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Thermal Management Systems´ Design Methodology for Transport Applications

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Abstract

More efficient use of energy and better environmental performance are becoming important requirements for the transport sector. Therefore, hybrid operation is increasingly being adopted in vehicles as a means of recovering braking energy. One of the most promising solutions is to develop mobile storage applications which consist of onboard energy storage systems (ESS). This technology requires large scale modules and packs conformed by large format lithium-ion cells. Safety is one of the main concerns regarding this technology, which is closely related to the cells´ operating behavior and temperature asymmetries in the system. Therefore, the temperature of cells in battery packs needs to be controlled by thermal management systems (TMSs). An improved design methodology of TMSs is proposed which involves the development of different mathematical models for heat generation, transmission and dissipation on the one hand and their coupling and integration in different simulation environments on the other hand. The methodology is validated by comparing simulation results with laboratory measurements on a single module of the battery pack designed in IK4-IKERLAN for a traction application. The models developed have shown the potential to be used in battery thermal management studies for EV/HEV applications since they allow for scalability with accuracy and reasonable simulation time which is of prime importance while designing the TMS.

Keywords: lithium battery, battery model, regenerative braking, water cooling, thermal management

1 Introduction

More efficient use of energy and better environmental performance are becoming important requirements for the transport sector. In this context, the transport sector is facing the major challenge of providing transport solutions that are environmentally-friendly, yet which also meet the growing global demand for modern, comfortable transport networks.

Hybrid operation is increasingly being adopted in vehicles as a means of recovering braking energy and operating the engine in its most efficient speed range. One of the most promising solutions is to develop mobile storage applications which consist of onboard energy storage systems in which the braking energy is stored, allowing vehicles to save energy due to the complete recovery of the braking energy. When the vehicle accelerates, energy is used in priority from the ESS to propel the vehicle.

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 this battery packs is critically related to the cells´ operating behavior and cell temperature [1]. Therefore, battery packs need to be managed by TMSs in order to improve battery safety [2], performance, reliability and overall cell life [3].

IK4-IKERLAN has developed a regenerative power battery storage system that uses pouch type lithium-ion batteries for a traction application in order to provide a means of making effective use of the regenerative energy produced during braking. A multidisciplinary team is required that covers, in an integrated way, all the aspects of the development of the SW/HW of such a complex system [4-6].

This work is focused on the description of the integral design process of the TMS that covers preliminary design, design, validation, and optimization stages. Laboratory measurements are carried out in a simplified but representative sample prototype in order to check the validity of the proposed design methodology.

2 Thermal management systems´ design methodology

The design methodology is based on the sequence of steps shown in Fig. 1 which finally provides an optimum battery system in order to achieve a fixed battery thermal performance and other battery pack specifications such as maximum energy efficiency and minimum weight/volume.

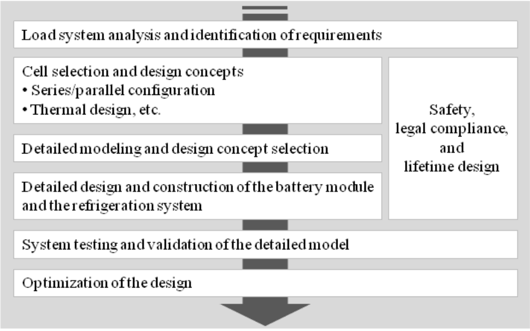


Figure1: Flow chart for the optimum design of energy storage systems.

First, the behavior of the load system has to be understood in order to identify its requirements. The most appropriate cell for the application is then selected and characterized in order to ensure that the requirements previously identified can be fulfilled. Different design concepts are proposed and analyzed by means of detailed models developed using *Computational Fluid Dynamics, CFD,* techniques [7] and more compact models developed using *Differential Algebraic Equation, DAE,* approach [8, 9] which allow selecting the final design concept before building the battery module and the refrigeration system. Experimental tests carried out in the prototype constructed are used to probe the correct thermal behavior of the module as well as to validate the detailed model of the final design concept. Once it has been validated, the model will have the potential to be used in the optimization of the thermal management system design. Each of these steps will be thoroughly explained in the following subsections.

