Thermal Modelling, Simulation and Evaluation of a High Power Battery Cell for Automotive Applications

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***Abstract*—This paper deals with the thermal and electrical modelling and simulation of an automotive high power battery cell. The electrical modelling is implemented for determining the electrical losses. The electrical losses are converted to heat losses and therefore a heat flow in the cell. The thermal modelling is based on a 1D implementation by means of discrete volume elements. The resulting simulation model includes the thermal and electrical behavior of a high power cell. All simulation models of the investigated cell are implemented and developed in the simulation environment *Dymola*, using *Modelica* programming language, [1].**

Thermal and electrical measurements have been carried out to validate the simulation results of the thermal and electrical modelling. Three tests setups have been developed to measure electrical and thermal signals for determination of the parameters for the simulation model. The measurement and simulation results will be presented in this paper.

I. Introduction

At the moment electrical vehicles and electrical powertrain components are allocated in niche markets. However, they will considerably gain market share when electrical component development and production get cheaper. Furthermore the oil prize will increase constantly since global oil resources are said to go down and end soon. Full electric vehicles that could meet consumers' expectations are still far from realization since suitable electric energy storages that facilitate acceptable cruising ranges have not been developed yet.

Considering these facts, a thermal simulation of a high power cell was developed by *Austrian Institute of Technology* (AIT). Some simulations using the investigated high power cell will be executed and simulation results will be provided. The final thermal and electrical results of the high power cell will be compared with measurements.

The investigation of new vehicle components at AIT is based on the interconnection of three phases; simulation, methods and components and testing and validation. The development process starts with modelling and simulation of the thermal, electrical and mechanical sub-components as well as the entire vehicle. Subsequently, methods and components have to be developed and finally testing and validation on components and system level has to be carried out. Each thermal, electrical and mechanical component can be optimized, validated and realized very effectively using this process.

II. Simulation Environments

Libraries developed for simulations of automotive applications at the AIT usually are based on the *Modelica* simulation language. This libraries consist of elementary components for developing vehicle drive systems. Two simulation libraries, the *SmartElectricDrives* (SED) library and the *SmartPowerTrains* (SPT) library can be used to model the components of an electrical vehicle or vehicle systems.

SmartElectricDrives Library

The SED library is a tool for modeling, simulation and tuning of electric drives in electromechanical systems, according to [2], [3], [4]. This library is particularly designed for simulations of automotive applications with a *Modelica* development platform.

The SED library contains elementary components for developing drive systems and the powerful 'ready-to-use' models. These 'ready-to-use' library models include the characteristics of fully controlled modern electric drives in only one component. Furthermore, the SED library supports modeling and simulation on different levels of abstraction. The users can choose between transient and quasi stationary models. In the latter case, electrical transient effects are neglected.

SmartPowerTrain Library

The SPT library includes models and blocks for modeling and simulation of mechanical components of a vehicle, in this work were used only basic components from this library, according to [5], [6]. The library allows longitudinal dynamic simulations of vehicles. All driving effects such as aerodynamic and rolling resistances are included in models of this library.

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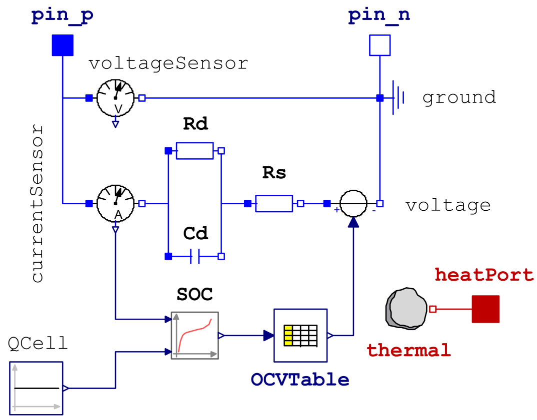

