

Electro-thermal simulation of Lithium Ion battery for EV/HEV applications

L. Kostetzer; S. Nallabolu; E. Rudnyi; L. Krüger, CADFEM GmbH,
Grafing bei München, Germany

M. Geppert; D. Quinger, LION Smart GmbH

Abstract

Highly power energy storage systems are necessary for the new age of electric vehicles. Lithium ion batteries have the advantage of high energy density, good aging characteristics and high efficiency, but at the same time the thermal range of operation is limited. By temperature under 0°C, the power capacity of the lithium battery is reduced about 70% and by temperature over 40°C irreversible damage (over 70 °C also thermal runaway) could happened. Hence an efficient and accurate thermal management is necessary.

A battery cooling system is analyzed and designed with aid of numerical tools; we propose a modeling methodology starting with CFD and ending at a low dimensional but accurate compact thermal model for system level simulation. This model is ready to be coupled with other physical domains like electrical, chemical and mechanical. Detailed CFD simulation is performed to analyze the air flow over corrugated channels. Heat transfer coefficients are calculated with CFD and then used in a finite element (FEM) thermal model of a Li-Ion battery pack with one-dimensional flow (FLUID116). After that model reduction produces a compact thermal model for system level simulation.

Our electrical Li-ion battery model is based on work [9] and it can be classified as semi-physical. It is based on electrochemical equations developed by the group of Prof Newman [13] but with simplified assumptions to speed model simulation. The parameters of the model still have some physical meaning but they should be determined during a parameterization procedure. The battery model is developed in VHDL-AMS that make it simple to use it in many different environments.

Introduction. Electro thermal simulation at system level

Electro thermal simulation describes the interaction between electrical and thermal components. Electrical circuits are temperature dependent and at the same time the circuit produces power dissipation. On the other side, the thermal subsystem takes power

dissipation and evaluates temperatures in the system according to the heat transfer laws (see Fig 1).

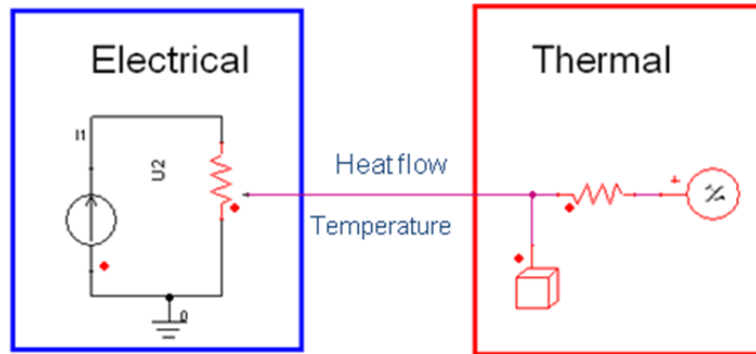


Fig. 1 Simple electrothermal simulation

As a simple example, let us take a temperature dependent resistance shown on the left in Fig 1. When the current passes through the resistor, it generates heat that in turn goes through a thermal mass and thermal resistor (on the right in Fig 1). The temperature of the system goes back to the electrical model of the resistor and thus we have two-way coupled electrothermal simulation.

The thermal model in Fig 1 is pretty simple and the question arises how one can develop it in the general case. Finite element modeling would be the best solution because with available software thermal modeling has already become a routine procedure. In principle, one can directly convert a thermal model into a circuit model. After the discretization by the finite element method one obtains an equation that can be considered as an electrical network where the vector T will be equivalent to unknown voltages, the matrix E will be a capacity matrix and the matrix K the resistance matrix.

$$ET + KT = F \quad (1)$$

The problem along this way is that the vector T is usually high-dimensional, say several hundred thousand degrees of freedom, and hence the Eq 1 is not compatible with system level simulation because of its large dimensionality.

