# Thermal FDM Battery Model

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## Motivation

The performance of lithium-ion batteries is very temperature dependent. Homogeneous battery temperatures of about 20…30°C are an ideal compromise between efficiency and durability. In order to develop optimized heating and cooling systems for lithium-ion batteries thermal simulation models are necessary.

## Fundamental Equations

Thermal battery models reproduce effects of heat generation and heat transfer. Heat generation comprises reversible heat, which is caused by entropy changes during charging and discharging, and irreversible heat, which describes Joule heating:

$$\dot{Q}_{irr} = \Delta U \cdot I \qquad (1)$$

Heat transfer inside the cell takes place according to Fourier's law of heat conduction. This leads to the governing equation of the thermal model [1]:

$$\dot{\vec{q}} = -\lambda \, \nabla T \qquad (2)$$

At the surface, there is interaction with the environment. Heat is exchanged by free or forced convection and radiation. These heat flows can be expressed by the following simplified equation [2]:

$$\dot{Q}_{env} = -h_{conv/rad} \cdot A \cdot (T - T_{\infty}) \qquad (3)$$

## Discretization

In order to solve Fourier's differential equation numerically, the cylindrical, prismatic or pouch cell has to be transformed into a mathematical model. Figure 1 shows the 1D, 2D and 3D discretization of a cylindrical battery. Each discretization element contains a heat capacity and heat conduction properties in the different spatial directions.

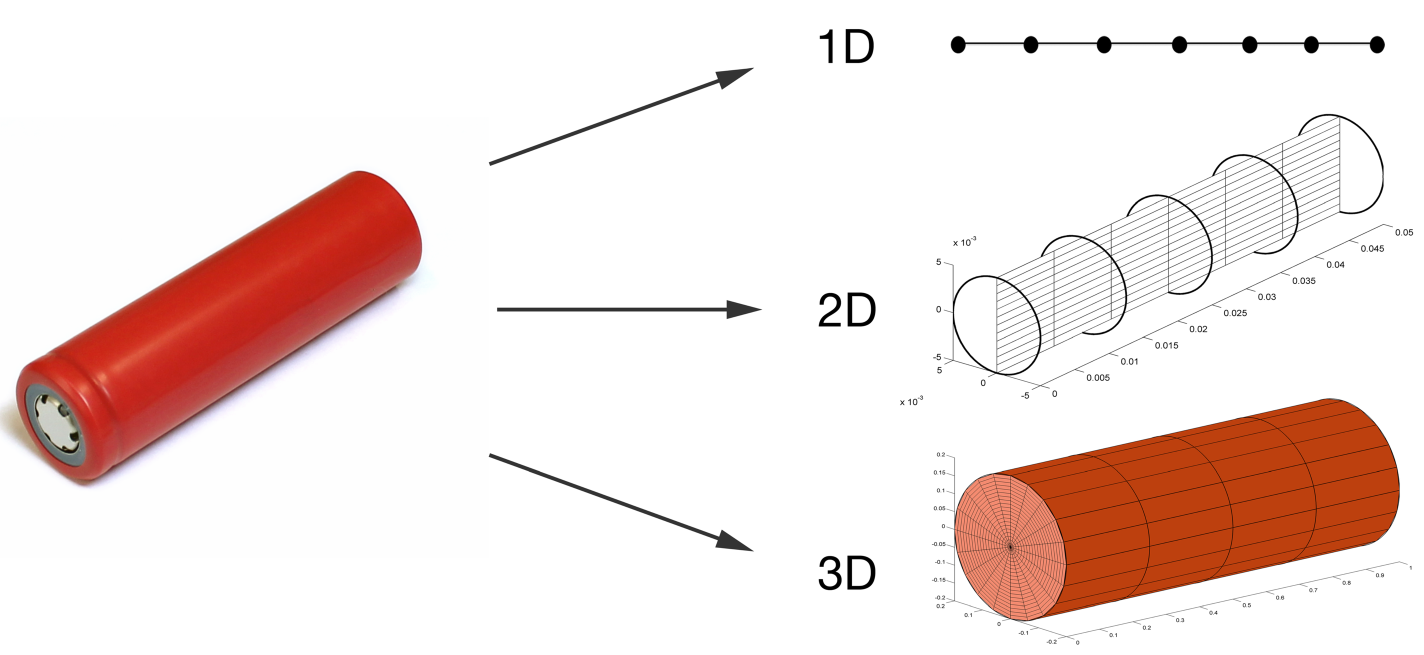


Figure 1: Possible discretizations of a cylindrical lithium-ion battery (1D-3D)

