

Power tool battery packs: shortening intervals of operation and charging by improved cooling strategy

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In the fast growing but also highly competitive market of battery-powered power tools short charging times are essential to achieve customer acceptance and to create unique selling propositions. To prevent loss of performance and fast charging capability due to cell aging, the knowledge of proper use conditions in everyday practice is important. In this study, a COMSOL model of an 18V power tool battery pack was developed to be able to evaluate different application scenarios of practical relevance. Hereby, a special focus was on the interaction of cell performance and cooling system. The simulation comprises battery models of commercially available 21700 cells as well as heat transfer models to evaluate the influence of different cooling systems such as phase change materials for latent heat storage. The model allows to quickly assess different operating scenarios and main influencing parameters and thus, to develop new cool down and fast charging strategies adjusted to different cooling systems and areas of application.

After high duty use phases, battery packs reach temperatures of more than 70°C. To prevent accelerated aging due to high temperatures in the cells in the following charging step, the pack manufacturers have to ensure that the cells in the battery packs cool down to a certain temperature before charging. This cooling step significantly prolongs total charging times. Consequently, reducing these downtimes in between high duty use and charging as well as improving fast charging strategies (which fit the used cooling system) can significantly reduce the total charging time and ageing risk. These improvements are therefore beneficial for customer acceptance (usability) and long service lives (guarantee and maintenance risk for the manufacturer).

The following use case was investigated: The fully charged battery pack was discharged with 50A to zero SOC (step A, resembles e.g. working with an angle grinder). After it has cooled down to acceptable temperature (step B, cool down step), a charging step with 1.5C (6A, step C) followed. The performance of four different cooling systems were compared: (I) Non-convective air (reference), (II) heat transfer polymer I, (III) heat transfer polymer II, (IV) latent heat storage materials (using phase change for cooling).

Introduction

Increasing power- and energy densities in modern Li-ion battery cells allow the electrification of energy intensive power tools like e.g. chainsaws, drilling hammers and angle grinders. However, these new application fields lead to new challenges for the cell pack design. Especially adequate cooling is of high importance during intensive use, which comes with high-energy consumption in very short time spans, and (fast) charging, as cells can get damaged if a certain temperature is exceeded during discharging or charging^[1]. For commercially available round cells like 18650 or 21700 format cells, which are used in most power tool battery packs, cell manufacturers provide, along with maximum currents, temperature ranges for charging and discharging to prevent short- and long-term damages of the cells. Power tool manufacturers have to ensure by pack design and management software, that these limits are not exceeded to guarantee safety and a long service life of the power tool battery pack.

Goal of this study is to set up a simulation tool, which can help power tool battery pack manufacturers to appropriately design battery pack cooling systems, which fit the requirements in terms of cell health and customer requirements. Special focus of the study was on shortening the use-charging cycle (figure

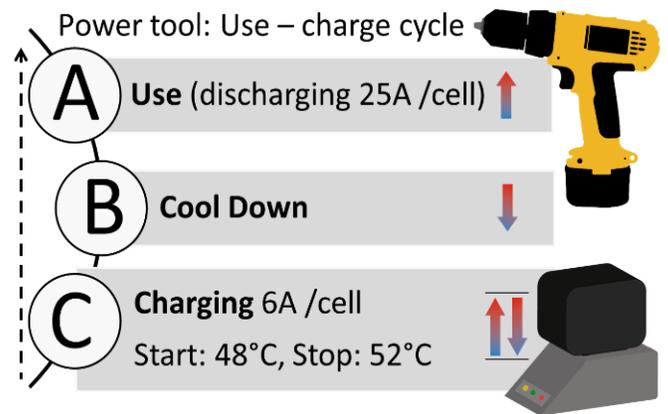


Figure 1. Use – charge cycle: While using the power tool, the battery pack is quickly discharged and heats up (Phase A: Use). After being totally discharged, it is then placed in the charging unit. However, before the charging can start, the cell pack has to cool down below the upper safety temperature limit (stop temperature) to prevent accelerated ageing of the cells (Phase B: cool down). This is controlled by the charging management system in the charging unit. At a certain temperature (start temperature, usually some degree celsius below stop temperature) set by the manufacturer, the actual charging starts (Phase C: charging). During charging the battery pack can heat up. If the upper safety temperature limit (stop temperature) is reached, the charging has to stop and cool down to start temperature.