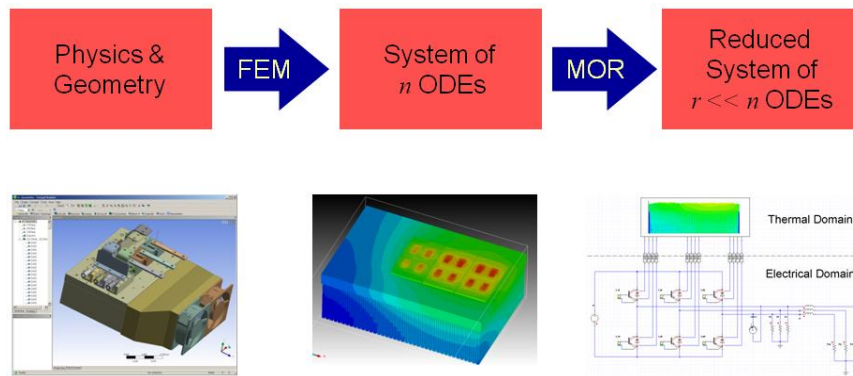


Fig. 2 The idea of model order reduction

Model reduction [2] allows us automatically to reduce the dimension of Eq 1 preserving at the same time good accuracy of the dynamic response (see Fig. 2). The reduced thermal model now can be used in a system level simulation to integrate to another domains e.g. electrical cell models, vehicle dynamics and power electronics. We apply model order reduction in order to develop a compact thermal model of a real battery pack in this work.

In a battery pack the cooling process is mainly done by conduction and convection phenomena. With a thermal model described by equation (1) the convection is defined by a boundary condition with the convection heat transfer coefficient or simply the film coefficient. The film coefficient can be obtained by using correlations, yet it may not be accurate in the case of complex geometry. In this work we use computational fluid dynamics to evaluate the film coefficient.

The finite element of the battery pack is briefly described in the next section. After that a CFD methodology is presented followed by a comparison with a finite element thermal model of the cooling channel. Finally the finite element thermal model is reduced to a system level by model order reduction and coupled with an electrical model of the battery cell model in Simplorer.

Battery pack thermal model

The finite element model of a battery pack has been developed by the company Lion Smart in ANSYS [3][4] (see Fig. 3). The model consists from 33 individual batteries that have been cooled through pipes modeled by means of one dimensional FLUID116 elements in ANSYS. The finite element model has the dimension roughly 50000 degrees of freedom and its transient simulation for 100 timesteps takes 40 min.

The convection boundary condition connects the fluid elements with the surface elements and consequently to solid elements that represents aluminum plates and battery cells. The film coefficient was evaluated by a CFD analysis of the detailed fluid flow geometry according to the methodology described in the next section.

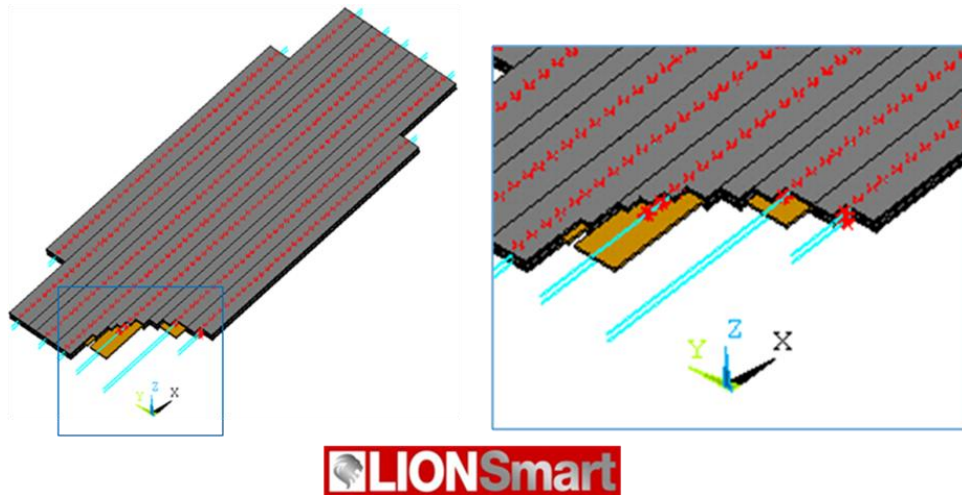


Fig. 3 The battery pack model (<http://www.lionsmart.de/>)

CFD of cooling channels

Cooling channels of the present battery pack have a sinusoidal cross section with metallic walls, see Fig. 4. Due to periodical and symmetrical pattern a simplified CFD domain is chosen, dashed area in Fig. 4. Battery (solid material) is also included to account for heat conduction.