2.1 Load system analysis and identification of requirements

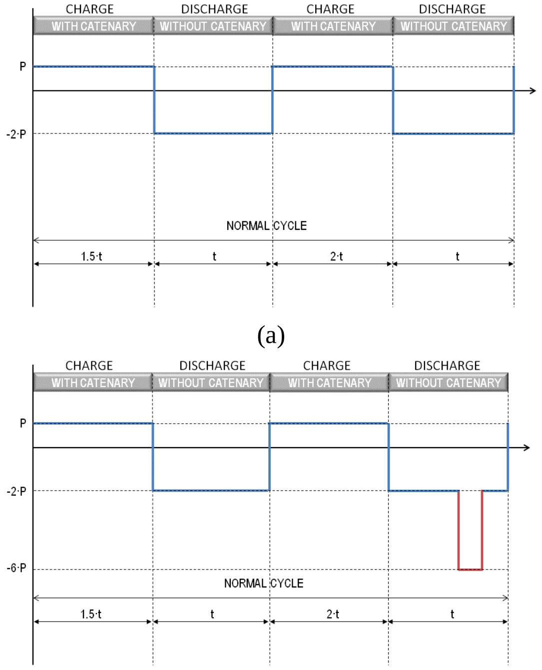
The battery system is configured by connecting a number of battery modules in series or parallel. These battery packs in turn are made up of cells connected in series with the number of cells being determined by the power, voltage and current requirements of the load system. However, maintaining the performance and long life of an assembled battery is not simply a matter of connecting lithium-ion battery cells in series and parallel to achieve the required voltage, current and power. Instead, understanding the behavior of the load as well as the resulting charging and discharging behavior and then designing a battery system specific to those requirements has a major influence on the system´s performance and lifetime.

The objective of the regenerative power battery storage system developed in IK4-IKERLAN for a traction application is to make effective use of the regenerative energy produced during braking.

From the electrical point of view, the power and energy requirements for this application are based on two types of operating modes: normal mode and backup mode (Fig. 2). Real values cannot be shown due to the confidentiality of the data.

From a mechanical point of view, the principal requirement is the limitation of available space to integrate the battery system in the vehicle. It is also desirable to minimize the weight of the complete system. An external enclosure guarantees that the system can operate in high humidity conditions. The battery should be capable of resisting the vibrations produced by the vehicle in its movement. The necessary electrical power connections should generate as low as possible losses due to ohmic irreversibilities.

From a thermal point of view, the system should operate correctly in a range of ambient temperatures between 5ºC and 40ºC. The lower temperature may not be a limit since the battery is self-heated during operation. Moreover, there is an electric heater for the cold start-up. The complexity of the cooling system depends on the top temperature that can be assumed in the battery system in order to obtain a design that maximizes the lifetime (active refrigeration to obtain cooling below ambient temperature) or minimizes the overall cost and auxiliary power consumption (simple water cooling system).



(a)

(b)

Figure2: Cycle corresponding to (a) the normal and (b) the backup mode in the application.

Regarding the lifetime of the ESS, it has been found that every degree of cell temperature rise reduces the lifespan of the Li-ion battery by approximately 2 months in an operating temperature range of 30-40 ºC [10]. In addition, large temperature non-uniformity in the battery pack affects adversely overall cell lifespan as well as available cell capacity. Therefore, cell temperature differences should be kept below 5 ºC to achieve a full lifespan [10].

2.2 Cell selection and characterization

A wide range of tests which make possible the analysis of electrical and thermal properties of various cells, as well as mechanical and safety aspects are performed in order to select the most appropriate cell for the application [4]. As a result of these tests, the battery pack is made up of NMC based pouch-type lithium-ion cells. The nominal voltage is 3.7 V and the nominal electric capacity is 40 A·h.

A precise determination of heat generation in those cells could improve the TMS design process. Therefore, the heat source is determined according to [6]. The heat generation within a cell is calculated based on homogenization of the cell with averaged properties. This methodology makes it easier to develop the thermal model and implement it in battery system design tools since there is no need to combine the thermal model with complex electrochemical models to estimate heat generation. In comparison to coupled multiphysics models, faster simulations which require less computational effort are feasible when using such a compact thermal model. Although there is no proper resolution in order to model the temperature distribution at cell level, this is not the aim of the model, i.e., the objective is not the thermo-chemical design of the cells, but to assure that the temperature of all the cells within a battery pack is kept below a certain value and that there is not a significant variation between them.

