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JOURNAL ARTICLE

Battery Thermal Management in Electric Vehicles

Advanced numerical simulation helps accelerate the development of safe, long-lasting and cost-effective batteries for electric vehicles.

Xiao Hu, Ph.D.
Lead Engineer, ANSYS, Inc.

In the wake of growing concerns over petroleum supplies and air pollution, electric vehicles (EVs) – including hybrid electric vehicles (HEVs) – are being developed and refined as cost-effective, reliable and safe alternatives to conventional gasoline and diesel engines. The race is on to design electric batteries as the power source for this new class of vehicles. Competition is intense and the stakes are high. Organizations that succeed in bringing cost-effective, long-lasting batteries to market first are in a strong position to dominate the future automotive industry, not to mention reap a sizeable share of profits.

The preferred candidate for EVs is the lithium-ion battery due to its outstanding characteristics such as high energy-to-weight ratio, high voltage, good stability and slow loss of charge when not in use. Lithium-ion batteries have been used extensively since the early 1990s in consumer portable electronic products such as mobile telephones and laptops. Batteries for powering EV powertrains plus auxiliary automotive equipment, however, must ideally provide orders of magnitude more energy, typically 15 or more kilowatt-hours for a driving range of 300 to 400 miles, for example. Battery size for EVs is also proportionately greater, with nearly 300 individual cells sealed in a pack often weighing over 400 pounds and occupying more than four cubic feet – about the space of more than 200 books stacked side by side for more than five feet. Fitting these large batteries into available space is, thus, an important consideration.

Technical requirements for these massive sources of power present engineers with daunting design challenges in meeting the reliability, durability, safety and packaging standards of automotive applications.

CHALLENGES IN BATTERY DESIGN

Batteries are very different from the products traditionally developed by auto manufacturers and suppliers. Chemistry, electricity and flow–thermal–structural physics inside batteries operate in a complex interplay that must be strictly controlled within narrow margins to ensure long battery life and low cost. The slightest deviations from these margins can lead to dramatically shortened battery life – and to serious safety hazards.

One of the major concerns in the development of lithium-ion battery packs for EVs is thermal management. The temperature of all cells must be strictly maintained within a few degrees C across the entire pack. Cells are vulnerable to overheating from rapid discharging, overcharging or excessive ambient heating. Such overheating and uneven temperature distribution can lead to rapid cell degradation and shorten battery life. In extreme cases, thermal runaway may occur in a cell as heat builds up uncontrollably, possibly causing catastrophic destruction, such as fire and explosion.

For these reasons, EV battery packs incorporate extensive cooling systems to dissipate heat and provide for uniform temperatures throughout the battery pack. For air cooling, battery pack housings are shaped for optimal cooling provided by a blower and guiding vanes to direct an adequate airflow, as indicated in Figures 1 and 2. Alternatively, liquid coolant can be circulated through heat exchanger elements in contact with cells. To provide for uniform, adequate cooling, a battery management system (BMS) comprising a controller and control algorithm varies loads on different cells based on temperature and charger status.

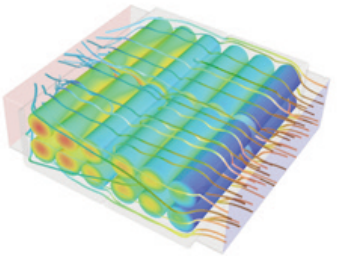


Figure 1. EV battery pack cooling flow paths with temperature distribution on cells

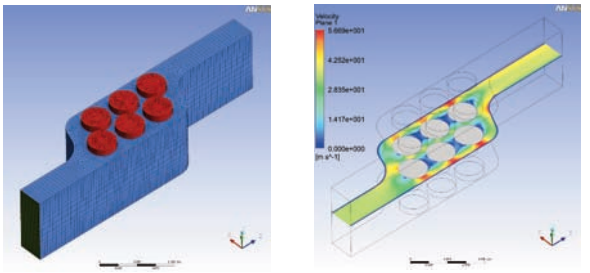


Figure 2. Mesh for air-cooled cylindrical cell module (left) and cooling flow velocity (right)

MANY ASPECTS OF COMPLEXITY

Design of the thermal management system requires extensive knowledge of cooling systems and the amount of heat generated by cells throughout the battery pack. Engineers must also weigh various tradeoffs and factors such as cost, packaging, manufacturability, efficiency, reliability of heat dissipation components, and battery pack as an integrated, modular system.

