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Novel thermal management system design methodology for power lithium-ion battery

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HIGHLIGHTS

- An improved design methodology for developing TMSs based on CFD is proposed.
- A heat generation model at cell level is developed.
- The methodology is validated with laboratory measurements on a battery module.
- The maximum difference between model predictions and experimental data is 2 °C.
- Cell temperature and module thermal dispersion are below 35 and 5 °C, respectively.

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ABSTRACT

Battery packs conformed by large format lithium-ion cells are increasingly being adopted in hybrid and pure electric vehicles in order to use the energy more efficiently and for a better environmental performance. Safety and cycle life are two of the main concerns regarding this technology, which are closely related to the cell's operating behavior and temperature asymmetries in the system. Therefore, the temperature of the cells in battery packs needs to be controlled by thermal management systems (*TMS*s). In the present paper an improved design methodology for developing *TMSs* is proposed. This methodology involves the development of different mathematical models for heat generation, transmission, and dissipation and their coupling and integration in the battery pack product design methodology in order to improve the overall safety and performance. The methodology is validated by comparing simulation results with laboratory measurements on a single module of the battery pack designed at IK4-IKERLAN for a traction application. The maximum difference between model predictions and experimental temperature data is 2 °C. The models developed have shown potential for use in battery thermal management studies for *EV/HEV* applications since they allow for scalability with accuracy and reasonable simulation time.

1. Introduction

More efficient use of energy and better environmental performance are becoming important requirements for the transport sector, which is facing the major challenge of providing transport solutions that are environmentally friendlier, but which also meet the growing global demand for modern, comfortable transport networks. In this context, due to the considerable ecological benefits it offers, railways powered with an auxiliary electric storage system are one of the most efficient and competitive transport solutions around and they have the tremendous potential to reduce environmental impact and actively contribute to the protection of the ecosystem.

One of the most promising solutions is to develop mobile storage applications consisting of onboard energy storage systems (*ESS*) which allow trams to run without catenary between stops, and also to save energy due to the complete recovery of the braking energy.

This paper presents a novel methodology for the development of a thermal management system for a regenerative power battery storage system. The battery system uses pouch type lithium-ion batteries and has been designed for an innovative railway product solution which improves the energy efficiency and the

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flexibility of today's transport solutions. This technology requires large scale modules and packs conformed by large format lithium-ion cells. The main drawback is related to the high safety constraints due to the passengers onboard. The safety of these battery packs is critically related to the cells' operating behavior and cell temperature [1].

Overall battery pack cycle life is also strongly dependent on temperature conditions during both operation and storage. As a general trend, it can be said that every degree of cell temperature rise reduces the lifespan of the Li-ion battery by approximately 2 months over an operating temperature range of 30–40 °C [2]. In addition, large temperature non-uniformity in the battery pack adversely affects the overall cell lifespan as well as the available cell capacity. Therefore, battery packs need to be managed by thermal management systems (*TMS*s) in order to improve battery safety [3], performance, reliability and overall cell life until the battery pack reaches its end of life [4].

As a result, battery thermal management has attracted considerable research and development efforts. Various thermal management models and techniques, such as air or liquid thermal management systems, have been proposed for effectively managing the heat dissipated from the batteries during operation [5–7]. Liquid cooling provides a higher heat transfer rate than air cooling. Moreover, liquid cooling favors the compactness of the design and it is insensitive to the location inside the vehicle [8]. As *HEV*s mature, more battery thermal management systems will use active systems [9].

There have also been studies on the design of the battery *TMS* [10–13]. However, previous work predominantly relies on modeling and numerical simulations with limited experimental validation [14–16], which restricts the reliability of such models. In addition, most of the previous studies have modeled the Li-ion cell thermal behavior separately for charge or discharge, and have not considered the combined effect of them, typically present in electric vehicle load conditions [17].

This work presents the design process of a *TMS* based on a *CFD* (Computational Fluid Dynamics) model which simulates detailed dynamics of the cooling of battery modules. The heat generation model developed experimentally at cell level [18] is improved in order to be included in the *CFD* model by means of a user defined function (*UDF*).