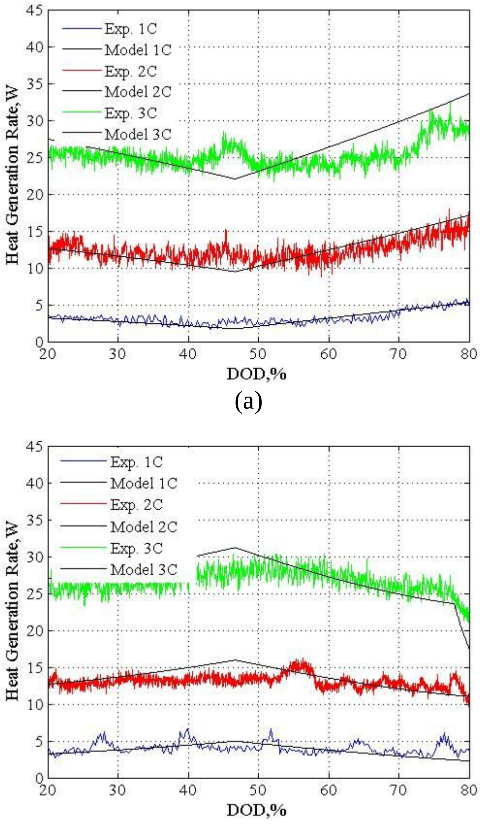
The validation of the heat generation model is based on direct heat generation measurements on individual cells. Calorimetry of the cells during charge/discharge at various currents is carried out by operating the instrument adiabatically. Fig. 3 compares the heat generation rate for low to high discharge/charge rate (1-3C) profiles with predictions of the heat generation model.

The discharge/charge rates cover the range recommended by the manufacturer and also the rates used in both the normal and the backup modes of the application. Average errors of 7% and 8% have been determined for the maximum charge and discharge rates, respectively.

For better design of the thermal management system, understanding the real time behavior of the Li-ion cells in vehicle operating conditions is critical. Therefore, its thermal behavior has also been modeled in various drive cycles, i.e., calorimetry of the cells during the cycle corresponding to the normal operating mode shown in Fig. 2a has been carried out. The heat generation rate measured for 3 cycles corresponding to the normal operating mode as well as the cell surface temperature are shown in Fig. 4.

2.3 Design concepts

The TMS has to be designed in order to achieve an energy efficient and safe battery thermal performance. The average temperature of the cells should be kept in a safe operating range for restrictive demand and ambient situations, trying to reach an ideal value around 25 ºC most of the time. According to [10], a temperature variation of 5 ºC is established in the module as an additional design criterion in order to prevent electrical disequilibrium and inhomogeneous degradation of the system.



(a)

(b)

Figure3: Validation of the heat generation model for (a) discharge and (b) charge processes.

The compactness of battery packs poses a challenge for effective thermal management. Therefore, the battery thermal management system has to be compact, lightweight and easily packaged. In addition, it must be reliable and serviceable and its cost should be as low as possible.

In this preliminary design stage different design alternatives are evaluated. Finally, the temperature of the battery system is managed by a cooling liquid circulated between two cold plates, since liquid cooling provides a higher heat transfer rate than air cooling. Moreover, liquid cooling favors the compactness of the design and it is location insensitive.

With maturing of HEVs, more battery thermal management systems will use active systems [11]. Therefore, the heat is dissipated from the cold plates to the environment using an active refrigeration system or even a heat exchanger depending on the final system scale and the ambient requirements of the application. The second option is selected in this case.

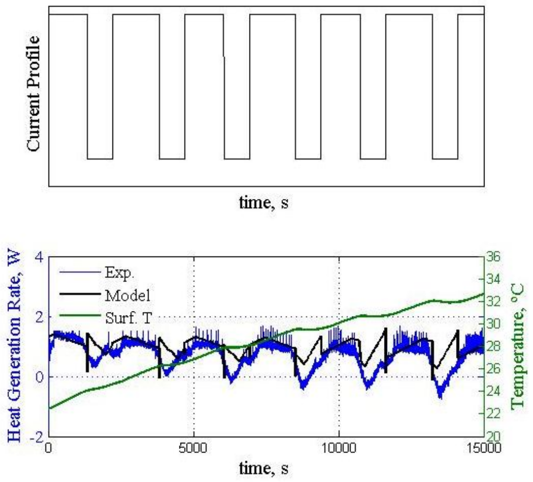


Figure 4: Heat generation rate and cell surface temperature measured during the normal operating mode cycle.

