Development of a directly heated solid media thermal energy storage system with high storage and power density for flexible heat supply in battery electric vehicles

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Abstract

The integration of thermal energy storage (TES) systems in battery electric vehicles (BEVs) introduces an innovative thermal management concept that opens up new possibilities for heat supply, thereby extending range during cold seasons by conserving battery capacity while driving [1]. The successful implementation of TES systems in BEVs depends on meeting two critical requirements: achieving high systemic storage densities compared to today's battery-powered PTC (positive temperature coefficient) heaters and ensuring high charging and discharging powers. The basic idea is to electrically heat the storage medium while the battery is being charged, efficiently store the thermal energy, and release it at a predetermined temperature level during the vehicle's operation. This is achieved by mixing the hot air exiting the storage with cold ambient air through a controlled bypass to achieve constant temperatures at defined levels for heating the interior.

As part of this research, for the first time, directly heated solid media TES systems based on high-temperature resistant, electrically conductive ceramic materials are investigated. Compared to previous concepts, which used an electrically non-conductive honeycomb structure with integrated metallic heating wires for indirect resistance heating [2,3], direct resistance heating enables higher and more uniform charging power, as the electrical current is flowing directly through the storage inventory. Furthermore, directly heated solid media TES systems significantly reduce installation effort, as the integration of heating wires into a porous structure is no longer required. This approach also mitigates high-temperature oxidation while maintaining high systemic thermal storage densities and charging powers, as shown in [2,3]. Additionally, additive manufacturing of ceramic materials facilitates the implementation of customized and complex storage designs.

The objective of the development work comprises the elaboration of design solutions for a directly heated TES system with high storage and power densities, which will be experimentally validated using a functional prototype. To identify favored design variants for the storage inventory, a comprehensive material screening was conducted. Electrically

conductive ceramic materials were selected, and their temperature-dependent specific resistance was experimentally measured across a range of 20–1000 °C.

A simplified design tool was then developed with these temperature-dependent material properties, introducing a geometry parameter (electrical tortuosity) to capture the effective electrical resistance of various porous structures. This preliminary design tool enables computationally efficient and extensive design studies without requiring an exact representation of the structures. Feasible and favored solutions were derived from extensive parametric studies, exploring variations in material, geometry, electrical, and storage-specific boundary conditions. Based on the favored design variants for the storage inventory, model detailing and extensions are currently underway, particularly for electrothermal charging and thermal discharging, as well as for thermomechanical and fluid dynamics aspects. This includes, e.g., the analysis of local heating effects at the electrode connection using electrothermal 3D models, assessments of heating uniformity, and derivations of geometry adjustments within the structure (hole pattern), storage shape, and electrode configurations.

The focus of current and upcoming work is now on conducting comprehensive parametric studies based on the implemented model improvements and identifying a guiding concept for future experimental investigations. In parallel, preliminary laboratory investigations are being conducted on the preferred, force-locked electrical connection and the storage inventory using functional prototypes. These include, among other things, the experimental measurement of a simplified, downscaled functional prototype, as well as experimental studies on electrical tortuosity.

The contribution covers key aspects of the development work leading to a prototype functional model, as well as subsequent laboratory infrastructure work for upcoming measurement campaigns at the end of 2025.

References

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