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Improving Battery Design with Electro-Thermal Modeling

Preprint

A. Pesaran, D. Bharathan, and G. Kim
National Renewable Energy Laboratory

A. Vlahinos
Advanced Engineering Solutions

T. Duong
U.S. Department of Energy

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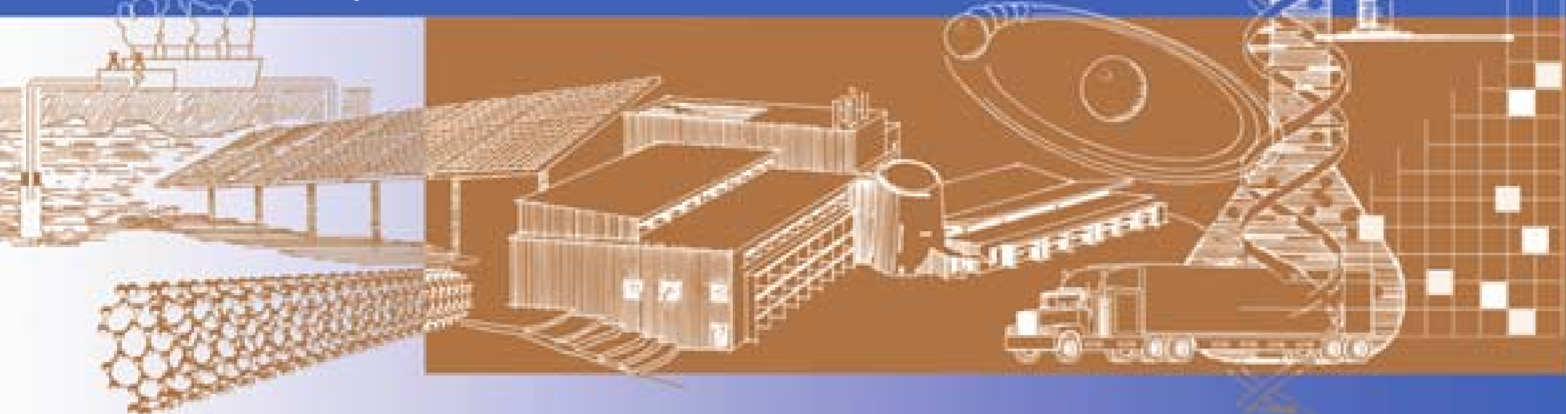

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Improving Battery Design with Electro-Thermal Modeling

Ahmad Pesaran, Andreas Vlahinos, Desikan Bharathan, Gi-Heon Kim, Tien Duong

Abstract

Temperature greatly affects the performance and life of batteries in electric and hybrid vehicles under real driving conditions, so increased attention is being paid to battery thermal management. Sophisticated electrochemical models and finite element analysis tools are available for predicting the thermal performance of batteries, but each has limitations. In this study we describe an electro-thermal finite element approach that predicts the thermal performance of a cell or module with realistic geometry, material properties, loads, and boundary conditions. To show the process, we simulated the thermal performance of two generations of Panasonic prismatic nickel-metal-hydride modules used in the Toyota Prius. The model showed why the new generation of Panasonic modules had better thermal performance. Thermal images from two battery modules under constant current discharge indicated that the model predicts the experimental trend reasonably well. These tools will greatly enhance the opportunity for lithium and other advanced batteries to perform better and become cost-effective alternatives in the future. The model has been used to improve the thermal performance of cylindrical lithium-ion batteries.

Keywords: HEV (hybrid electric vehicle), thermal management, nickel metal hydride, battery model, simulation

1 Introduction

Temperature greatly affects the performance and life of batteries, so battery thermal control must be used in a hybrid electric vehicle under real driving conditions. In recent years, automakers and their battery suppliers have paid increased attention to battery thermal management, especially with regard to life cycle and related warranty costs. A thermal management system could be designed ranging from “simple energy balance equations” to more “sophisticated thermal and computational fluid dynamic models.” However, the basic performance of the management system is dictated by the thermal design of each cell or module. So it is critical to design cells and modules that have inherently good thermal performance. Sophisticated electrochemical models are available for predicting the performance of electrochemical cells [1 and 2], but they can’t capture the heat transfer aspects of the actual geometry with cell or module hardware (case, terminal posts, connectors, interconnects, relief valves, current collectors, seals, etc). Some finite element models can capture geometry [3 and 4], but can’t capture heat generation aspects because of currents in the hardware components. In the past, we have used ANSYS commercial finite element analysis software, which captured the thermal aspects only [3]. The heat generation terms were added by estimating the Ohmic heating and enthalpy of electrochemical reactions.