Hybrid mesh with prismatic and hexahedron elements is generated in ANSYS meshing with small size hexahedrons in the boundary layer for higher accuracy in the film coefficient predictions (see Fig. 4 right).

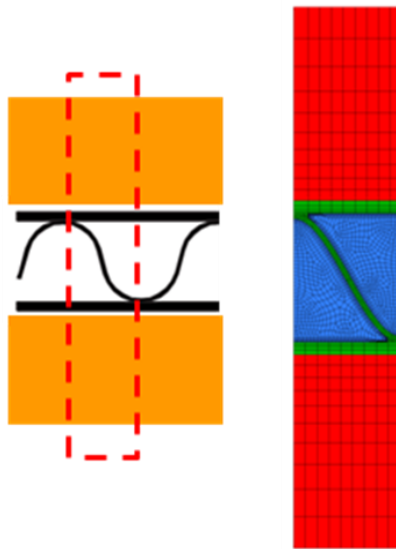


Fig. 4. CFD domain and mesh

A typical operation condition is with velocities around 10m/s for air cooling. The correspondent Reynolds number falls inside the turbulent region; in the order of 3000. The SST turbulence model is used due to good resolution of boundary layer effects and stability in the free stream region.

Heat generation is present in the battery region. The heat conductivity in the battery cells was modeled as orthotropic with lower value in the vertical direction of the cross section. Uniform temperature and velocity profiles are used for air inlet condition. The outlet is average constant pressure.

A steady state model with high resolution of advection terms is solved in ANSYS-CFX v12. The fluid flow and the thermal boundary layer are already fully developed in the first 1/3 of the domain, see Fig. 5 right.

Sinusoidal walls influence strongly the cooling effect of the air because the heat transmitted through the sinusoidal walls creates additional contact area for convection. This is helped by the good thermal conductivity of the aluminum. Just 30% of the heat generated is transferred to air by the upper and lower surfaces; inclined surfaces correspond to the complementary energy, which quantify the thermal effects of these walls.