1). This cycle resembles the typical use scenario of a power tool battery pack e.g. used by a professional worker working with the power tool at a construction site over several hours. It consists of intensive use (A), cool down (B) and charging (C). A long use phase is favorable for the customer. It is mainly limited by the pack energy density and size. However, phases B and C have to be minimized to guarantee an interruption-free workflow with low downtimes. Especially cool down intervals during phase B and phase C limit the use of the pack. It is the task of a good battery pack cooling system to minimizing these downtimes.

In most handheld power tool battery packs cooling is achieved by passive cooling systems, as active systems are in most cases too heavy and energy consuming. This study uses the COMSOL simulation tool to evaluate three different materials, which are used in passive cooling systems of battery packs in a typical use scenario and at normal, non-extreme ambient conditions. A material sweep study (variation of cooling material assignment) was undertaken and the suitability of the different materials for the task evaluated.

Computational Methods

A model of a 18V power tool battery pack was developed using COMSOL Multiphysics. A special focus was on the interaction of cell pack performance and cooling system and their practical relevance for pack design and customer experience. It comprises battery models of commercially available 21700 cells as well as heat transfer models.

Battery cell model

The “lumped battery model” provided by COMSOL was used to simulate the cell performance as well as the heating up of the cell pack (heat source). Key input parameters of the battery model are summed up in table 1. Cell parameters were deter-

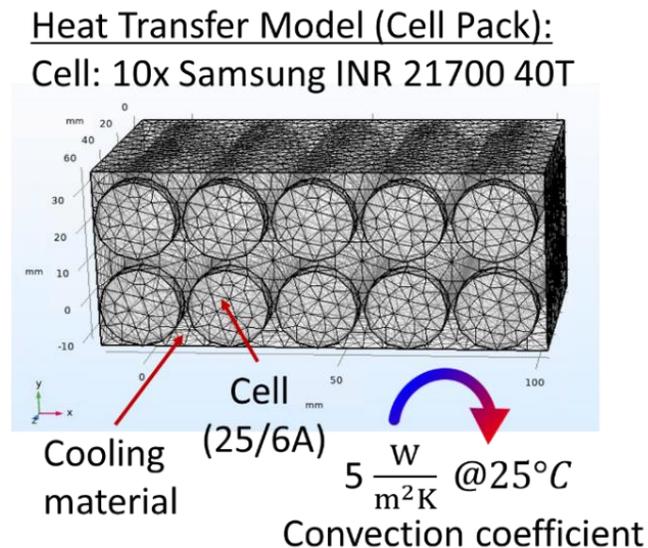


Figure 2. 3D geometry of the investigated power tool battery pack. Ten Samsung INR2170040T cells are enclosed in a matrix of passive cooling material.

mined by performing a parameter estimation study to fit experimental charge and discharge curves at different C-rates. The parameter estimation was supported by interpretations of EIS-measurements. A reasonable agreement of simulation and experimental data was achieved in terms of electrochemical and thermal behavior. An event interface was used to control battery mode (charging, discharging) and charging mode (CC, CV) with respect to state of charge. To link battery and thermal model an electrochemical heating coupling was used. Further documentation of the COMSOL lumped battery model and the used equations can be found in the COMSOL documentation^[2]. The electrochemical cell characterizations were carried out using a BaSyTec XCTS system and a Biologic VSP system in controlled ambient temperature (climate chamber).

Heat transfer model

The heat transfer model is set up in COMSOL by a simplified 3D geometry of the cells and the surrounding passive cooling system (heat transfer material) as depicted in Fig. 2. Heat transfer in the cells and the cooling material is computed by COMSOL heat transfer in solid materials. Heat loss to the environment is taken into account by a convective heat flux surface boundary condition at all surfaces with contact to air. Ambient temperature was set to 25°C and convection coefficient to 5 W/m²K (moderate air movement). Event interfaces were used to control charge stop at stop temperature and charge restart at start temperature. Non-convective air (as reference) and three solid passive cooling materials were investigated in this study. Table 2 sums up the key parameters of the materials. Phase change in the latent heat storage material was implemented by adapting the heat capacity of the material at melting/solidifying temperature. Further documentation of the heat transfer in solids as well as the convective heat flux surface boundary condition and the used equations can be found in the COMSOL documentation^[3].

Results & Discussion

Influence of cooling material (material sweep study)

The performance of three different cooling materials was investigated in the use (discharge) and cool down (Figure 3, a) as well as the charging phase (Figure 3, b).

Caused by the high discharge current, the cells quickly heat up in the **use phase (A)** and reach temperatures in the range of 70°C - 107°C. In the **cool down phase (B)**, during which no new heat is created in the cells, all four configurations cool down. Charging start temperature (cells have cooled down to 48°C) is attained after 51-90 min and room temperature after 170 – 190 min (see Fig. 3a).