For this study, we focused on integrating the electrical aspects of the cells and modules (including the cell hardware) into a finite element thermal analysis model. Our goals were to (1) develop the electro-thermal process or model for predicting thermal performance of cells and modules; (2) apply the model to predict the thermal performance of a baseline design (such as the 2001 Panasonic nickel-metal-hydride [NiMH] module) and compare it to the performance of a next-generation design (2004 Panasonic NiMH module); and (3) compare the predictions with infrared thermal imaging of modules under discharge.

2 Approach

It is particularly challenging to capture and model all the physical elements and details of a cell and drive the design parametrically for simultaneous electrical and thermal (electro-thermal) modeling, while considering performance limits and specifications for optimum efficiency and cost considerations. The process of engineering optimization via highly connected computer-aided engineering approaches is considered to be the best method, but it is not standard industry practice. During this project, we worked closely with a battery developer to develop such a tool. If the cell design is complicated, we use ProEngineer (ProE) software, a computer-aided design (CAD) tool, to build detailed virtual model of a cell or module. The CAD model consists of the cell core (positive electrode, negative electrode, separator, and electrolyte), the case of the cell or module, internal connectors from the core to the terminals, connectors to posts of terminals and (in the case of a module) cell-to-cell interconnects.

We generally assume that the core (the electrochemically active part of the cell) is orthotropic—a homogenous combination of all its elements, but with different thermal and electrical properties in different directions. The CAD model is transferred to ANSYS to create a finite element model that can perform both electrical and thermal analysis. If the design of the cell is simple, we use ANSYS to capture the geometry and details of the cell or module. Once the geometry and material properties are selected and specified, ANSYS can calculate the electrical resistance of each component. The direct current (DC) resistance of the total cell or module could be also used to adjust for any unknown components to come up with the proper resistance. A current flows through the cell when a voltage drop is applied across the two terminals. This causes resistive heat generation that increases the temperature of all components proportional to the internal DC resistance. We also add the heat caused by the electrochemical reactions to the core. ANSYS uses the heat generated in each element to estimate the temperature distribution in the cell. Hot spots could be identified during steady-state or transient loads.

To our knowledge, this is the first time that this type of electro-thermal analysis process has been applied to batteries. The designer can use this approach to improve the thermal design by reducing resistances, improving the power capability of batteries, and avoiding extreme hot spots in cells that lead to premature failure of cells.

3 Modeling and Results

To illustrate how this process works, we first applied the electro-thermal process to the prismatic Panasonic NiMH module used in the 2001 Toyota Prius and then compared it with the new Panasonic module used in the 2004 Prius. Figure 1 shows a picture of the 2001 Panasonic module, which has 6 cells, with total capacity of 6.5 Ah, module voltage of 7.2 V, and power capability of 1000 W/kg [5]. Figures 2 and 3 show the associated finite element model that we captured with ProE and ANSYS based on a good geometrical understanding of how the modules are built. We captured six cores, cell-to-cell interconnects, weld junction, current collectors, and terminals. We ignored the capturing dimples on the surface of the case, but captured their impact with an adjusted heat transfer coefficient on the case. We made assumptions for properties of each material based on our understanding of the construction of NiMH batteries. The major cell features that we captured are six homogenous cores connected to current collectors on the each side, the current collectors are connected in series on top using a circular weld, cells on each side are connected to the external terminals. All the components are encapsulated in a polypropylene case.

Figure 1: Panasonic NiMH module used in 2001 Toyota Prius

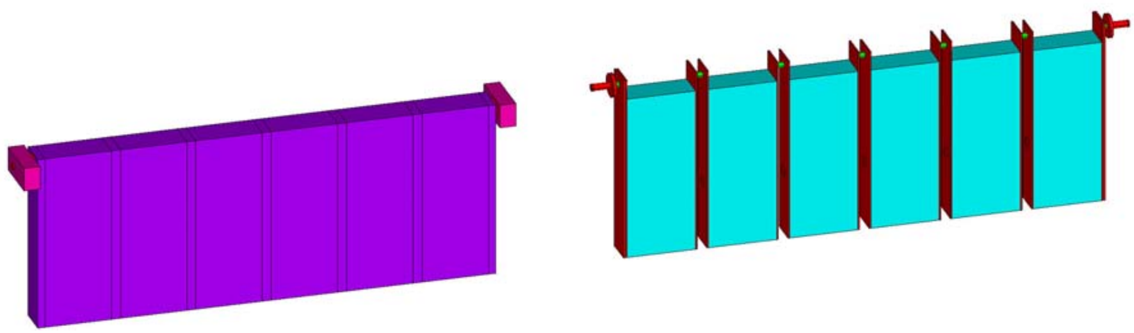

Figure 2: Simulated model of the 2001 Panasonic module. The polypropylene case with terminal connectors is shown on the left. The case is removed to show the core and current collectors on the right.