CFD commercial software is used as basic tool to optimize the heat transfer inside the module by design modifications. Coarse or conceptual steady *CFD* 2D/3D models help the designer to discriminate between different design alternatives in an early stage when the heat generation is barely known.

For the above simulations the pressure losses, the convective heat transfer coefficient and the thermal resistance of the cold plates can be extracted for different mass flow rates from a detailed thermal model of the cold plate shown in Fig. 5.

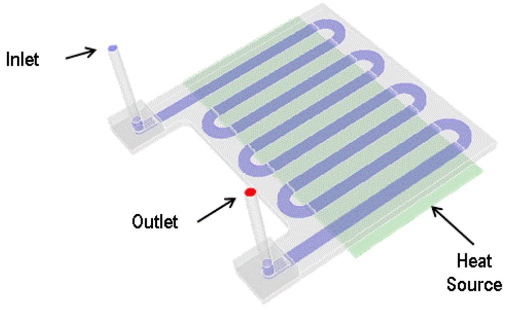


Figure5: Detailed *CFD* model for the cold plates.

Specific low Reynolds number turbulence models have been employed to obtain a precise description of the hydrodynamic and convective heat transfer phenomena inside the complex small channels found inside the cold plates. The model has been numerically verified and experimentally validated [12].

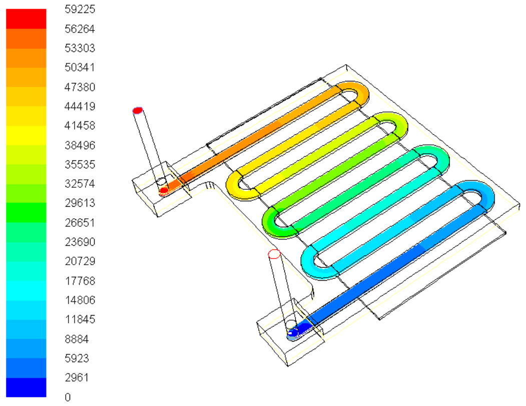


Figure6: Contours of static pressure (Pa) for 4 L/min.

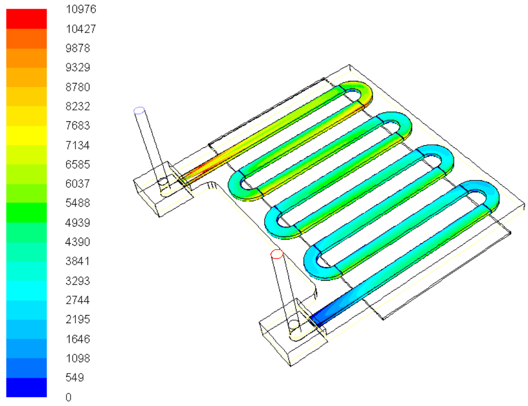


Figure7: Contours of convective heat transfer coefficient (W/m^{2}K) for 6 L/min.

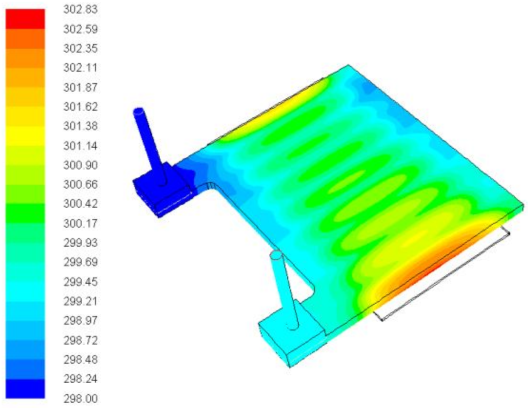


Figure8: Contours of static temperature (K) for 4 L/min.

Results corresponding to the pressure drop, the convective heat transfer coefficient, as well as the temperature contours obtained during the simulations are shown in Fig. 6-8. The numeric values are depicted in Fig. 9.

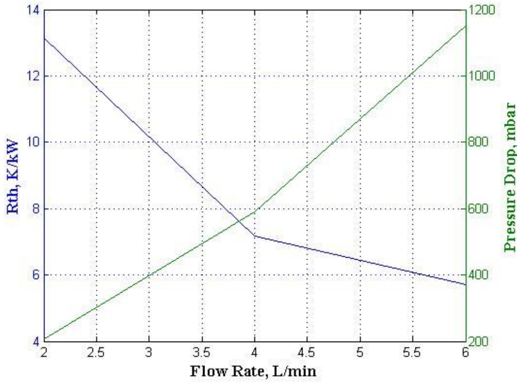


Figure 9: Heat transfer model parameters.