## Finite Difference Method

The Finite Difference Method is a common mathematical approach to numerically solve differential equations. Derivatives are approximated by differences between nodal values.
To approximate temperature gradients inside the battery, each discretization element contains a concentrated heat capacity in its center which represents the element's nodal temperature. Heat conduction can then be calculated from temperature differences between neighboring elements. Heat exchange with the environment is considered by appropriate boundary conditions (3).
Regarding the entire battery, this leads to the following linear system of equations:

$$\mathbf{C_p} \cdot \dot{T} = \mathbf{W_{cond}} \cdot T + \mathbf{W_{env}} \cdot T_{\infty} + \dot{Q}_{rev} + \dot{Q}_{irr}$$

with vector of element temperatures $T$, heat capacity matrix $\mathbf{C_p}$ (diagonal matrix), heat conduction matrix $\mathbf{W_{cond}}$, heat exchange matrix $\mathbf{W_{env}}$, environmental temperature $T_{\infty}$, vector of reversible heat $Q_{rev}$ and vector of irreversible losses $Q_{irr}$.

## Model Parameterization

Heat capacity, heat conductivity and heat exchange coefficients for convection and radiation have to be determined for the thermal battery model. This is performed either by applying an alternating rectangular current onto the battery until stationary thermal conditions have been reached or by Thermal Impedance Spectroscopy [3].
Irreversible heat is calculated from the difference between terminal voltage and equilibrium voltage multiplied by current [1]. For estimating reversible heat, constant current charging/discharging is performed. SOC dependent reversible heat is then calculated from a power balance which also includes irreversible heat, heat exchanged by convection/radiation and the amount of heat which is dissipated by a change in battery temperature.

## Results

Figure 2 shows the surface temperature of a high power lithium-ion pouch cell during constant-current charging and discharging with 2 C, 8 C and 4 C. Simulation results with and without reversible heat are compared to real measurement data. Good agreement between measurement and simulation can be achieved when reversible heat effects are taken into accout.