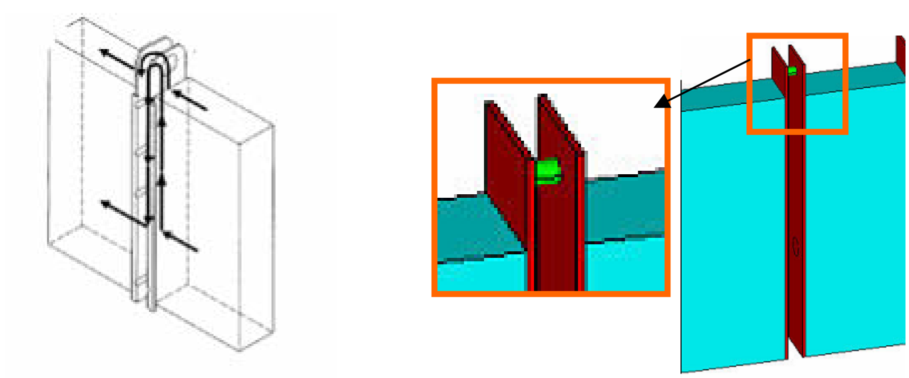

Figure 3: 2001 NiMH module. Left: Schematic of cell-to-cell connections by Panasonic [5]. Right: Our model of the weld junction.

The DC resistance of the cell that we used to find the effective resistivity of the core was assumed to be 15.0 mOhm [5]. We applied a voltage drop of 1.5 volts across the terminal to have a current of about 100 A through the cell. Figure 4 shows the voltage distribution and current density in the cores and the weld. The weld junction has the highest current density and one would expect more heat to be generated in the weld junction because of higher current density and thus the weld junction would be the hottest spot. In fact, Figure 5 shows the transient temperature distribution obtained for a module, with an initial temperature of about 28°C, being cooled with natural convection while discharged with constant current of 100 A. This simulates a similar case that we tested while obtaining infrared thermal images for comparison. In Figure 5, the voltage drop across the terminals is 1.5 V, the bottom of the module is insulated, and the heat transfer coefficient on all other sides is 5 $W/m^2/°C$. As seen in Figure 5, the hottest spot is at the weld junction of the cell-to-cell connectors.

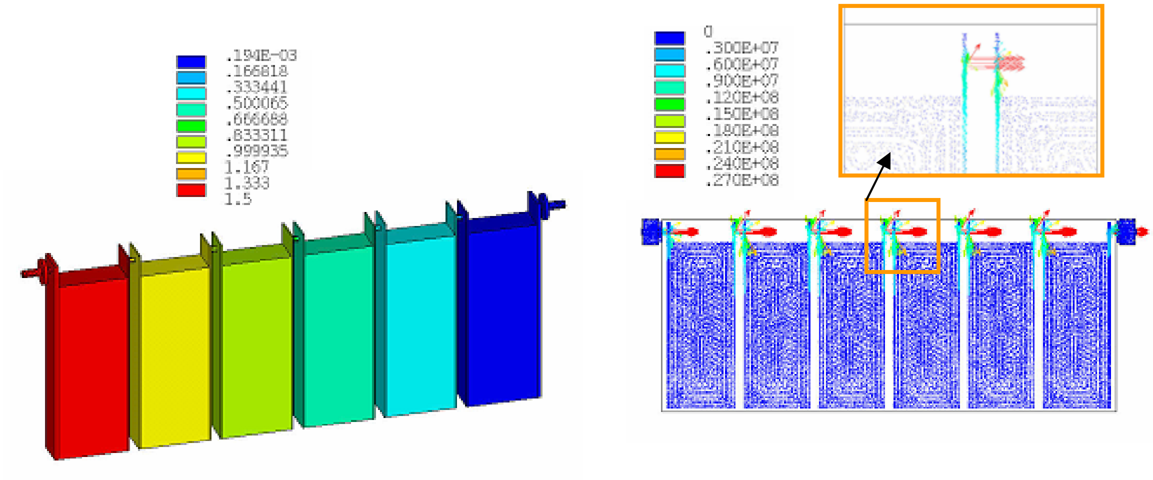

Figure 4: 2001 module. Left: Voltage distribution in each cell. Right: Current density in the module; insert shows the highest current density through the weld junction.