The description of the *CFD* model and its validation for a wide matrix of laboratory measurements are presented. The work is firstly carried out on different components of the final system, and then on the final system itself, in order to check the validity of the model and design methodology. The tests include different charge/discharge profiles with distinct current rates and depths of discharge (*DOD*). Different cooling conditions are also included by changing the inlet coolant temperature and flow rate. Experimental validation allows the potential of the field of design engineering, which is based on modeling and numerical simulations, to be maximized. The maximum difference between model predictions and experimental temperature data is 2 °C. Finally, a realistic current profile is applied to the sample prototype in order to validate its thermal design. The maximum cell temperature is always kept below 35 °C. Furthermore, cell temperature differences are kept below 5 °C. Thus, the thermal management system guarantees both safety and full lifespan.

2. Description of the battery module and its thermal management system

The main objective of the regenerative power battery storage system developed for a traction application directed to the railway industry is to make effective use of the regenerative energy produced during braking, allowing trams to run without a catenary between stops.

The battery pack is made up of several interconnected modules, which in turn are composed of several NMC ($LiMnNiCoO_2$ cathode) based pouch-type lithium-ion cells. In each module, twelve cells are connected in series in a vertical position with the tabs connected upwards, and the modules are connected in an appropriate way in order to fulfill the desired power and capacity requirements of the application. Cells are manufactured by KOKAM and their dimensions are 222 mm in length, 214 mm in width, and 10.7 mm in thickness. The nominal voltage of each cell is 3.7 V and the nominal electric capacity is 40 A h.

From a thermal point of view the system must operate correctly in a range of ambient temperatures between 5 °C and 40 °C. The temperature of the battery system is managed by a cooling liquid circulated between two cold plates in order to ensure that the battery module is symmetrically cooled, which increases the thermal uniformity between cells and makes it possible to obtain significantly lower central temperatures. In addition, lithium ion cells are placed between aluminum sheets to facilitate the heat dissipation from the cells to the cold plates. The heat is dissipated from the cold plates to the environment using an auxiliary system that depends on the final system scale, power and the ambient requirements of the application as well as the top temperature that can be assumed in the battery system in order to obtain a design that either maximizes the lifetime (active refrigeration to obtain cooling below ambient temperature) or minimizes the overall cost and auxiliary power consumption (simple water cooling system with heat exchangers). The lower temperature may not be a limit since the battery is self-heated during operation. Moreover, there is an electric heater for cold start-up.

The thermal design criteria established are to keep the maximum cell temperature below 35 °C for the worst thermal conditions and to keep cell temperature differences always below 5 °C to achieve a full lifespan [14,19].

An exploded drawing of the final design can be seen in Fig. 1. The electric insulation of the system is guaranteed by using a specific Thermal Interface Material, TIM, which is placed between the module and each cold plate (Cold Plate interface in Fig. 1). A thermally conductive gap filler from RS is selected due to its good thermal conductivity and soft and high compressibility. In addition, it is easy to assemble and it is a good insulator and a shock and vibration absorber. The material's properties are summarized in Table 1.

3. Thermal modeling

Once the final design concept is decided and thermal requirements defined, a detailed model of the simplified but representative sample prototype consisting of a single module and two cold plates which will later be built has to be developed to check the validity of the design. The ANSYS/FLUENT 14.5 *CFD* package has been used for modeling purposes.

The non-homogenous and anisotropic structure of the layers in a pouch cell, the extreme thickness of each layer and the complicated interfaces between different materials make the thermal modeling of a battery cell very complex. Therefore, the most widely used approaches found in literature for thermal modeling, i.e. electrochemical-thermal coupled models and lumped thermal models, were first analyzed.

In the first type of models, the cell geometry and configuration, as well as the physical, chemical and electrochemical properties of the cell materials are accurately delineated, which allows for an accurate thermal analysis. The non-uniform current density distribution across the face of a plate in a monopolar system or the