In terms of total vehicle development, engineers face the challenge of minimizing battery cooling system noise, since the packs are usually located close to the passenger cabin. Such sound levels would normally be drowned out by engine and exhaust noise in petroleum-powered vehicles but may disrupt the ultra-quiet operation drivers expect in an EV.

Engineers must take into account the physical placement of the battery pack within the EV, not only to minimize the effects of ambient temperatures and maximize heat dissipation but also to avoid excessive mechanical stresses, structural fatigue from road vibrations, and potential impact from road debris. The team also must consider crash scenarios in which passengers must be protected from toxic acids released from the battery pack.

HOW ADVANCED SIMULATION CAN HELP

Numerical simulation has been used for decades in automotive development, but batteries require that a unique range of issues be taken into consideration in such studies. First, detailed models and submodels are needed to simulate the chemical and physical phenomena inside battery cells. Then, these models need to be tied into a system-level model of a battery pack, which can comprise hundreds of cells and cooling circuits. Finally, the battery pack model needs to be integrated with the system model of the entire powertrain and vehicle.

In this respect, system integration is perhaps the greatest challenge in the development of battery packs and other major subsystems, all of which must work together in a coherent, tightly coupled manner for the EV to perform at peak performance and efficiency within a wide range of loads and operating conditions. Consequently, the performance of the battery pack cannot be developed in isolation but rather carefully matched with the attributes and characteristics of all others.

VALUE OF AN INTEGRATED SIMULATION PLATFORM

Many simulation codes are available to handle individual aspects of such complex designs. To adequately represent the many interrelated complexities of the battery pack – especially thermal management – simulation solutions must be in the form of an integrated platform. Engineers need tools capable of multidimensional, multiphysical and multiscale simulation that address a wide range of multiphysics phenomenon within the context of the entire vehicle.

- Multidimensional indicates a system comprised of subsystems and components governed by a mixture of physical phenomena that could be 0-D (circuit logic and block diagrams, for example), 1-D (such as modeling flow through long channels), 2-D (stresses on shells, etc.), 3-D (problems such as flow through complex 3-D passages), or 4-D (having time-varying 3-D fields of flow, stress, thermal or magnetic fields). Engineers may use 0-D simulation in creating battery control algorithms tightly integrated with 4-D physical models (fluid dynamics and mechanical) in the control circuit simulation.

- Multiphysical indicates that a system or component is governed by more than one physics. Development of a battery pack may entail the use of fluid flow for studying cooling rates, heat transfer for evaluating thermal levels inside the pack, electrochemistry for characterizing cell behavior, structural stress/strain distributions for solving mechanical scenarios such as a crash or foreign body penetration of the battery pack, electric and magnetic fields radiated

throughout the vehicle, etc. In the commercial arena, ANSYS, Inc. is the only simulation software provider with industry-standard mechanical, fluid dynamics, thermal, magnetics and electrical tools for multiphysics simulation.

- Multiscale means a system has important physical phenomena occurring at different physical scales. In a battery pack, for example, electrochemical reactions occur at a nanoscale, whereas heat transfer and cooling flow are at a macro scale; the battery controller works at the pack level. The capability to span these multiple levels is critical in evaluating the many interrelated aspects of battery development, particularly issues related to thermal management.

An integrated simulation platform is of particular value in battery thermal management on two levels: cell and system. Cell level refers to single battery cell, and system level could be either a battery module or a complete battery pack.

CELL-LEVEL HEAT GENERATION

Studies of detailed heat generation and temperature distribution within individual cells are performed mainly by battery manufacturers and battery researchers investigating how the rate of heat generation varies with time over the course of charging and discharging. Heat can be generated from multiple sources including internal losses of joule heating and local electrode overpotentials, the entropy of the cell reaction, heat of mixing, and side reactions.

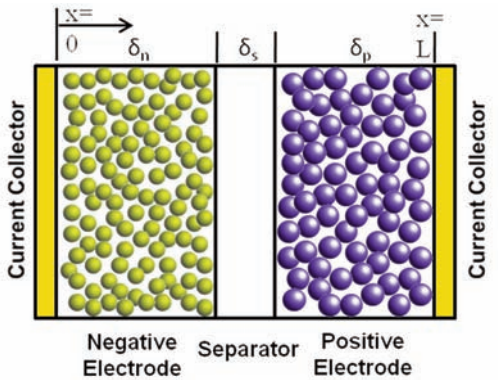


Figure 3. Schematic of lithium-ion cell sandwich consisting of composite negative and positive electrodes and separator

If only the most important effects of joule heating and local electrode overpotentials are considered in such studies, heat generation can be expressed by open circuit potential and potential difference between positive and negative electrodes. Figure 3 shows how electrodes are sandwiched together using a separating insulator. Models then can be used to predict the electric potential and current density distribution on cell electrodes as a function of discharge time. Based on these results, battery temperature distributions can be calculated. Results can then be used to examine thermal behavior with regard to electrode configurations, such as their aspect ratio, placement of current collecting tabs and discharge rates. Figure 4 shows typical results from such models.