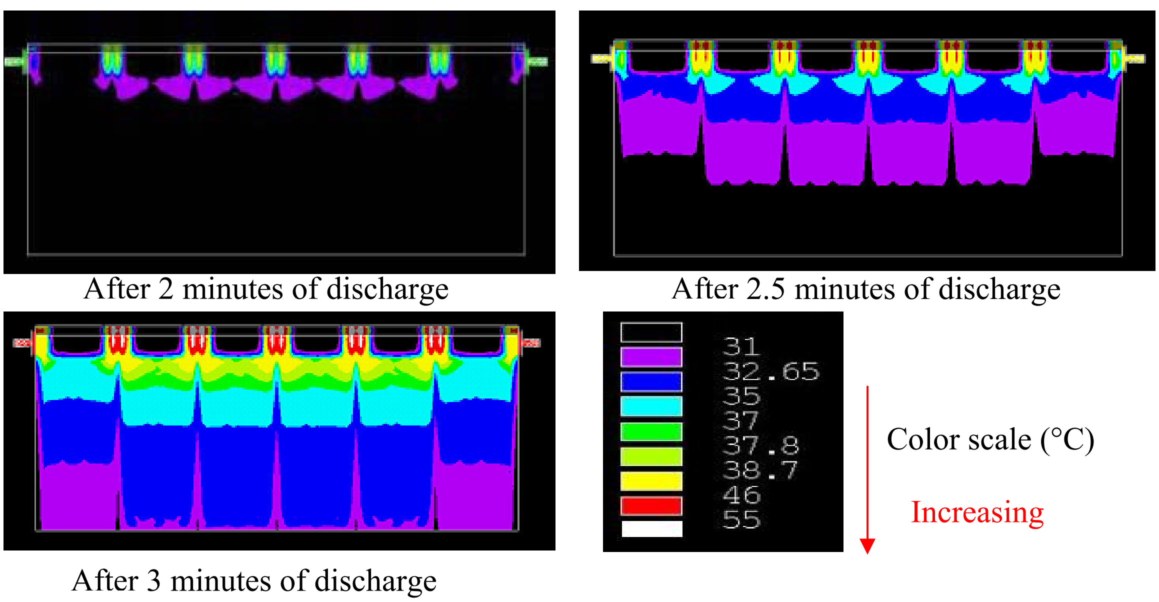

Figure 5: Model predictions for 2001 module. Temperature distribution in the polypropylene case after the start of 100 A discharge.

To validate the predictions of the model, or at least its trends, we obtained the infrared thermal image of the 2001 Panasonic module under constant current discharge of the 100 A while the module sat on a table with no cooling except natural convection in a room that was 25°C–28°C. Infrared thermal images show the external temperature. Figure 6 shows the thermal images of the 2001 module after start of the 100 A discharge. The hot spots are at the weld junctions similar to the electro-thermal model predictions. Comparing the model predictions in Figure 5 with the experimental images in Figure 6, we conclude that the electro-thermal model predicted the trend of temperature distribution reasonably well.