Once the final design concept is decided, a detailed model of the battery module has to be developed which uses the heat transfer model together with the heat generation equation in order to model the lithium ion battery pack thermal performance for different operating conditions in design stage. The heat generation equation is implemented by a user defined function (*UDF*).

Two different models have been developed as it can be seen in Fig. 10. The model that only considers the central hottest part of the module using vertical symmetry planes allows transient analysis of the thermal performance of the module with a reasonable computational cost. Different mass flow rates, ambient temperatures and electrical operational conditions can be easily checked using this model. The complete model of the module with the cold plates permits the analysis of the thermal asymmetries between the different cells of the module in a steady situation for diverse mass flow rates, ambient temperature and operating conditions. The computational cost of this model does not tolerate transient simulations in practice. Both models have been verified and validated.

The detailed results of the different *CFD* models can be used to adjust very compact *DAE* models and to analyze the dynamics of the complete thermal management system and control strategies. The description of such models is out of the scope of the present document.

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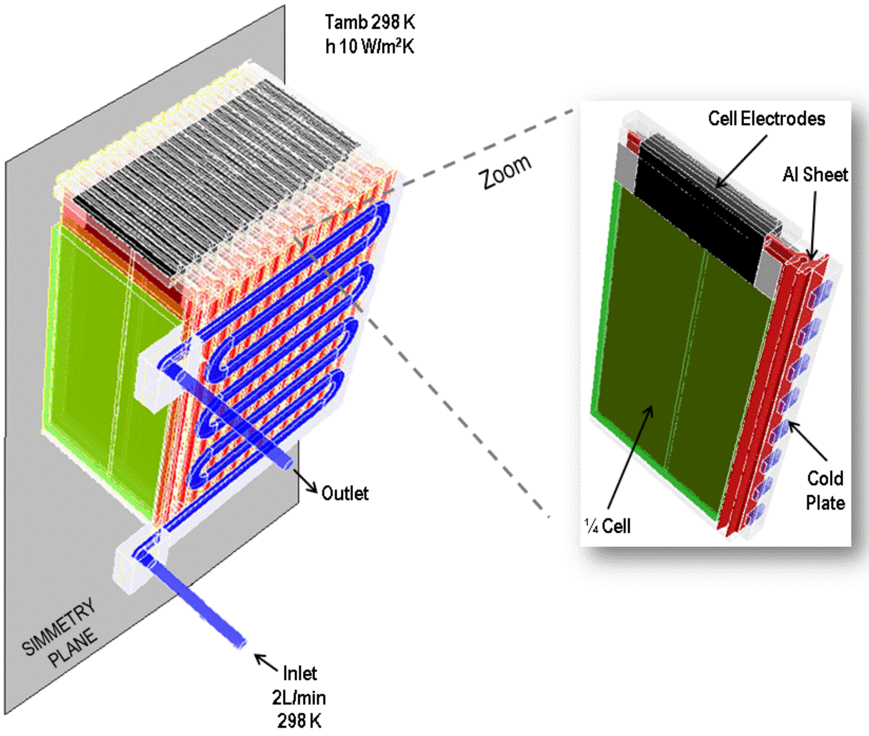

Figure10: Detailed models developed in *CFD* corresponding to the final design concept.

2.4 Detailed design, modeling and construction of the battery module

An exploded drawing of the detailed design is shown in Fig. 11. In order to validate the model, a prototype was constructed. It is made of 12 lithium-ion cells connected in series. Up to 20 thermocouples make possible the analysis of the temperature distribution in the system: thermocouples are located between the battery module and the cold plates and in various aluminum sheets and cells as well as in the inlets and outlets of the cold plates.

2.5 System testing and validation of the detailed model

Experimental temperature measurements obtained while cycling the battery module have been used to validate the TMS models from Fig. 10.

All the tests were carried out in a climatic chamber (CTS, Clima Temperatur Systeme) in order to keep the desired ambient temperature within ±0.3 K. During the experiments the battery module was connected to a programmable cycler (IBT, Industrial Battery Tester, which runs with Digatron/Firing Circuits BTS-600 software for data evaluation) for charging and discharging the cells.