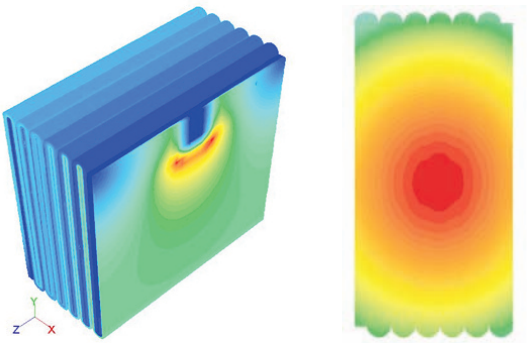
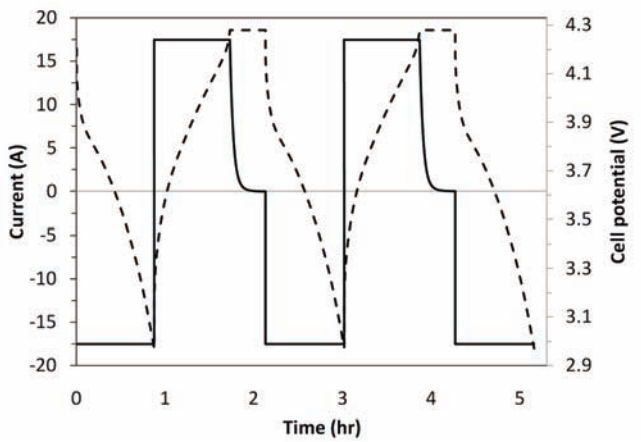


Figure 4. Models based on joule heating experimental data can predict current density distribution (left) and the resulting temperature distribution (right) within a battery cell.

While this type of model is simple to use and gives detailed information about temperatures and current density distributions, it requires entering data from experimental tests. So this type of model cannot predict the impact of design changes on battery thermal performance without performing an entire set of tests again on a modified prototype: a lengthy and expensive process.

In contrast, a physics-based electrochemistry model can be used to more readily investigate the impact on battery performance of design parameters including battery geometry, properties and, most importantly, temperature. In this way, a physics-based model can accurately provide performance data that otherwise would be impractical through testing. The most widely recognized physics-based model originally was proposed by Professor John Newman from the University of California Berkeley. The model has been implemented in Simplorer® advanced simulation software from ANSYS for design, modeling, analysis and optimization of complex multidomain systems. Figure 5 shows charge/discharge results and discharge concentration profiles from Newman's electrochemistry model.



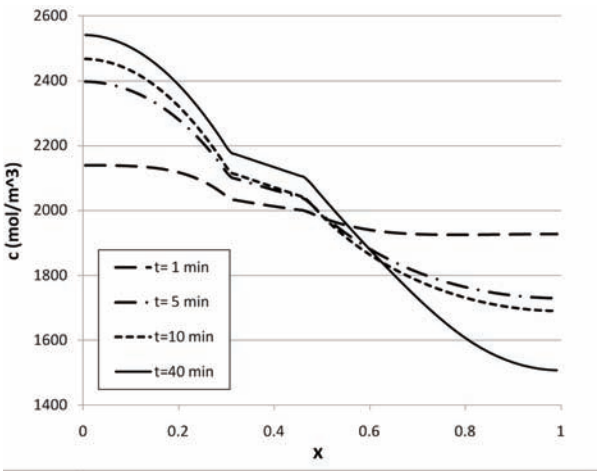
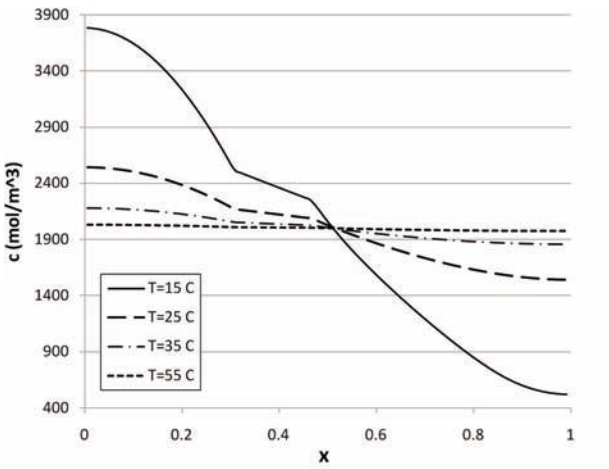