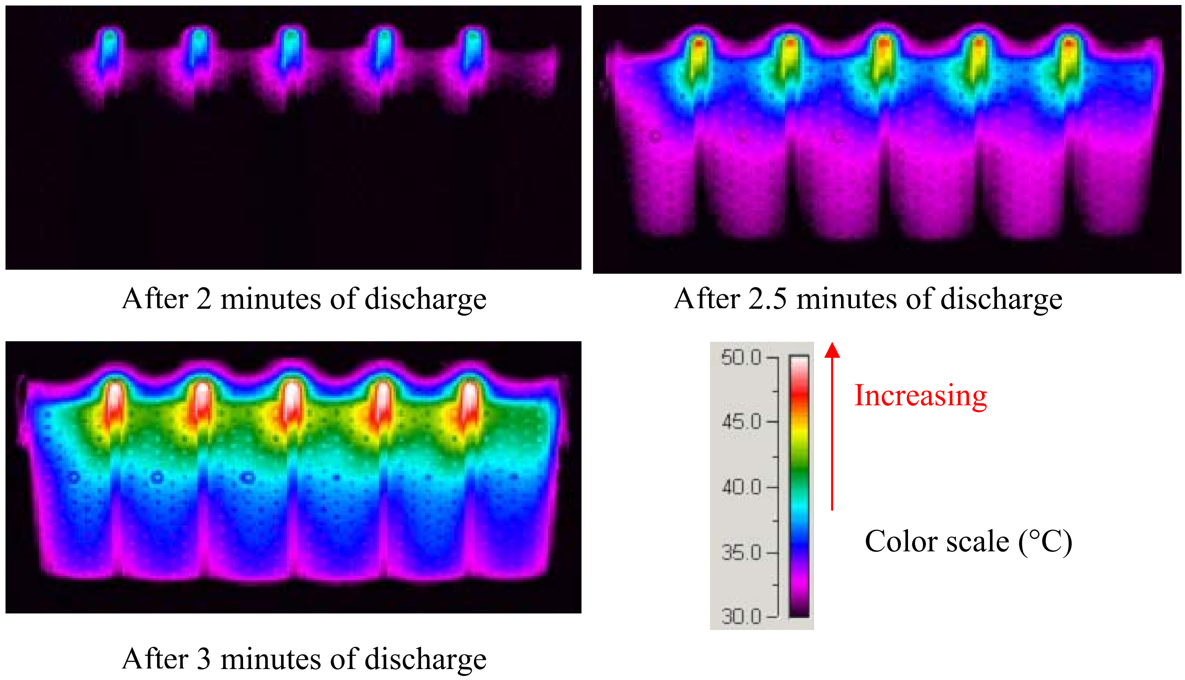

Figure 6: Thermal images of the 2001 NiMH module after the start of 100 A discharge

One of the objectives of developing the electro-thermal model was the ability to find hot spots with a particular design, and proposing solutions to eliminate it or reduce its impact. By looking at the thermal images of the 2001 Panasonic NiMH module, we can suggest reducing the current density at the weld by adding an additional weld junction between current collectors of two adjacent cells. Although this could be difficult or expensive to do, it could improve both thermal and electrical performance of the module. In fact, the engineers at Panasonic have found a way to add additional weld junctions between the current collectors of each adjacent cell [5 and 6] for the 2004 generation, as shown in Figure 7. The five new weld junctions are about 2/3 of the way down the module below the top weld. Panasonic indicates that the DC resistance of its 2004 prismatic NiMH modules has decreased to 11.4 mOhm, and thus its power capability has increased by a factor of 30% to 1300 W/kg while its capacity remains the same [5 and 6].

Figure 7 shows the finite element model of the 2004 Panasonic NiMH module. The weld junctions were simulated as small cylindrical rods. Figure 8 shows the model prediction for current density in the 2004 NiMH module under 100 A discharge. As could be seen, the current density is less in the top welds compared to the 2001 module under the same 100A discharge (Figure 4) since now almost half of the current is going through the second set of welds below the middle of the module. With lower current density in the weld, less heat is being generated and thus its temperature increase is expected to be less.

