In-Vehicle Testing and Computer Modeling of Electric Vehicle Batteries

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Abstract

A combined simulation and testing approach has been developed to evaluate battery packs in real driving conditions as opposed to purely experimental testing. The new approach is cost-effective, greatly accelerates battery development cycle, and enables innovative battery design and optimization. Several fundamental models for valve-regulated lead-acid (VRLA), nickel-metal hydride (NiMH), and Li-ion batteries were developed to simulate in-vehicle performance of battery packs on field trips. Field testing was performed for both VRLA and NiMH batteries using Penn State University's electric vehicle, the Electric Lion. The computer results of voltage and current responses were compared to the field-test data to provide model validation. Furthermore, the model results for the evolution of internal conditions inside batteries were used to reveal their limiting mechanisms.

Introduction

In recent years there has been increasing use of battery modeling and simulation in the exploration and development of advanced batteries for electric and hybrid-electric vehicles. A thorough understanding of battery systems from the point of view of performance, safety, longevity, etc. is critical for these applications. Using traditional testing methodologies to evaluate battery characteristics and obtain a performance envelope under a myriad of operating conditions and environments is a time consuming and an almost impossible task. The present work aims to develop a new approach to evaluating electric and hybrid-electric vehicle batteries by integrating first-principle computer simulation with in-vehicle testing. The approach will be demonstrated specifically with lead-acid, Ni-MH and Li-ion batteries, and the focus is placed on obtaining scientifically sound results for battery packs in real-world driving conditions. Such data are critically needed to test the ultimate ability of a battery model to predict actual EV trips. By combining simulation with field testing at our test track and dynamometer facilities, we shall demonstrate that the performance of a battery pack in actual vehicle trips can be accurately and rapidly predicted. The integrated approach will overcome many existing barriers to the development of EV/HEV batteries by offering the following new capabilities:

- Enable innovative design and improvement by providing insight into the internal conditions of a battery, such as active material utilization, electrolyte distribution, etc.
- Accelerate the development cycle of advanced batteries by allowing engineers to evaluate many design alternatives before building a physical prototype.
- Provide accurate predictions of battery state of charge on-board and hence vehicle driving ranges corresponding to specific battery systems, driving profiles, and terrain conditions.
- Create digitally based (virtual) battery systems for vehicle simulation and integration.

- Facilitate the development of infrastructure such as rapid chargers and battery management systems via high-fidelity computer models rather than physical battery modules and packs.

In-Vehicle Testing

Test Batteries
Test batteries included Horizon lead-acid batteries of 85Ah and Panasonic Ni-MH batteries of 95Ah for electric vehicles.

Test Vehicle
All field testing was performed in the Electric Lion (see Figure 1). The Electric Lion began life as a 1992 Ford Escort Station Wagon. It has since been converted into a range-extending series hybrid electric vehicle (HEV) by the student members of the Society of Automotive Engineers (SAE). A series HEV is an electric vehicle with an auxiliary power unit (APU) that charges the battery pack. The battery pack consists of 12 12V modules. The pack has a capacity of 15 kWh and a nominal voltage of 144 Volts. Two Solectria GTX-20 AC induction motors, which are connected to the front wheels through one speed transmissions, make up the drivetrain. The motors are controlled by Solectria AC-325 controllers and Penn State purpose-built Z80 microprocessor controls.

Figure 1. Test vehicle and track at PTI.

Test Track
The test track also shown in Figure 1, operated by the Pennsylvania Transportation Institute (PTI), is the site of all federal bus testing. Located at this facility are a one-mile oval track, vehicle durability course, impact pendulum, emission testing facility, as well as other equipment. Besides bus testing, crash tests between vehicles and common obstacles found on the road (such as signs and barriers) are performed.

Dynamometer
The Penn State HEV laboratory owns a single roll (soon to be converted into a double roll) eddy current dynamometer manufactured by Clayton Industries. See Figure 2. It is controlled by a personal computer using the Virtual Test Track software. With this software, different types of tests can be performed including constant force, constant power, and even a ¼ mile drag race. Data on the power, torque, speed, and acceleration of the vehicle during these tests is collected and can be displayed graphically or exported to an excel file to be plotted.