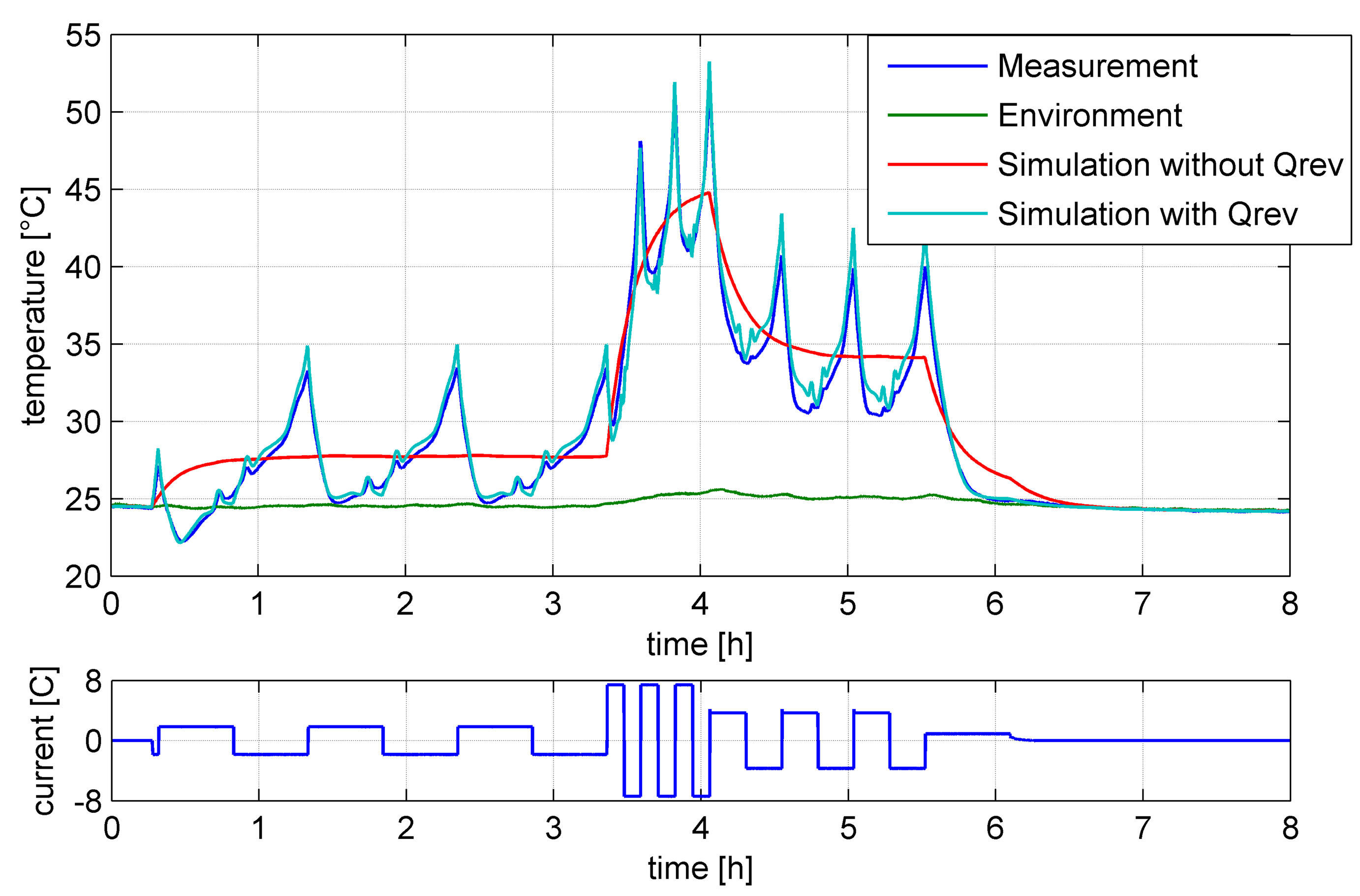


Figure 2: Temperature of high-power li-ion battery during constant-current charging and discharging with 2 C, 8 C and 4 C (3 cycles each)

The presented graphs clearly show that reversible heat has a significant influence on battery temperature at all current levels. Even at high currents of 4 C or 8 C, where irreversible heat is the major reason for temperature changes, reversible heat is not negligible.

Figure 3 visualizes temperature distributions inside a cylindrical cell.
The presented thermal battery model serves as a basis for analyzing temperature distributions inside single cells and entire battery packs. This provides information for an optimized design of heating and cooling systems which can increase lifetime of the batteries substantially.

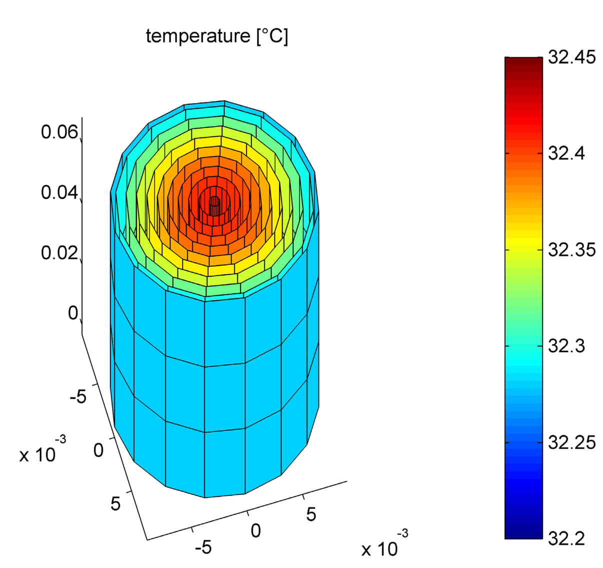


Figure 3: Temperature distribution

## References

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