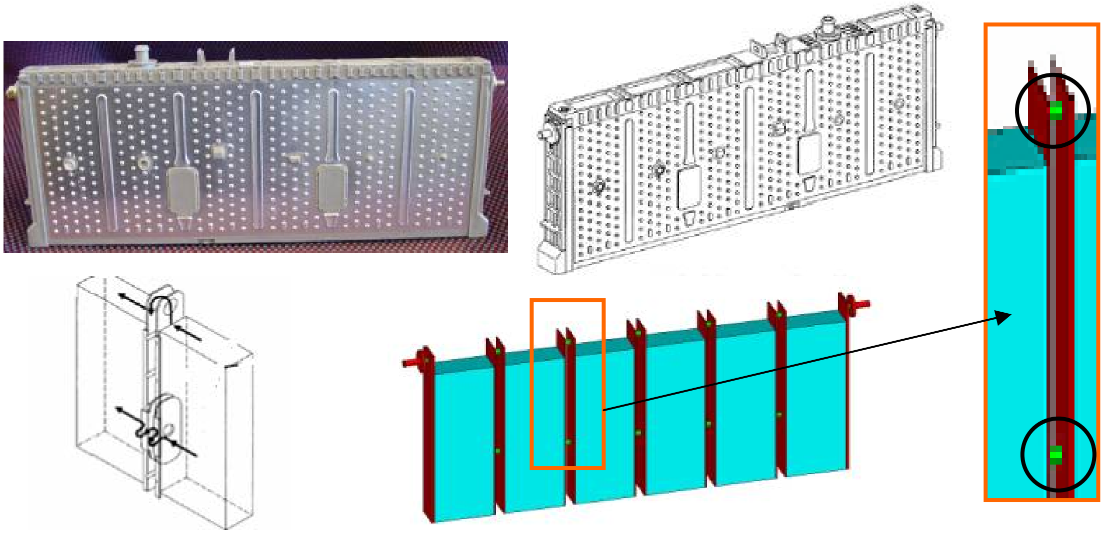

Figure 7: New Panasonic NiMH Module used in 2004 Toyota Prius (top picture and schematic; schematic of cell-to-cell connections by Panasonic [5] (bottom left); our simulated model of the module and weld junction (colored images on the right)

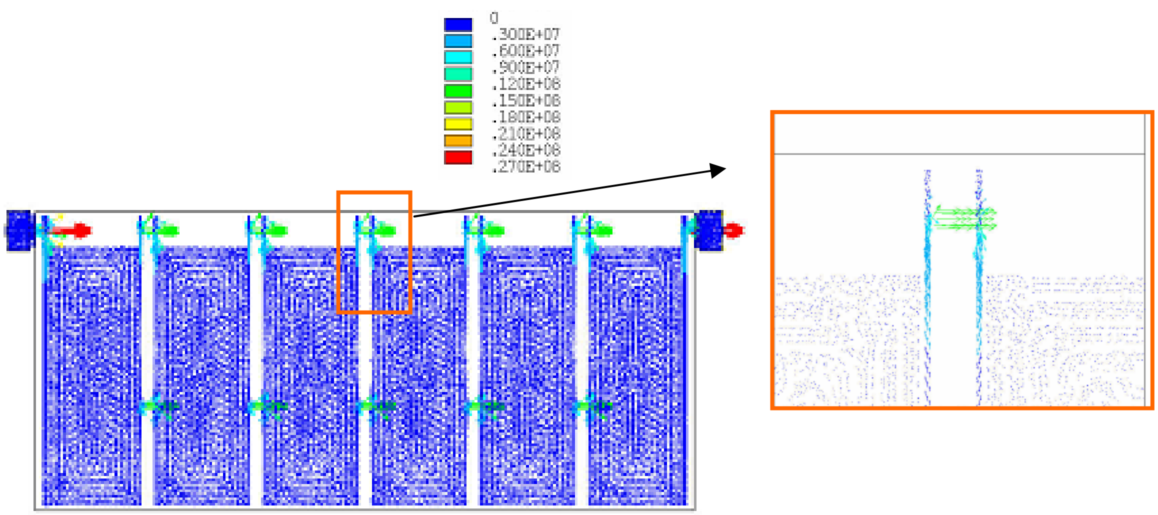

Figure 8: Current density for 100 A discharge for 2004 NiMH module

Figure 9 shows the temperature distribution in the 2004 module at the end of 3 minutes of discharge. In the left side image, the polypropylene case temperature is shown, the right image shows the core, current collector, and cell-to-cell interconnects. By comparing these results with similar case in Figure 5, we can see that the overall temperature of the 2004 module is lower than that of the 2001 module (maximum of 48°C vs maximum of 55°C), and also 2004 module has a much better temperature uniformity; both of which would help the battery to perform better and last longer.