Figure 2. Clayton dynamometer

Computer Modeling

Since 1994 we have been developing mathematical models for Lead-Acid, Ni-MH, Li-ion and Li-polymer cells using advanced computational fluid dynamics (CFD). CFD technology is a numerical tool used to analyze and optimize fluid flow, mass and thermal transport, and related phenomena (e.g. chemical reactions) that may simultaneously take place in a complex system. The broad scope, power, convenience, user interface, and pre- and post-processing capabilities developed for CFD over the last decade have made the technique very attractive. Over the past few years, we have successfully adapted the CFD modeling technique for a variety of battery systems such as VRLA, Ni-MH and Li-ion batteries for electric and hybrid vehicles, alkaline primary cells for portable electronics, primary $Li/SOCl_2$ batteries for military applications, and $Ni-H_2$ batteries for aerospace application [1-8]. Our current modeling capabilities can include multiple electrode reactions, charge transfer, multi-component species transport via diffusion, convection and migration, solid state diffusion, gas generation and transport, and heat generation and transport. CFD codes are particularly suited for comprehensive modeling of electrochemical, thermal and gassing behaviors. The CFD battery codes are also Matlab and Simulink compatible so that they are readily integrative in vehicle simulations. The computational efficiency is between 10 and 100 times (10-100x) faster than real-time testing.

Recently, an Internet-based battery simulation environment was also created to provide convenience for using battery models[9]. This online simulation system allows users to submit input files, execute simulations, and receive results via the Internet in an encrypted format anywhere, anytime. With fully interactive pre- and post-processing interfaces as well as visualization and animation tools, this system is particularly useful for battery designers and vehicle builders to collaborate via the Internet in real-time.

Results and Discussion

In the following, in-vehicle testing of Horizon lead-acid and Panasonic Ni-MH batteries on the dynamometer is described and test data are compared to the corresponding computer simulations. Subsequently, a simulation of battery pack performance during a field trip is presented along with its comparison with actual data. Finally, additional modeling capabilities are illustrated through applications to several battery systems.

In-Vehicle Evaluation

Figure 3 displays results of drive testing and corresponding simulation of Horizon lead-acid and Panasonic Ni-MH batteries in Electric Lion on the dynamometer, respectively. It can be seen that the computer simulations reproduce reasonably well the general trends and fluctuations of voltage responses for both types of batteries. Note also that the actual testing took about one hour in both cases, but the computer simulations required only one minute of CPU time on a standard PC.
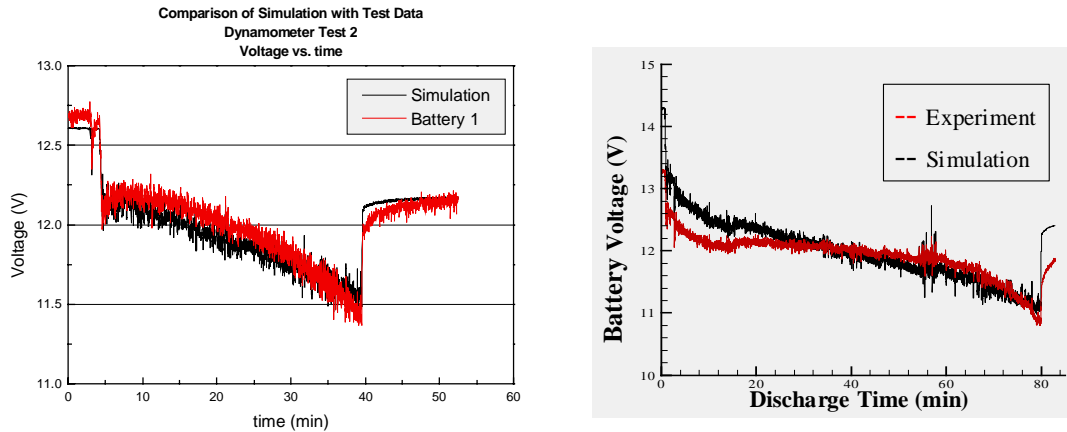

Figure 3. Comparison of in-vehicle test data and simulation results: (a) Horizon lead-acid battery, and (b) Panasonic Ni-MH battery.