The highest temperature in the simulation is reached with non-convective air (reference). Even though the temperature transport to the battery pack surface is high in comparison to the other materials, the system is not able to transfer enough heat in the use phase (A). In combination with the very low heat capacity, this leads to the very high temperature of 107°C in the cells at the end of discharging. This is far beyond the typical specification of commercially available cells. During cool down the cells cool down fast and room temperature is achieved after a time span comparable to the heat conductive polymers.

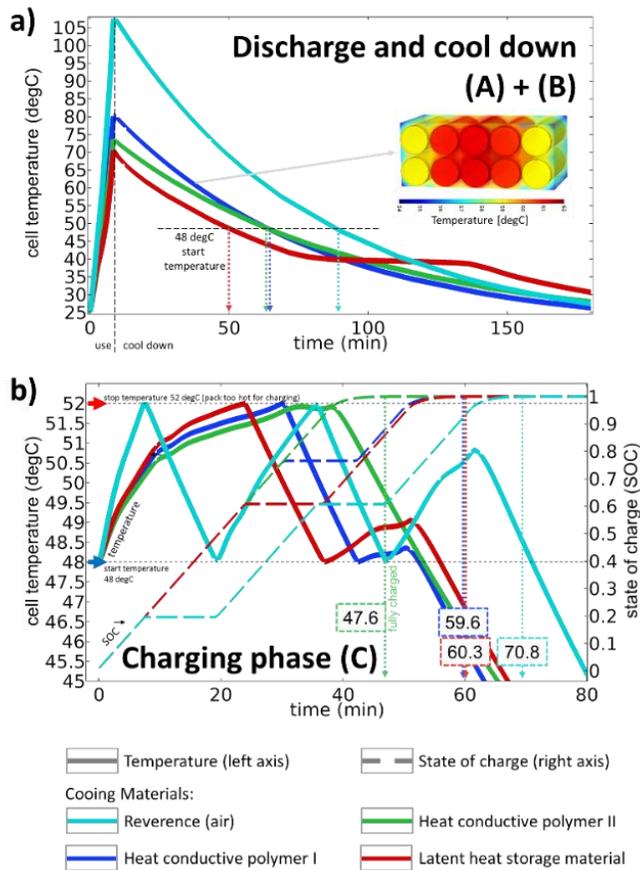


Figure 3. Influence of cooling material surrounding the cells in the pack. a) Use phase (6.25C=25A discharge) and cool down phase with different cooling systems. b) Charging (6A =1.5C) with different cooling systems. Charging starts as the battery pack has cooled down to 48°C (start temperature) and is stopped if the temperature reaches 52°C (stop temperature). Thick solid line: cell temperature (left axis); thin dashed line: state of charge (right axis).

However, it takes 90 min to cool down to the charging start temperature.

Heat conductive polymer I is characterized by high thermal conductivity but low heat capacity. With a peak temperature of 80°C it performs better in the use phase (A) than the reference system but worse than the other two solid materials. Even though the peak temperature is 27°K lower than the reference state, it is still too high for most commercially available cells and thus, the use of this system cannot be recommended for the investigated use scenario. Cool down takes place quick and thus charging start temperature is achieved after 65 min and room temperature after 170 min.

Heat conductive polymer II exhibits the lowest peak temperature (73°C) of all materials without latent heat storage (phase change). The high heat capacity is able to take up enough of the thermal energy created in during discharging in a short time span. Cool down by contrast is slower compared to the other materials. Charging start temperature is reached after 65.5 min and room temperature after 174 min.

The Latent heat storage material is able to absorb a certain amount of thermal energy by a phase change (solid to liquid) at 39°C. This significantly lowers the maximum temperature at

the end of the use phase. With this and the high specific heat it reaches 70°C only and outperforms all other materials, even though it has the lowest thermal conductivity. However, the thermal energy stored in the phase change is released during cool down and therefore prolongs the cool down to room temperature. Note, that if the transition temperature of 39°C is not reached in the cool down phase and thus, re-solidification does not happen, the latent heat is not available in the following use phase. Charging start temperature is reached in comparison with the other materials fastest after 51 min but room temperature after 189 min only.

Figure 3b shows the cell behavior during **charging (C)**. For the comparison, all materials start at the charging start temperature of 48°C (onset temperature of the charging unit at cool down) with 6 A charging. During charging the cells heat up until the upper safety temperature limit (stop temperature) of 52°C is reached. Charging pauses at this temperature to let the battery pack cool down until it has reached the starting temperature (48°C) and charging starts again.