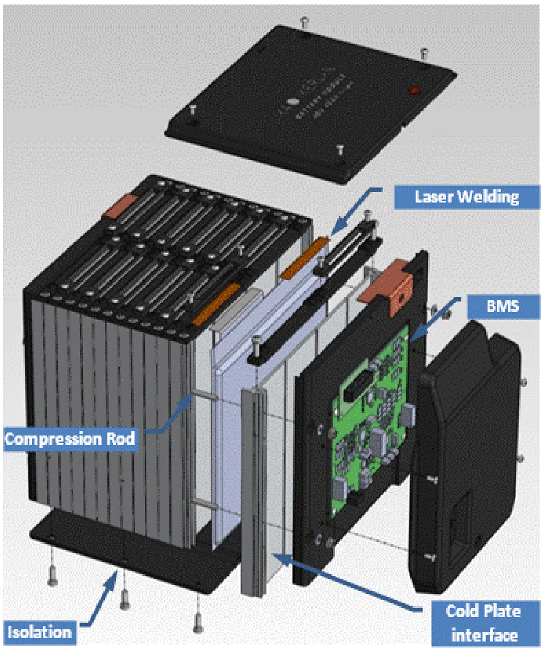

Figure11: Exploded drawing of the final design.

The cooling liquid circulated between the 2 cold plates was a 50% ethylene glycol-water mixture and it was pumped with a chiller (KODIAK® recirculating chiller, RC011) that allows fixing the inlet temperature as well as the coolant flow (25ºC and 2 L/min, respectively). The current profiles used for validation of the TMS models are shown in Fig. 12.

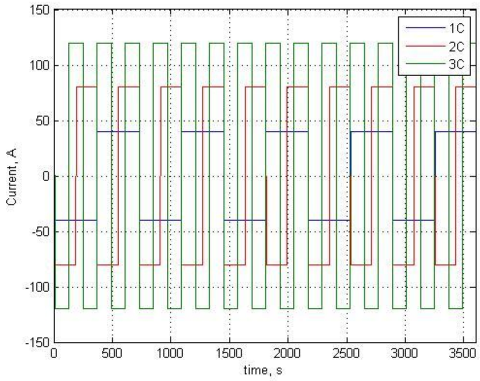

Figure12: Current profiles used for validation of the TMS models.

The first test was carried out with the weakest current profile and without activating the cooling system, which provided temperature measurements to adjust the convective heat transfer coefficient inside the climatic chamber. Once the convective heat transfer coefficient in the climatic chamber was established, a set of tests was performed with the battery module being cooled by the cold plates while the current profiles shown in Fig. 12 were applied. Fig. 13 compares the experimental temperature measurements at the surface of the 7th cell with the simplest TMS model results for each of the current profiles shown in Fig. 12. Model predictions follow closely the experimental measurements. Fig. 14 shows the temperature contours corresponding to the weakest current profile once the steady state is reached.

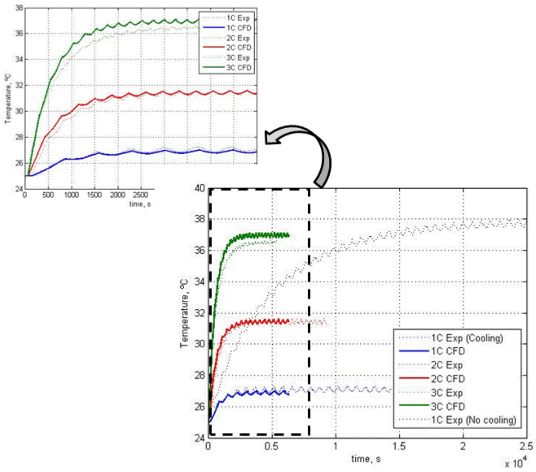

Figure13: Measured and simulated temperature profiles corresponding to 3 different current profiles.

If the black and blue temperature profiles in Fig. 13 are compared, the effectiveness of the cooling system is obvious. The surface cell temperature decreases from 38 ºC to 27ºC.

In order to analyze the thermal asymmetries between the different cells of the module in a steady situation, simulations with the complete model of the module were carried out. Simulation results are only shown for the strictest current profile (Fig. 15) as they are representative of the results obtained with the other current profiles.