Figure 4 further shows a case study to predict battery current and voltage characteristics of a lead-acid battery pack during an S-10 pickup field trip. It is encouraging to see that the predictions follow quite closely with the measured fluctuations.
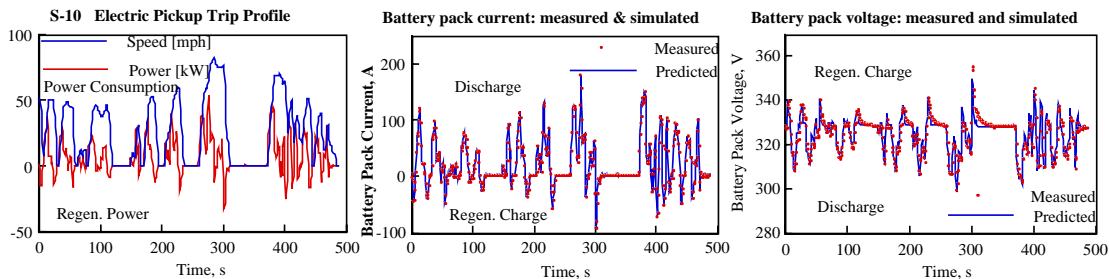

Figure 4. Predicted and measured current and voltage responses of a lead-acid battery pack in an S-10 electric pickup field trip. The field data were obtained from Hawaii NDC.

Additional Modeling Capabilities

The valve-regulated lead-acid (VRLA) battery model has also been extensively validated against laboratory testing under complex EV battery test procedures such as the dynamic stress test (DST). A detailed account of this work was presented in Ref.[4]. A sample result is displayed in Figure 5, which demonstrates the high-fidelity of our model in simulating a commercially available lead-acid battery module undergoing the complex DST. It can also be seen from Figure 5 that the experimental DST cycling has to be terminated at the 80% depth of discharge (DOD) (at about 76 min) in order to avoid battery overdischarge and hence permanent damage, while the virtual simulation can continue the cycling beyond 80% DOD

until the battery is fully discharged (i.e. t≈100 min). This information, not available through pure testing, allows determination of the ultimate limit of a battery under the DST cycle or in a real driving cycle in a non-destructive fashion. More important, the predicted acid distribution in the battery, as shown in Fig.6, indicates that the end of discharge of this battery is due to acid depletion in the positive plate. Figure 6 also reveals that the battery under-utilizes the active material by as much as 70%. Determining the utilization of active materials in a battery is highly desired but extremely difficult, if not impossible, to perform experimentally. The computer simulation provides a powerful alternative. The low utilization that we have found indicates a potential of increasing the energy density and reducing the cost of existing battery technologies by improving the utilization of active materials through better design and engineering.
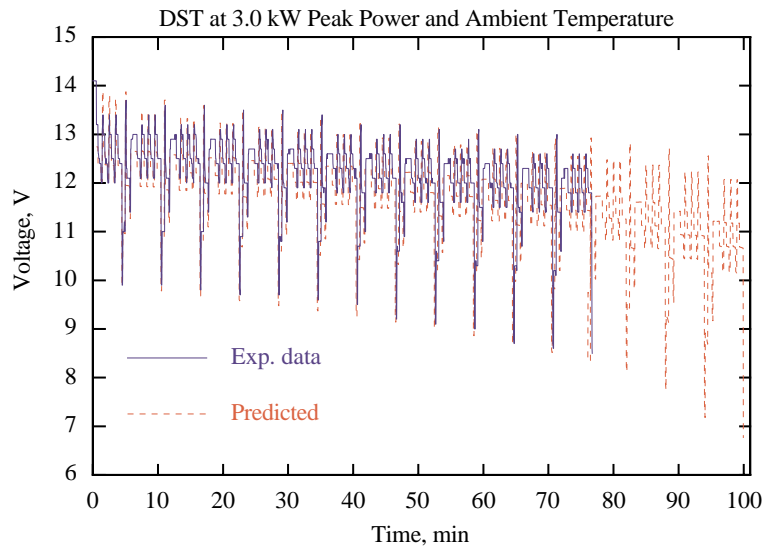