Figure 1. Simulation model of the high power cell in *Modelica*

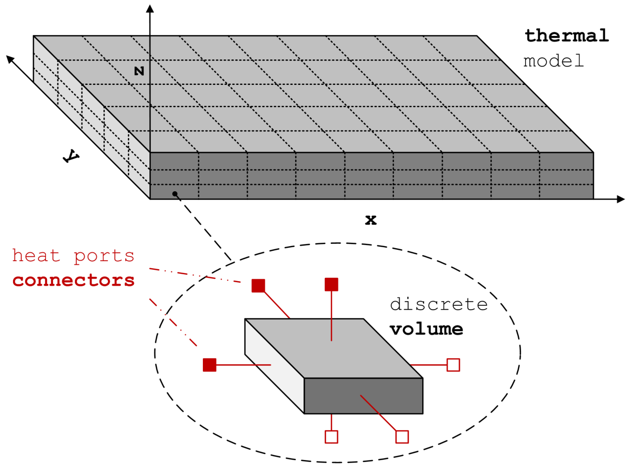

Figure 2. Thermal model of the high power cell in *Modelica*

Additionally, this library contains components for modeling and simulation of thermal effects of a vehicle. A virtual driver with operating strategy for controlling the acceleration pedal position, the brake pedal position and the clutch pedal position is implemented in this library, too.

The communication between these two developed libraries as well as the independent control of each model allows the highest flexibility in the design of new vehicle concepts. All 'ready-to-use' models from both libraries include a bus connector extended from *ModelicaStandard* library for providing external communication. This type of modeling allows a high harmonizing level between developed libraries.

III. Thermal and Electrical Model of the High Power Cell

The modelling was conducted in two steps. The first step is the electrical modelling of the high power cell. The electrical model of the high power cell comprises algebraic and ordinary differential equation. The electrical model of the high power cell is presented in figure 1.

The cell is modelled with two resistances (`Rs` and `Rd`) and one capacitor (`Cd`) model, they are connected with the positive and negative electrical pins (`pin_p` and `pin_n`) of the battery. The determination and calculation of the state of charge (SOC) is based on the integration of the battery current. The open circuit voltage (OCV) is provided as characteristic curve (`OCVTable`).

The second step is the thermal modelling of the cell. The model is developed by means of discrete volume elements, [7]. In this thermal model the coefficient of heat transfer for each discrete volume is calculated (`thermal` in figure 1), according to [8], [6]. The heat flow inside the high power cell was regarded in all three directions.

The model is parametrized using geometrical and thermal measurement data, such as thermal conductivity, specific thermal capacity, density and thickness of the layer materials (anode, cathode, separator, etc), etc. Heat losses in the `thermal` model are generated using equation (1).

$$\dot{Q}_{flow} = Rd \cdot i_{Rd}^2 + Rs \cdot i_{Rs}^2 \qquad (1)$$

Figure 2 shows the distribution of the discrete volume of investigated cubical-shaped cell in all three directions, `x`, `y` and `z`. The discrete volume number can be defined in each direction.

For investigation of the thermal behaviour of the battery package which includs cylindrical cells, first a detailed thermal model of one cell should be implemented. This base model includes the same equations and models as described in equation (1). The heat losses distribution of the anode and cathode in this cell is implemented homogeneously.

This heat flow in `x` and `y` direction, cross directions, has the same size and conductivity coefficents. Therefore the model of the cell is reduced from a $3D$ to a $2D$ problem. This reduced model of the cubical-shaped cell is used in this paper for evaluation of the simulation model. The discrete volume (`discrete volume` in figure 2) consists of six thermal connectrors (`heat ports`). In each direction exist two connectors to connect the discrete volume with the next.

Each of the connector includs two variables, temperature and heat flow rate. This connectors allow the heat flow in all three, `x`, `y` and `z` directions. The connvection to air (heat exchange with environment) is ensured based on connection the face discrete volumes with environment components using outside connector (`heatPort` in figure 1)

IV. Experimental Setup and Measurement

The thermal measurement was performed in three stages. The first steps includes the determination of the specific

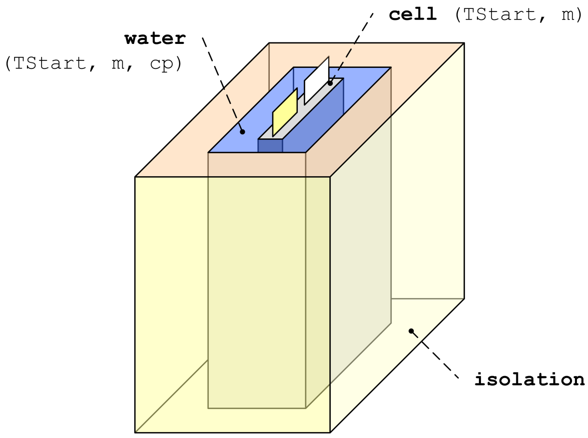

Figure 3. The testing scheme for determination of the specific heat capacity of the high power cell