Figure 5. Battery charge and discharge cycle results (left) and concentration profiles during galvanostatic discharge (right) from Newman's electrochemistry model



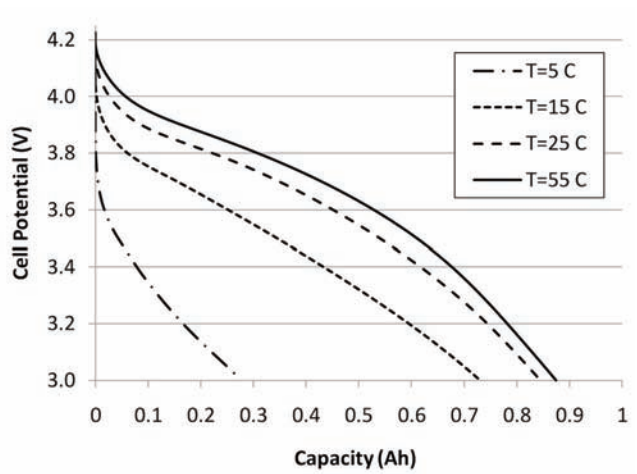


Figure 6. Concentration profiles at the same time and discharge rate but for different temperature based on simulations with Newman's electrochemistry model (left). Discharge curves for different temperature (right)

One optimization problem that suggests itself immediately when examining discharge concentration profiles from Newman's electrochemistry model is determining the initial concentration of electrolyte in the cell. Concentration profiles are presumably determined based on maximum conductivity levels at this concentration. However, discharge profiles may show that the bulk of the composite cathode is at a significantly lower concentration. Conductivity is consequently much lower, leading to severe transport limitations in the depth of the electrode. This provides important insight into electrode behavior: specifically, that a higher initial concentration leads to a somewhat lower conductivity in the separator but a much larger conductivity in the composite cathode.

The simulation can also readily display concentration profiles under different temperatures, as shown in Figure 6. The information contained in such data indicates where the limiting current occurs and, thus, can help battery designers specify temperature ranges that the cooling system must maintain.

Other implications of these profiles for different temperatures is that battery run-time is a strong function of its time in use and that battery life is longer with higher operating temperatures. This is also confirmed in Figure 6 from the physics-based electrochemistry model. Of course, higher temperature is a major safety concern, so this becomes another possible factor in optimizing battery designs.

SYSTEM-LEVEL THERMAL SIMULATION

System-level design engineers working on battery modules and packs have different sets of requirements and goals since they cannot afford to simulate as many details as engineers working on the cell level. For instance, computational fluid dynamics (CFD) engineers working in battery thermal management are interested primarily in maintaining required temperature ranges, reducing pressure drop and maintaining temperature uniformity. For these engineers, detailed heat-generation mechanisms and battery cell structure are not of prime interest.

CFD has been widely used for predicting thermal flow and heat transfer, so the technology is well suited for battery thermal management applications. Significant steps have been taken to make the process easier for users. For example, rather than having different tools for geometry, meshing, post-processing and optimization for CFD analysis, all the aspects of the simulation can be performed under one umbrella with all tools integrated in the ANSYS® Workbench™ environment. Geometries built within these tools or imported from other CAD packages are all parameterized. An update of results due to change of geometric parameters takes just one button click. Data transfer between different simulation tools are handled seamlessly. In this manner, a complete battery thermal CFD analysis including optimization can be done entirely within the same unified environment. Figure 7 shows an automotive CFD application using such an integrated set of tools.