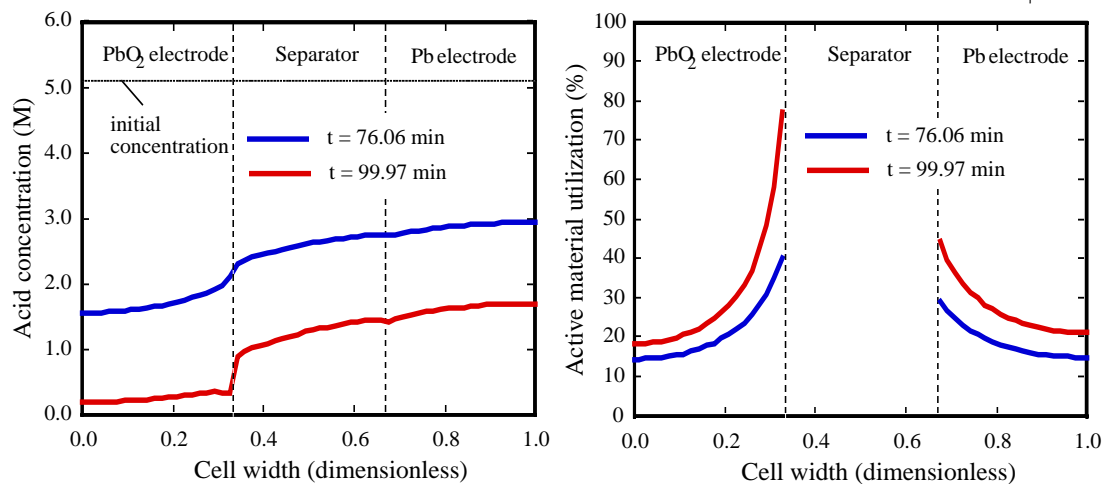**Figure 5. Comparison of experimental and simulated voltage curves in dynamic stress test (DST) cycles.**

Figure 6. Predicted distributions of acid concentration and electrode active material utilization across a lead-acid battery at t=76.06 min (corresponding to 80% DOD as in testing) and t=100 min (corresponding to full discharge as in simulation).

Figure 7 illustrates the capability of a CFD battery model to capture electrochemical, gassing and thermal behaviors of a Ni-MH cell. The cell potential, pressure and temperature can all be predicted simultaneously as shown in Fig.7 [6]. The coupled thermal and electrochemical modeling is necessary because the heat generation rate due to electrochemical reactions and Joule heating can only be calculated via a detailed electrochemical model and, in turn, the resulting temporal and spatial variations in the cell temperature strongly affect the electrochemical and transport processes through temperature-dependent physico-chemical properties. This coupling is also required to capture thermal runaway phenomenon in advanced battery systems[10].
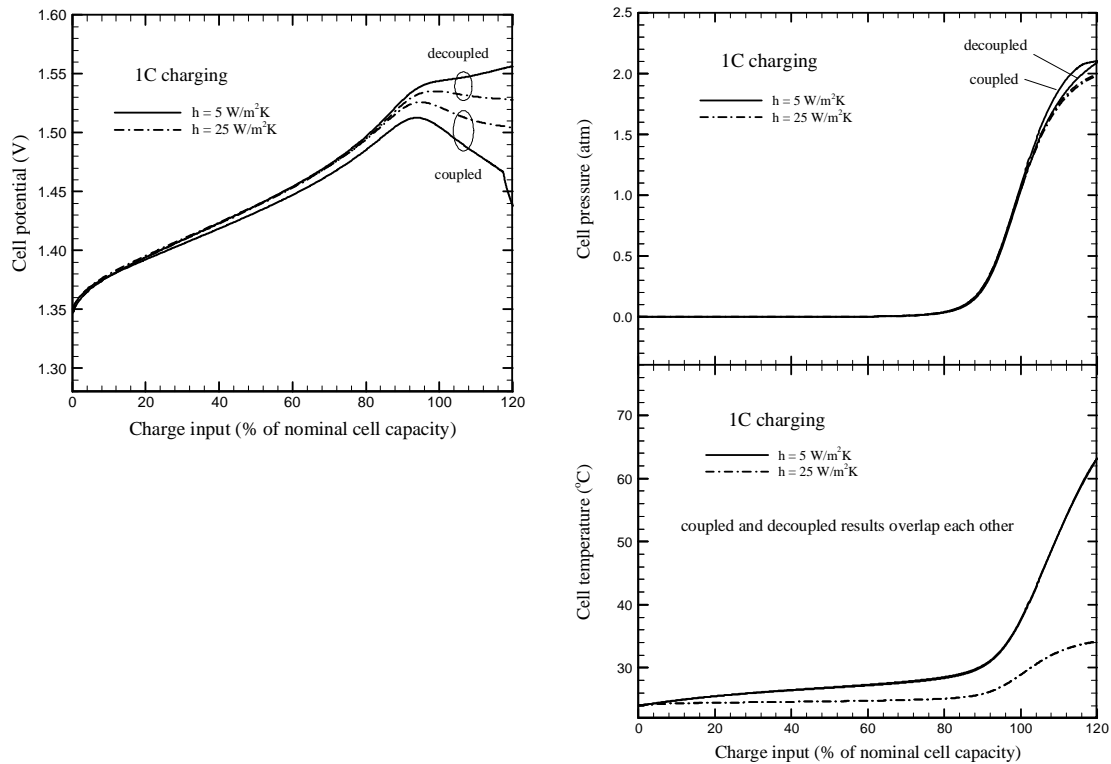

