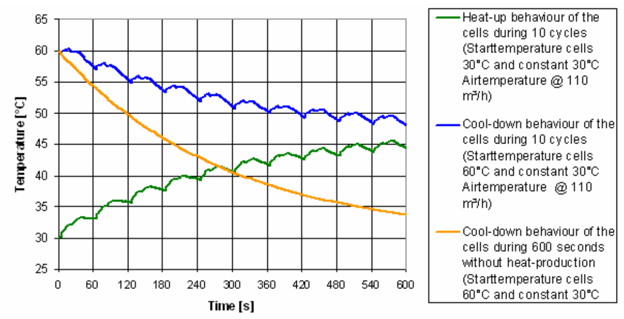


Fig. 9 Comparison of heat up and cool down behavior for a constant coolant temperature of 30°C and a constant mass flow.

Figure 10 compares the cooling down and heating up during cyclic loading and unloading when a realistic cool down behavior of the interior is assumed. The starting temperature of the coolant (orange line) is 60°C.

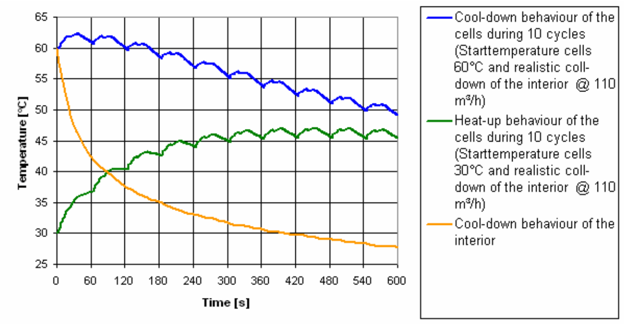


Fig. 10 Comparison of heat up and cool down behavior for a realistic cool down behavior of the passenger compartment.

4 Summary and Outlook

The coupling between the 3D CFD Software FLUENT and the 1D tool KULI to efficiently reduce simulation time within the virtual development process was presented. Physical quantities, predicted with CFD, are used as input and starting values for transient simulation runs with KULI. Several iterative loops finally led to results with appropriate accuracy.

The comparison with measurements of the heating up of the cells was presented, showing the excellent agreement with simulations. Validation of the complete system are important tasks to be done in future to compare and improve the simulation model.

5 References

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