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# Battery thermal models for hybrid vehicle simulations

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**Abstract**

This paper summarizes battery thermal modeling capabilities for: (1) an advanced vehicle simulator (ADVISOR); and (2) battery module and pack thermal design. The National Renewable Energy Laboratory's (NREL's) ADVISOR is developed in the Matlab/Simulink environment. There are several battery models in ADVISOR for various chemistry types. Each one of these models requires a thermal model to predict the temperature change that could affect battery performance parameters, such as resistance, capacity and state of charges. A lumped capacitance battery thermal model in the Matlab/Simulink environment was developed that included the ADVISOR battery performance models. For thermal evaluation and design of battery modules and packs, NREL has been using various computer aided engineering tools including commercial finite element analysis software. This paper will discuss the thermal ADVISOR battery model and its results, along with the results of finite element modeling that were presented at the workshop on "Development of Advanced Battery Engineering Models" in August 2001.
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*Keywords:* Battery thermal model; Battery thermal management; Vehicle simulations

## 1. Introduction

Electric and hybrid electric vehicles are more energy efficient and cleaner than conventional vehicles. These vehicles' performance depends strongly on their battery pack performance. In general, temperature affects several aspects of a battery including:

- operation of the electrochemical system;
- round trip efficiency;
- charge acceptance;
- power and energy capability;
- reliability;
- life and life cycle cost.

Therefore, it can be concluded that the battery temperature impacts vehicle performance, reliability and life cycle cost. A battery's temperature changes from its initial value because of internal heat generation due to electrochemical reactions and resistance or Joules effect heating known as $I^2R$ heating ($I$ = current and $R$ = internal resistance). External heating or cooling from the surroundings, such as conduction, convection and/or radiation will also change the temperature. Depending on the geometry, material or construction and location of positive and negative terminals, there could be a temperature distribution in a module. As the battery temperature changes, its state of charge, open circuit voltage, internal resistance, power and available energy can change.

In a battery pack, the location of each module, external conditions and type of heating and cooling could create an uneven temperature distribution in the pack. Uneven temperature distribution in a pack could lead to electrically unbalanced modules and thus lead to lower performance for the pack and vehicle. Each battery type works better in a particular temperature range, for example, lead/acid, nickel metal hydride (NiMH) and lithium ion (Li-ion) batteries operate best at temperatures between 25 and 40 °C and at these temperatures they achieve a good balance between performance and life. It is desirable to have a temperature distribution of <5 °C from module to module. In a vehicle, in order to achieve the optimum performance from a battery, a thermal management system is necessary to: (1) regulate the batteries to operate in the desired temperature range; and (2) to reduce uneven temperature distribution.

In order to quantify the impact of temperature on the performance of a battery and thus on the vehicle, temperature dependent battery performance models are needed. The National Renewable Energy Laboratory's (NREL's) advanced vehicle simulator (ADVISOR) [1] predicts battery and vehicle performance for conventional (e.g. non-electrified vehicles on the road today), hybrid, electric and fuel cell vehicles as they vary with drive cycle. There are several

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battery performance models developed at NREL [2] for ADVISOR. These battery models outlined in a companion paper in this publication are: resistance, resistance–capacitance, partnership for a new generation of vehicles (PNGV) model, fundamental lead/acid and neural network. Each of these performance models has an associated thermal model in ADVISOR.

In order to evaluate the thermal performance of battery models and packs and to come up with improved designs, NREL has been using computer aided engineering tools. We have extensively used ANSYS, a finite element analysis, to analyze and design better modules and packs.

In this paper, details of the thermal models for ADVISOR will be discussed and typical results are provided. Interesting results from our finite element thermal analysis will also be provided.

## 2. Battery thermal models in ADVISOR

There are five Matlab-based battery models available in ADVISOR as described by Johnson [2]:

1. an internal resistance model;
2. a resistance–capacitance model;
3. a PNGV capacitance model;
4. a neural network lead/acid model;
5. a fundamental lead/acid battery model.

The first three are equivalent circuit models. ADVISOR has a main lumped capacity battery thermal model and an integrated thermal model in the fundamental lead/acid model. This main thermal model is based on a simple lumped capacitance approach. No thermal model was used in the neural network model in ADVISOR. Battery test data at an operating temperature of 25 °C was used to train the neural network model. Due to the limited temperature range of test data available at the time of the training of the model, the model did not show sensitivity to temperature. Thermal behavior of a battery in the fundamental lead/acid is modeled as an integral part of the electrochemical model. In Section 2.1, we provide a detailed discussion on the lumped capacitance model and a brief discussion of the thermal model in the fundamental lead/acid model.