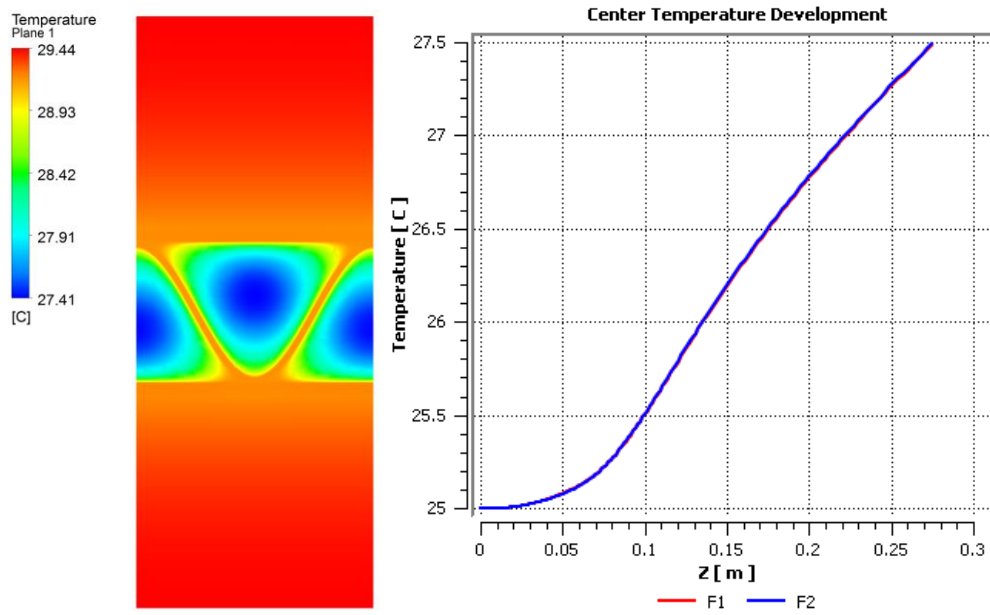


Fig. 5. Temperature field in the outlet (mirrored results) and temperature of air along the domain (channel center).

The definition of the film coefficient is an engineering decision and in this case influences the finite element model that receives the film coefficient information (battery pack model and channel model). The effect of the sinusoidal walls is included in the film coefficient and then a discretization of those walls is not necessary in the FE model. Film coefficient is calculated by Equation 2 where the heat transfer of the wall is defined in the selected areas in the Fig. 6. An average in area is used for the heat flux. Temperature of the wall uses the same area and average. The fluid temperature is volume averaged. To exclude boundary layer developing effects the averaging formulas are applied in the selected region near the outlet, see Fig. 7. The average film coefficient is $164.4 \text{ W m}^{-2} \text{ K}^{-1}$.

$$h_{Ave} = \frac{-q_{Wall}}{T_{Wall} - T_{Fluid}} \quad (2)$$



Fig. 6 Area definition of the film coefficient



Fig. 7. Volumetric fluid location of averaging procedures for film coefficient calculation

Thermal modeling (FEM)

A comparison of the finite element model of the cooling channel with the CFD is needed to validate the film coefficient numerical experiment and to allow further use of the methodology in the battery pack thermal model.

The mathematical domain in the finite element thermal model is a simplification of the CFD domain, Fig. 4. Here the fluid flow is modeled by one dimensional elements and without sinusoidal walls. The convection boundary conditions are used with the film coefficient calculated in the CFD analysis. Air mass flow, inlet temperature and cell heat generation are identical to the CFD simulation. ANSYS FEM solver is used to solve the steady-state simulation.

Maximum and minimum temperatures in the cell material are selected to validate the cooling model. Results showed excellent agreement of the FE model and CFD (see Tab. 1).

Tab. 1 Thermal results CFD and Thermal model comparison

	CFD	Thermal
Battery, T_{\max}	29.41	29.41 (<0.1%)
Battery, T_{\min}	27.58	27.75 (0.6%)

Computational effort is drastically reduced in the FE model with the one dimensional CFD approach, here just energy equation is solved for the fluid and not conservation of momentum is accounted. FE mesh has $14 \cdot 10^3$ elements and the CFD $312 \cdot 10^3$. With smaller mesh and simpler model in the FE case it is expected a reduced CPU time, in this case is 15s. For the CFD simulation is necessary 4h and 40 min in the same hardware configuration.

Model Order Reduction

Model reduction is an area of mathematics that in other words can be referred to as approximation of large scale dynamical system [5]. Model reduction starts after the discretization of governing partial differential equation when one obtains ordinary differential equations (1). In order to use model reduction, Eq (1) is rewritten as

$$\begin{aligned} E\dot{T} + KT &= Bu \\ y &= CT \end{aligned} \quad (3)$$

The difference is 1) splitting of the load vector to a product of a constant input matrix B and a vector of input functions u and 2) the introduction of the output vector y that contains some linear combinations of the state vector that are of interest in system level simulation. Model reduction is based on an assumption that the movement of a high

dimensional state vector can be well approximated by a small dimensional subspace (Fig. 8 left). Provided this subspace is known the original system can be projected onto it (Fig. 8 right).