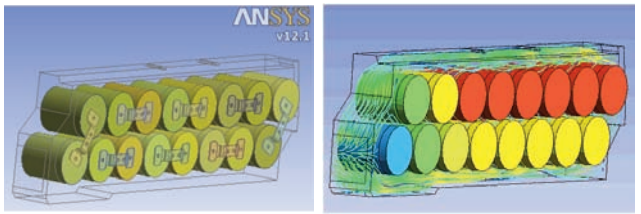


Figure 7. Model of a battery module (top) used for a CFD simulation to study airflow around the 16 cells (bottom)

While CFD can give detailed thermal information about battery thermal management systems, it is time consuming to perform multiple sets of simulations. For these cases, a model order-reduction technique can be used to extract a model from CFD results. The extracted model (called Foster network model) gives the same solution as that from the full CFD model but much more quickly. A CFD model that might take two hours or more to simulate on a single CPU, for example, could be completed with an extracted Foster network model in only about 20 seconds: a time reduction of more than two orders of magnitude. CFD results from these two methods are compared in Figure 8. The model order-reduction process for these rapid simulations can be handled automatically by an advanced multidomain solution, opening the door for studies that would otherwise be difficult or altogether impractical for applications such as battery thermal control system analysis.

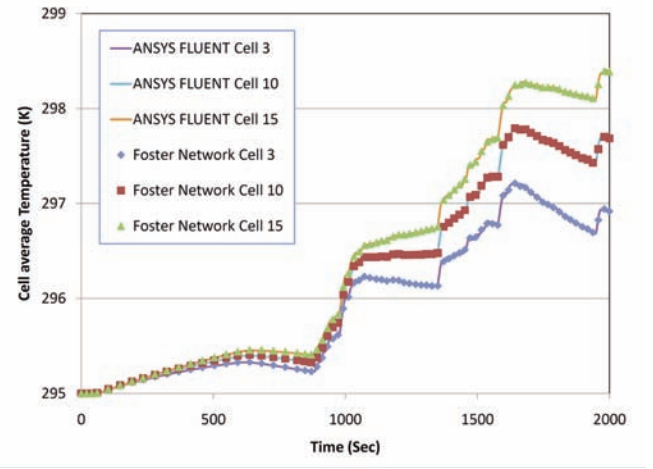


Figure 8. Comparison of CFD results with Foster network results

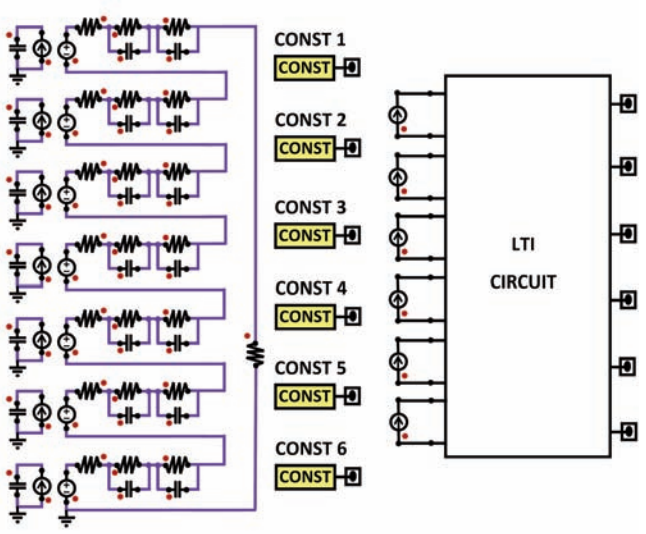


Figure 9. A complete dynamic model is created by coupling an electric circuit model with a Foster network thermal model.

A primary concern for electrical engineers in these applications is the electric performance of the battery, rather than thermal performance. With battery electric performance a strong function of temperature, however, electrical engineers often need an accurate yet simple-to-use thermal model that couples with their battery electric circuit model. The resulting complete dynamic circuit model in Figure 9 accounts for nonlinear equilibrium potentials, rate and temperature dependencies, thermal effects, and response to transient power demand.

While Figure 9 uses the more accurate Foster network as the thermal model, traditional thermal network model can also be used to couple with electric circuit models. With the help of VHDL-AMS (an IEEE standard hardware simulation language supported by advanced multidomain system simulation tools), a traditional thermal network model can be generated easily. In fact, VHDL-AMS can be used for much more complex multiphysics and multidomain problems, and the Newman electrochemistry model mentioned above was generated using VHDL-AMS in such an advanced solution. In this way, an integrated multidomain simulation platform greatly facilitates efforts of entire engineering team working on various aspects of battery thermal management.

ANSYS, Inc.
Southpointe
275 Technology Drive
Canonsburg, PA 15317
U.S.A.
724.746.3304
ansysinfo@ansys.com

Toll Free U.S.A./Canada:
1.866.267.9724
Toll Free Mexico:
001.866.267.9724
Europe:
44.870.010.4456
eu.sales@ansys.com