Figure 7. Predicted potential, temperature and pressure curves of a Ni-MH cell during 1C charging. Comparisons of decoupled and coupled modeling results

Figure 8 illustrates a capability of modeling electrolyte flow arising from the change in molar volumes of reactants and products during discharge of a lithium/thionyl chloride cell[6]. It can be seen that we not only accurately predicted the measured discharge curves, as shown in the left panel of Figure 8, but more importantly, the computer simulation has enabled the visualization of electrolyte flow inside the battery for the first time (see Figure 8, right panel).
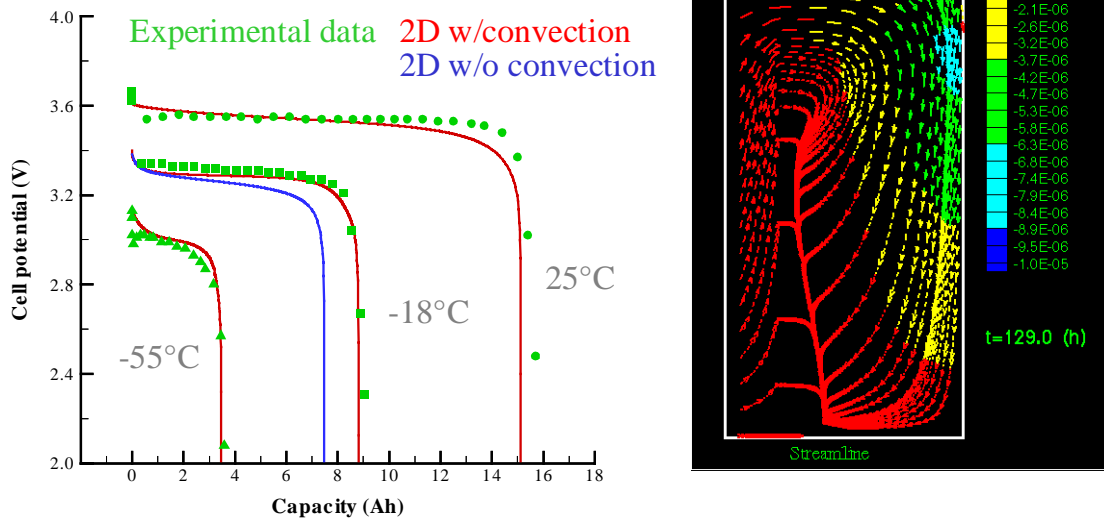
Figure 8. Measured and predicted discharge curves of a Li/SOCl$_2$ battery at various temperatures (left panel) and a snapshot of the computer-animated electrolyte flow inside the battery for the case of –18°C (right panel). The blue curve in the graph on the left represents the model prediction without including electrolyte convection; this indicates that the electrolyte flow must be modeled in order to obtain agreement with the test data.