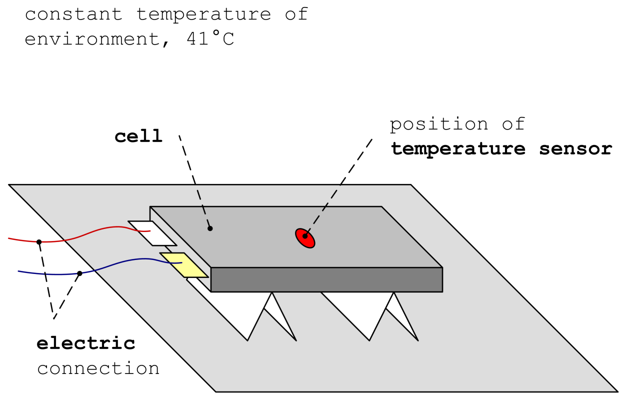

Figure 4. The testing scheme for measuring the heating of the high power cell

heat capacity. A cubical-box is build and bandaged with an isolation material (`isolation`), figure 3. This box is filled with water at a known temperature (in experimental sepup $20°C$). The water volume was exactlly defined.

The battery is cooled in a climate chamber to get a high temperature difference between water and battery. When the battery is immersed in the water a steady state temperature is approached. The stationary final temperature is then measured. These three temperatures (start temperature of the cell, T_{1c}, start temperature of the water, T_{1w}, and the stationary final temperature, T_{end}) can used to calculate the specific heat capacity, c_{pc}, of the high power cell, equation (2) and (3).

$$c_{pc} = \frac{m_w \cdot c_{pw} \cdot (T_{1w} - T_{2w})}{m_c \cdot (T_{1c} - T_{2c})} \tag{2}$$

$$T_{2w} = T_{2c} = T_{end} \tag{3}$$

The calculated specific heat capacity is used for parameterization of the thermal model of the high power cell in *Modelica*. This specific heat capacity was also compared with the data sheet of the cell to minimize the parameterization error.

The second step deals with the thermal measurement of the high power cell. The cell is inserted into a thermal chamber with a constant air temperature of about 41 °C. A thermal sensor is mounted on the cell face (`temperature sensor`), figure 4. During the measurement the thermal and electrical values like cell temperature, environment temperature, current and voltage are recorded.

With the third step the thermal conductances of the high power cell are determined. Three high power cells are stacked in a package. One temperature sensor is mounted on the cell face of the first cell and one temperature sensor on the cell face of the third cell to measure the temperature difference between this two faces.

The first cell was heated with a heat source. The heat flow of the heat source was constant. The third cell was cooled with a metal plate. The temperature of the metal plate was constant. Based on the measured temperatures and heat flow rate of the heat source was determined the thermal conductance of this three high power cells. Therefore the thermal conductance was re-calculated and prepared to characteristic thermal conductance of a material, in this case for high power cell in `z` direction (figure 2).

V. Simulation Results and Validation

For the validation of the high power cell model the measured and simulated values have been compared. Figure 5 shows the congruence between measured ($\mathtt{i}_{measured}$) and simulated ($\mathtt{i}_{simulated}$) current profile. The current profile for charging and discharging of the high power cell is used as a typical test profile. In this figure 5 are the both current profile the same. The current profile were depicted to verify that the current profile of the cell-testing bench and simulated current profile are the same.

The comparison of the measured and simulated voltages is presented in figure 6. It can be seen that the measured and simulated voltage correspond very well in the overall regarded time frame. This small deviation verifies that the quasi stationary electrical behavior of the high power cell was implemented in a satisfying way.

The transient electrical behavior of the high power cell was not modelled in this work. The transient modelling is not necessary to implement if the electrical model is only used for simulation the heat losses. The thermal time constants of a high power cell are relatively higher as the electrical time constants. The diference between the electrical quasi stationary and electrical transient modelling, in this case, is very low according to incluence of the simulated thermal results.