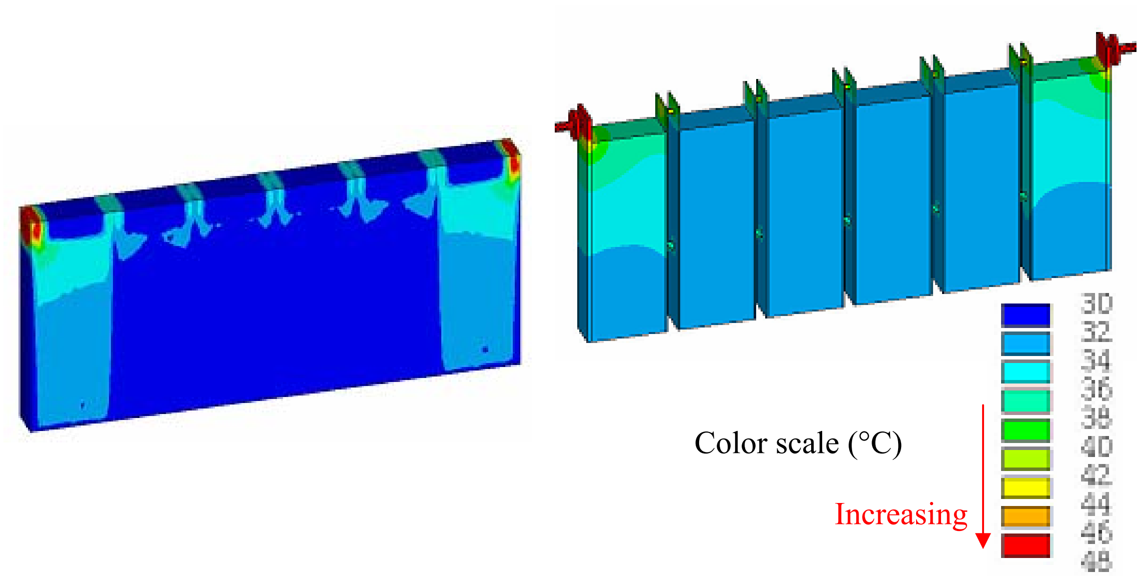

Figure 9: Model predictions for 2004 module. Temperature distribution in the case (left) and in the core (right) after 3 minutes from the start of 100 A discharge.

Figure 10 shows the thermal images of a 2004 NiMH module under 100 A discharge. Unlike the 2001 module (shown in Figure 6), it does not have any hot spots at the top cell-to-cell interconnects, it has lower overall temperature, and has better uniform temperature distribution. Our electrochemical model prediction compares reasonably well with these observations and these experimental thermal images.

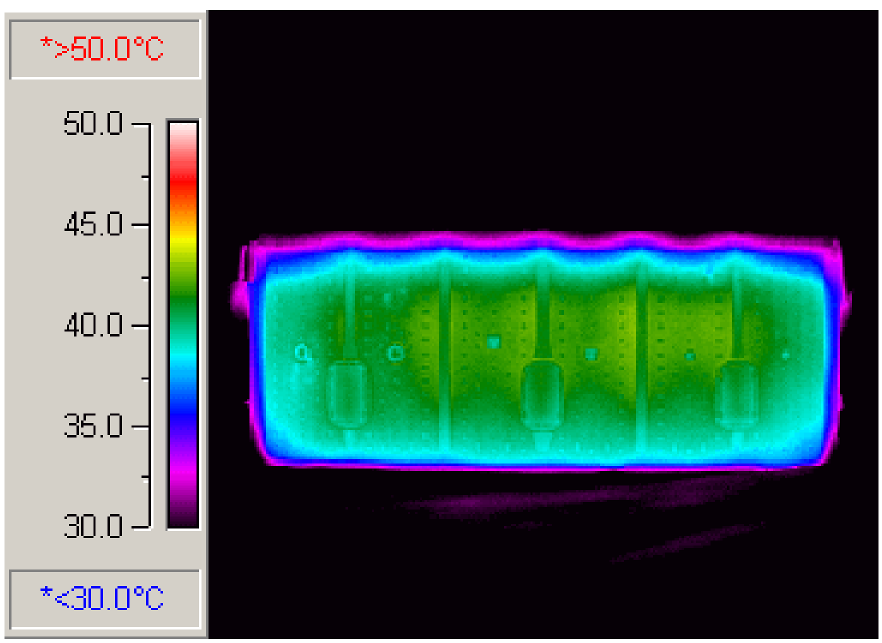

Figure 10: Thermal image of the 2004 NiMH module 3 minutes after the start of 100 A discharge.

4 Concluding Remarks

Thermal control is critical to ensure batteries provide the desired electrical performance and long life. Good thermal performance starts with designing good cells and modules. Using a commercial finite element analysis software, we developed a process to capture both electrical and thermal behavior of cells and modules with all of the geometrical details. To show how the electro-thermal modeling works, we applied it to the 2001 prismatic Panasonic NIMH module and found hot spots near cell-to-cell interconnects. The analysis showed the benefit of decreasing the contact resistance between the two adjacent cells by using additional welds to decrease the overall DC resistance, reduce hot spots, improve temperature uniformity, and reduce the overall temperature of the module. This is in fact what Panasonic has done in their 2004 module. We performed constant current discharges of 2001 and 2004 modules and obtained thermal images. Comparing the thermal images with model predictions indicated that the model predicts the thermal performance reasonably well. We have applied the electro-thermal process described here to two other batteries from FreedomCAR battery developers to help them improve thermal designs.