Figure 9 demonstrates our capability of modeling electrochemical and thermal behaviors of a Li-ion cell. Figure 9 compares the cell potential and temperature under isothermal and non-isothermal (adiabatic) conditions during a 3C discharge, clearly indicating that the thermal environment strongly influences the electrochemical performance of the Li-ion cell. Figure 10 further shows results from a two-dimensional simulation of the Li-ion cell in which two sides and bottom surfaces are thermally isolated but the top is exposed to strong cooling. It can be seen that the temperature gradients develop along the cell height during discharge. The maximum spatial temperature variation is as much as 40°C at the 75% depth of discharge. Such a large temperature gradient results in severe non-uniformity in the electrode reaction rate along the cell height, as also shown in Figure10. Two-dimensional effects are apparent from Figure10 for the large-size cell.
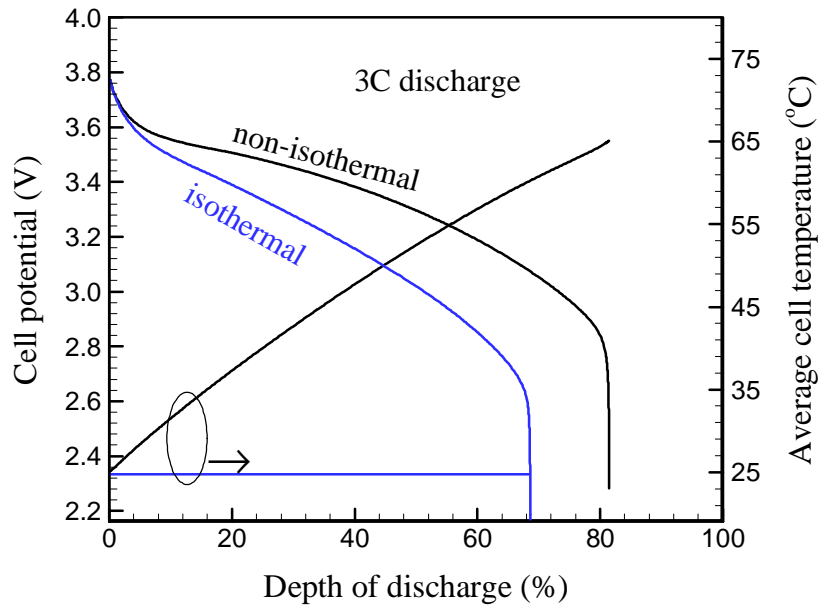
Figure 9. Potential and temperature evolutions of a Li-ion cell during 3C discharge (Gu and Wang, 2000b)
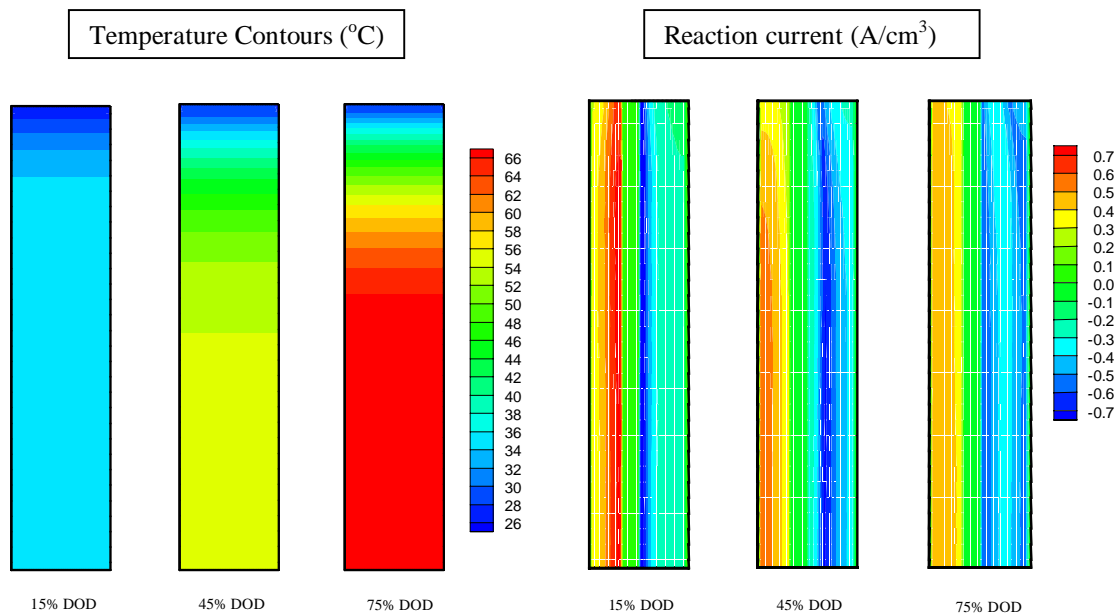

Figure 10. Contours of the temperature and reaction current at various depth of discharge during 3C discharge. The cell width is 0.042 cm with the height to width ratio of 1190. Heat is dissipated only through the tabs (Gu and Wang, 2000b).

Conclusions

Penn State GATE Center for Advanced Energy Storage has developed a novel approach to assessing and improving battery design and applications in electric and hybrid vehicles by integrating first-principle modeling with in-vehicle testing. Significant progress has been made in developing computer models for all EV battery systems based on efficient computational fluid dynamics. In parallel, there exists considerable capability to perform in-vehicle testing either on a dynamometer or a full-scale test track. Combination of the two capabilities promise to enable a completely new paradigm for the development of advanced battery technologies for electric vehicles.

Acknowledgments

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