Afterwards, the simulation results of the thermal model were compared with measurement results. Figure 7 shows

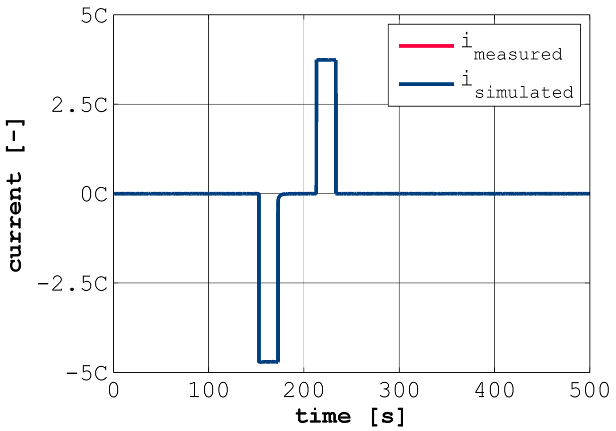

Figure 5. Measured and simulated current profile of the high power cell

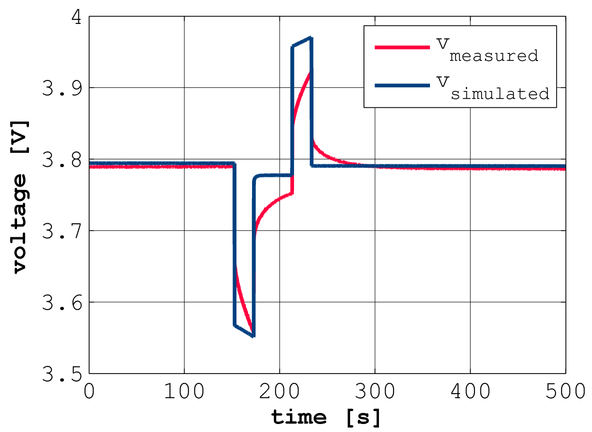

Figure 6. Measured and simulated voltage of the high power cell

the temperature profiles of the measured and simulated high power cell, where **Tambience** is the temperature of the environment, **Tmeasured** is the face temperature of the cell and **Tsimulated** is the face temperature of the simulated cell. The simulated temperature behavior is almost identical with the measured temperature. This good congruence between measured and simulated temperature of the cell proves that the thermal behavior of the high power cell was also modelled in a satisfying way.

VI. Conclusion

In this contribution an electrical and a thermal model of a high power cell were presented. The results of the distinct approaches were shown. Electrical and thermal measurements have been carried out to validate the simulation of the thermal modelling and were presented. The thermal model of the high power cell was implemented in *Modelica* and simulated using the *Dymola* simulation environment.

The described cell simulation allows the determination of the temperature behavior in a large number of applications. Due to accurate simulations a significant acceleration of the development process of electrical components

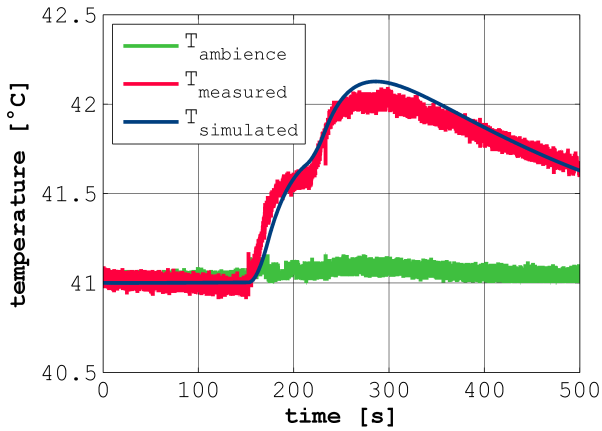

Figure 7. Measured and simulated temperature of the high power cell and measured temperature of the environment

has been achieved and effort and costs have been drastically reduced.

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Definition, Acronyms and Abbreviations

AIT	Austrian Institute of Technology
SED	SmartElectricDrives
SPT	SmartPowerTrains
SOC	state of charge
OCV	open circuit voltage