In non-convective air (reference) the charging has to pause two times for 12 min each. Caused by the low heat capacity, it heats up quickly and therefore can only partly charge the cells in each charging step. The cells are fully charged after 70.8 min.

Heat conductive polymer I and Latent heat storage material are characterized by a comparable behavior during charging. For both configurations, charging is only interrupted once. Caused by the lower thermal conductivity, pausing takes place 6.5 min earlier in case of the latent heat storage material. The cells were fully charged after comparable time spans of 59.6 and 60.3 min. The latent heat storage effect has no influence on the charging process, as the melting point (phase change temperature) is lower than the start temperature.

Heat conductive polymer II is fully charged without interruption in 47.6 min. Even though the thermal conductivity (0.74 W/kgK) is close to the one of the latent heat storage material, the high specific heat can take up just enough heat that the cells do not exceed the stop temperature during charging. However, it has to be mentioned that the cooling system is very close to its limit.

Summary (material sweep)

For the investigated ambient temperature of 25°C and moderate air movement (convection coefficient 5 W/m²K), all systems struggle to transport the produced heat out of the system during the use phase. In particular, the heat dissipation of the packs by surface convection is too low and is most likely the bottleneck. Therefore, systems which can take up and store high amounts of thermal energy in a short time span, like the heat conductive polymer II (high heat capacity) and the latent heat storage material (heat is absorbed by the phase change) perform best and lead to the lowest maximum temperatures. The thermal conductivity of the materials is of minor importance in this step for the given conditions.

High specific heat is also beneficial when it comes to charging, as demonstrated by the behavior of heat conductive polymer II. The ability to absorb the heat has to be - in combination with the heat transfer - high enough that the cells can be charged without interruption. For heat conductive polymer II the given

conditions (charging rate, temperature and convection coefficient) are the limit for this system. If one of the materials properties were slightly less favorable for the cooling system, there would also be an interruption during charging and the charging time would be comparable to the other two solid cooling material. This clearly indicates that it is necessary to carefully design the pack cooling system, as small differences can significantly prolong or shorten the duration of charging. Operating conditions like ambient temperature and ventilation (convection coefficient) are of high importance.

Conclusions

A simulation model for evaluating the performance of handheld power tool battery pack cooling systems with passive cooling was established, highlighting the performance of three different solid cooling materials in a typical use cycle.

- Caused by the ability to quickly absorb high amounts of thermal energy, latent heat storage material performed best during the use phase (discharging) followed by heat conductive polymer II with very high heat capacity.
- For the charging phase, a suitable combination of high thermal conductivity and heat capacity is decisive. Enough heat has to be transferred away or absorbed to prevent reaching the stop temperature and shorten cool down phases. Heat conductive polymer II performed best during the charging step, as the charging was not interrupted by a cooling step.
- Compared to the reference scenario (non-convective air), a shortening of the charging up to 33% was achieved using heat conductive polymer II in the shown use case. For the whole use – charging cycle a shortening of 30% was reached using heat conductive polymer II and latent heat storage material (the latter for the first cycle only).

For future studies, it is planned to...

- validate the simulation model with experimental pack data and optimize the model.
- carry out a parameter study highlighting the influence of key parameters like e.g. ambient temperature, convection coefficient (ventilation) and start temperature on the performance of the cooling systems.
- include convective air or liquid cooling systems in the model (active cooling).
- implement temperature effect on the cell performance in the cell model.

References

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3. COMSOL Multiphysics, Reference Manual, *COMSOL 5.5 documentation* (2019)

Acknowledgements

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Table 1: Key input parameters of the cell model

Input parameter	Value
Investigated cell	Samsung INR21700 40T
Cell capacity	4.0 Ah
Number of cells in pack	10x
OCV-curve	Experimental measured
Voltage losses:	
Ohmic overpotential	18 mV
Activation overpot.	0.97
Concentration overpotential	Part. diffusion, 1000 s, spheres
Current discharging	25 A / cell
Current charging	6 A / cell
Charging modes	CC + CV
Voltage range	2.5-4.2 V

Table 2: Investigated cooling materials and their key properties

Material	Density [kg/m³]	Specific heat capacity [J/kgK]	Volumetric heat capacity [J/m³K]	Thermal conductivity [W/mK]	Melting point [degC]	Heat of fusion [W/kg]
Reverence (non-conv. air)	COMSOL database "air"				-	-
Heat conductive polymer I	1540	1470	2263800	2.2	-	-
Heat conductive polymer II	980	3500	3430000	0.74	-	-
Latent heat storage material	1220	2100	2562000	0.4	39*	70 000*

**latent heat storage: Phase change at 39 degC*