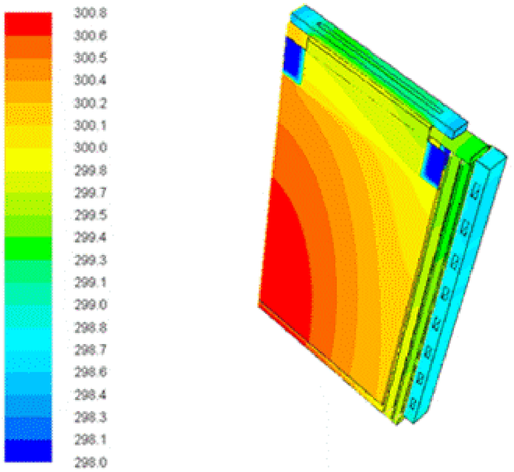

Figure14: Contours of static temperature reached during cycling with the weakest current profile.

As expected the cells in the middle are the ones with higher temperatures. The heat generated within the cells is dissipated through the aluminum sheets to the cold plates. Therefore, the temperature in the aluminum sheets is lower than in the neighboring cells and decreases symmetrically from the centre of the battery module to the boundaries. This is clearly seen in Fig. 16.

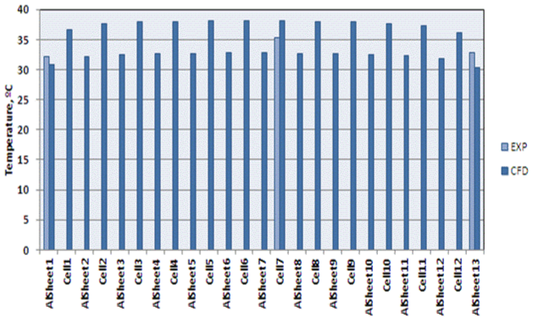

Figure15: Measured and simulated temperature distribution within the battery module.

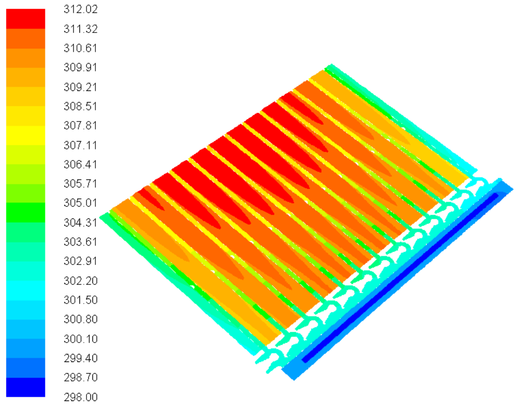

Figure16: Contours of static temperature reached with the strictest current profile. The plane is at half the height of the cells.

In the prototype there are few thermocouples placed in the aluminum sheets and in the 7th cell. The temperature measurements of these thermocouples are compared with simulation results in Fig. 15. Except for the 7th cell, lower temperatures are predicted by the detailed TMS model. However, the maximum error is smaller than 8%.

The rest of the temperatures measured during the validation tests are also shown in Fig. 17. The thermal management system maintains the temperature of the cells within the safety limits. The second thermal design criterion is also fulfilled, since cell temperature differences are kept below 5 ºC.

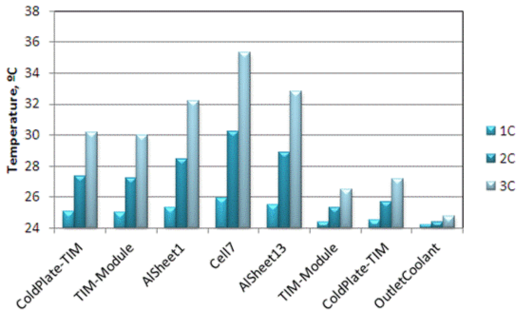

Figure17: Measured temperature distribution within the battery module for various current profiles.

3 Conclusions

A lithium-ion battery module has been built for transportation applications. The TMS maintains the temperature of the cells within the safety limits. The TMS model has been developed in order to predict battery module behavior for different operating conditions. The model consists of both a heat generation equation capable of predicting the heat generation of individual cells and hence their thermal behavior and a heat transfer model that estimates the heat transfer from the cells to the cold plates. The TMS model is validated in a real battery module by means of experimental temperature measurements.

The model allows for scalability with accuracy and reasonable simulation time which is of prime importance while designing the TMS. Therefore, the model has shown the potential to be used in battery thermal management studies for EV/HEV applications.

Based on the TMS model, further work is being done in order to optimize the cooling strategy and minimize the electric power consumption of the TMS so that the energy efficiency of the system is maximized.

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