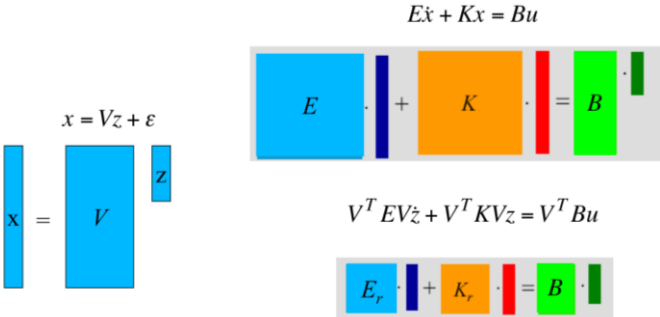


Fig. 8 Model reduction as a projection of the system onto the low-dimensional subspace

Theory of model order reduction is found in [2]. The dimension of the reduced model during the model reduction process is controlled by the approximation error specified by the user. Although the model reduction methods based on the Padé approximation do not have global error estimates, in practice it is enough to employ an error indicator [6]. In our experience it is working reasonably well for a variety of finite element models.

In order to employ model reduction in practice one needs software. The software MOR for ANSYS [7][8] reads system matrices from ANSYS FULL files, runs a model reduction algorithm and then writes reduced matrices out (see Fig. 8). The process of generating FULL files in Workbench is automated through scripting. The reduced matrices can be read directly in MATLAB/Simulink, Mathematica, Python, Simplorer and other system level simulation tools.

Battery pack thermal model at system level

The battery pack thermal model with film coefficient calculated by CFD is reduced to a system level with model order reduction. The system level model is coupled with an electrical battery cell model in Simplorer (see Fig. 9 left). For this case only three cells are coupled with the battery pack, other cells just produce constant 1W of heat.

A sub-circuit model describes the cell model (see Fig. 9 right). The electrical model is implemented in VHDL-AMS language based in [9]. The Lithium-ion cell is used and the model is described according phenomena described by Newman model (physical model) [10] using assumptions that reduce the final computational effort and the number of parameters [11], which we name by semi-physical model.

Kinetics of electrochemical reactions are modeled that translates to an overpotential which reduces the cell voltage (loss of energy), finally resulting in heat generation of the cell. The transport of Lithium ions inside the electrolyte is described by one dimensional diffusion-migration. Lithium diffuses inside electrodes diffusion limits can occur that translates in current limits or cell depletion.

The heat produced is mainly by joule effect in the electrodes and chemical reaction [12]. Physical properties are temperature dependent and values are taken from Dual Foil standard input [13].

The effect of discharge current is evaluated in 25Ah cells connected in series in 1,5 and 10 C-rates, see Fig. 10 and Fig. 11. Losses effects are present in higher currents showing a reduced total capacity and lower voltage, what can be observed in the voltage profiles, Fig. 10. Energy losses are transformed into heat and removed by cooling channels; the cooling conditions are made constant and the additional heat generated in higher c-rates is illustrated by higher temperatures in the battery cells, Fig. 11.