The current version of the electro-thermal model does not capture the transient nature of the internal resistance of the battery due to electrochemical changes in the battery as it charges or discharges. It also does not capture the chemical behavior of the various materials in the cells. We plan to update and upgrade the model to include these features. Including the chemical behavior of the materials in the cells may allow us to predict the thermal performance of a cell and its propagation to other cells in module under abuse conditions (overcharge, overheating, and short-circuit).

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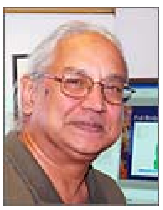
Authors

Ahmad Pesaran, Principal Engineer, National Renewable Energy Laboratory, 1617 Cole Blvd, MS 1633, Golden, CO, 80401, 303-275-4441, 303-275-4415, ahmad_pesaran@nrel.gov

Dr. Pesaran joined NREL in 1983 and has been working on various energy systems such as solar cooling, ocean thermal energy conversion, air conditioning, desiccant dehumidification/cooling for buildings and buses, and most recently hybrid electric vehicles. Since 1995, he has been working on hybrid electric vehicle projects. He is currently the project manager for various activities related to battery thermal characterization, battery thermal analysis, and battery modeling and management. Dr. Pesaran holds a B.S. in chemical engineering from Shiraz University, as well as an M.S. in engineering and a Ph.D. in mechanical engineering from UCLA. He is a member of the FreedomCAR Electrochemical Energy Storage Technical Team.

Andreas Vlahinos, Principal Advanced Engineering Solutions, 4547 North Lariat Drive Castle Rock, CO 80104, (303) 814-0455, (303) 814-0147, andreas@aes.nu

Dr. Vlahinos is the founder of Advanced Engineering Solutions. He received his Ph.D. in Engineering Science and Mechanics from Georgia Institute of Technology. He has been a professor of structural engineering at the University of Colorado, teaching courses in structural mechanics and computer-aided structural engineering and receiving the Professor of the Year Award several times. Dr. Vlahinos has written over 90 publications related to structural stability and dynamics, and design optimization. He has received a R&D 100 award and holds several patents. He has been instrumental in rapid product development through the implementation of Six Sigma and Computer Aided Concurrent Engineering for several government agencies and industry partners.



Desikan Bharathan, Principal Engineer, National Renewable Energy Laboratory, 1617 Cole Blvd, MS 1633, Golden, CO, 80401, 303-275-4613, 303-275-4415, desikan_bharathan@nrel.gov

Dr. Bharathan joined NREL in 1980. His experience includes developing solar-assisted gas turbine power systems, modeling and analyzing hybrid vehicles, and researching advanced power cycles using mixed working fluids. Dr. Bharathan holds a PhD and MS in Aerospace Engineering from the University of Virginia in Charlottesville, VA. He also holds a B. Tech. in Aeronautical Engineering from the Indian Institute of Technology in Madras, India. He has been awarded six patents and has received numerous awards including a Federal Laboratory Consortium for Technology Transfer award, a Colorado Technology Transfer award, and two R&D 100 awards.

Gi-Heon Kim, Post-Doctoral Researcher, National Renewable Energy Laboratory, 1617 Cole Blvd, MS 1633, Golden, CO, 80401, 303-275-4437, 303-275-4415, gi-heon_kim@nrel.gov

Gi-Heon Kim has worked as a post-doctoral researcher with the Advanced Vehicle Systems group since 2004. Before coming to NREL, Dr. Kim completed a Ph.D. in Mechanical Engineering from Colorado State University. His professional experience includes a position as a Research Assistant with the Engines and Energy Conversion Laboratory at Colorado State University and a position as a Research Assistant with the Institute of Advanced Machinery and Design, Seoul National University. His background includes work in heat and mass transfer, fluid mechanics, turbulence, combustion, and fluid dynamics. In addition to his Ph.D., Dr. Kim holds an M.S. and B.S. in Mechanical Engineering from Seoul National University in Seoul, Korea.

Tien Q. Duong, Office of FreedomCAR and Vehicle Technologies, U.S. Department of Energy, 1000 Independence Avenue, SW, Washington, DC 20585, USA 202-586-2210, 202-586-1600 (fax), Tien.Duong@ee.doe.gov

Mr. Duong is Vehicles Technologies Team Lead at the Department of Energy's FreedomCAR and Vehicle Technologies Program Office. Mr. Duong received his M.S. degree in Civil Environmental Engineering, and his B.S. degree in Electrical Engineering from Virginia Polytechnic Institute and State University in Blacksburg, Virginia. He is a member of USABC Managing Committee.

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