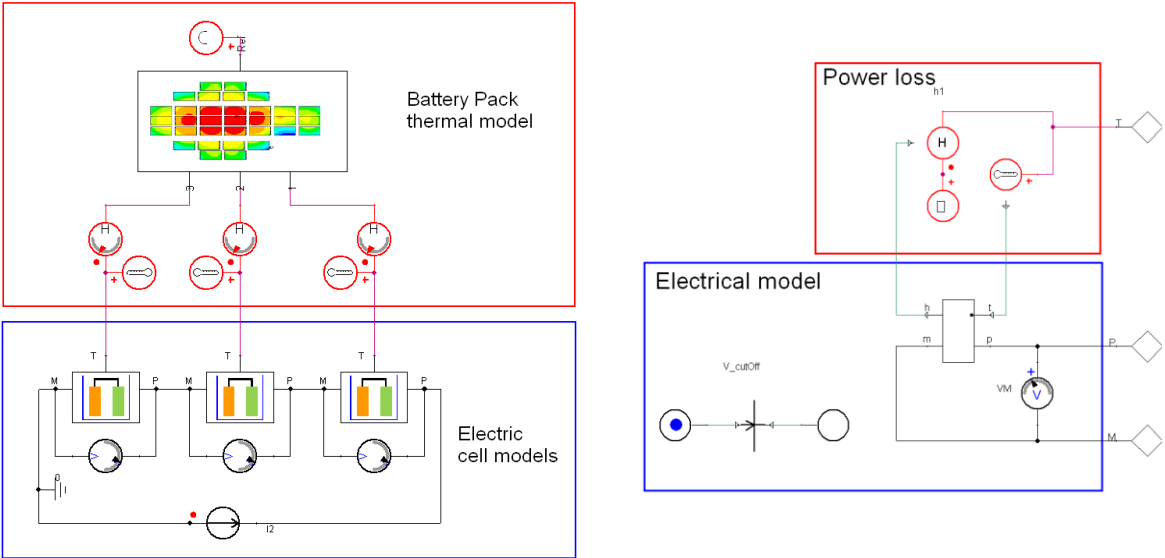


Fig. 9 Eletro-thermal battery coupling in Simpleror

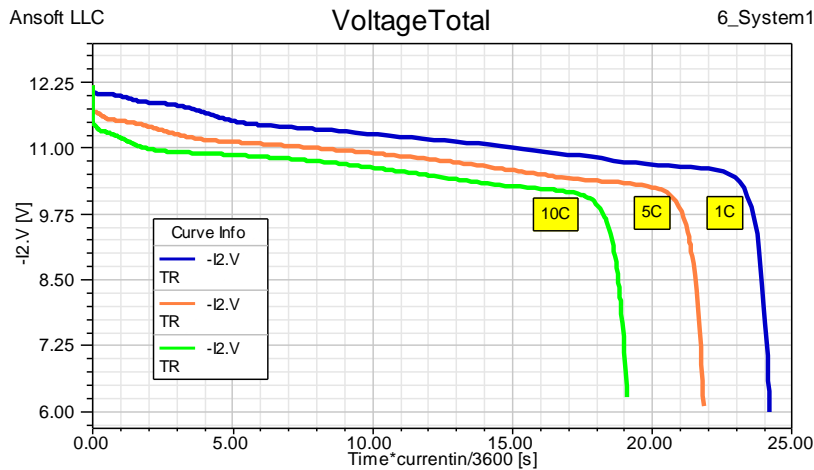


Fig. 10 Total voltage in constant current discharge

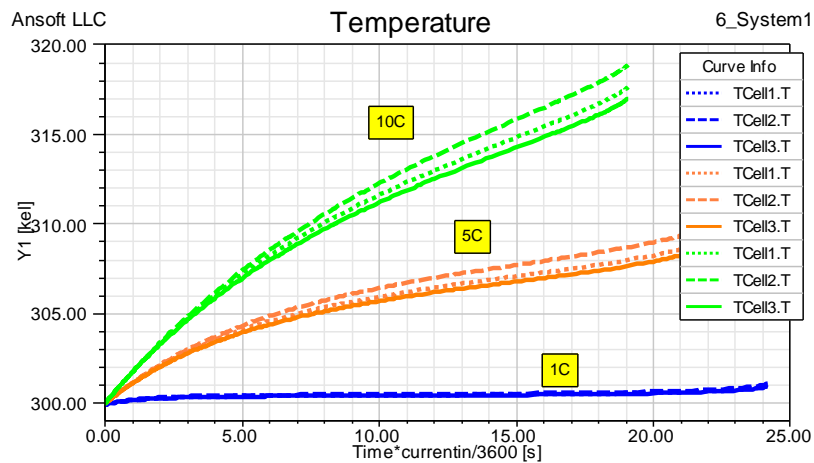


Fig. 11 Cell temperature response in constant current discharge cases

Conclusion

A solution of an accurate battery pack thermal model in the system level is presented. Spatial effects of cooling are taken to account through model order reduction techniques of the thermal finite element model. The FEM model is numerically validated by comparing to CFD simulation which provides heat transfer coefficients for FEM models. The battery pack model is integrated with an electrical semi-physical model at a system level simulator (Simporer).

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