### 2.1. Lumped capacitance thermal model

The lumped capacitance battery thermal model in ADVISOR was initially developed at NREL by Steve Burch and updated later by Valerie Johnson [3]. The model treats the battery core and battery case as two separate isothermal nodes as shown in Fig. 1. All the components inside the case, such as active material, cathode and anode, current collectors, separator, etc. are assumed to be a single homogenous material with averaged properties. The thermal conductivity of the core is assumed to be very large, making the core and the modules isothermal. Because of the small thermal mass of the case, its temperature is very close to the core/battery.

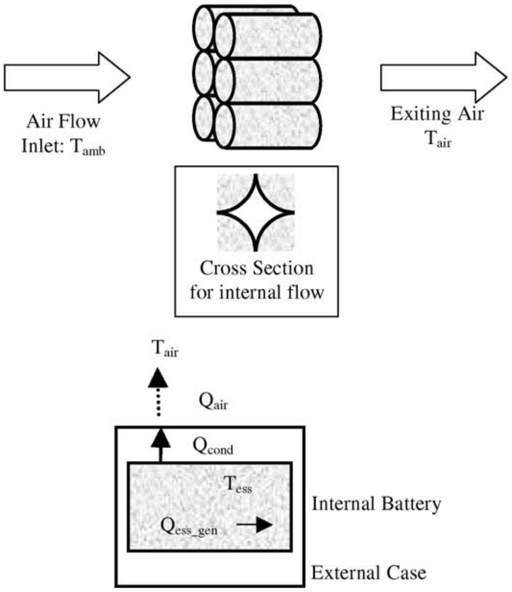

Fig. 1. Schematic of the battery model in ADVISOR.

A variety of active cooling/heating configurations are possible with battery packs, including air versus liquid cooling and parallel flow versus series. Currently the ADVISOR battery model uses the parallel airflow approach. This approach is used in the Toyota Prius and has also been used at NREL for domestic automaker HEV pack development. In this approach, the cooling air is distributed (usually) under the pack and flows up along each module, then is collected in a space above the pack and exhausted. This has the potential advantage of allowing every module to experience the same amount of air and inlet air temperature, leading to a more uniform pack temperature. From a modeling standpoint, it means that the pack thermal behavior can be reasonably represented by modeling a single module. The model is transient and predicts the average temperature of battery core, battery case and exit air.

The heat transfer equations for the battery model are based on the following assumptions. Heat generation ($Q_{ess\text{-}gen}$) in the core of the battery due to electrochemical reactions and resistive heating ($I^2R$) causes increased battery temperature. The subscript ‘‘ess’’ in ADVISOR stands for energy storage system. The heat is conducted through the case material and then convected from the case's external surface to the air or other fluid surrounding the battery.

$Q_{ess\_case}$ is a combination of the conduction and convection from the internal battery to the air:

$$Q_{ess\_case} = \frac{T_{ess} - T_{air}}{R_{eff}}$$

where $T_{ess}$ is the battery temperature (case or core) and $T_{air}$ the temperature of air or fluid surrounding the battery. The effective thermal resistance ($R_{eff}$) is calculated based on

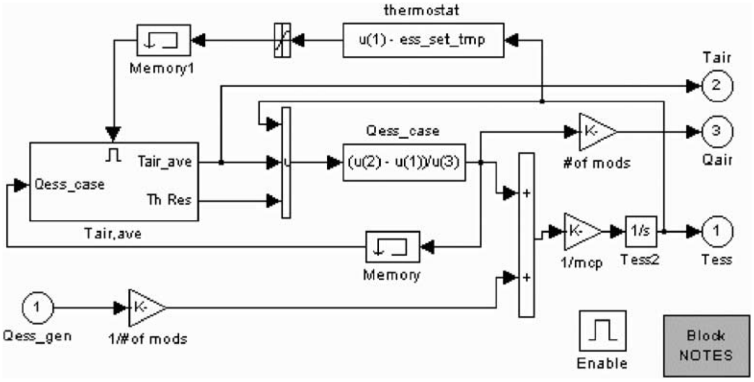

Fig. 2. Matlab/Simulink battery thermal model block diagram in ADVISOR.

conduction resistance through the case and heat transfer film coefficient ($h$) on the air-side:

$$R_{\mathrm{eff}} = \frac{1}{hA} + \frac{t}{kA}$$

$$\text{where } h = \begin{cases} h_{\mathrm{forced}} = a\left(\dfrac{\dot{m}/\rho A}{5}\right)^{b}, & T_{\mathrm{ess}} > \text{ess\_set\_tmp} \\ h_{\mathrm{natl}} = 4, & T_{\mathrm{ess}} \le \text{ess\_set\_tmp} \end{cases}$$

When the battery temperature is below a set point ($T_{\mathrm{ess}} \le$ ess_set_tmp), the airflow is zero and only natural convection provides air-side cooling. When the battery is above the set point ($T_{\mathrm{ess}} >$ ess_set_tmp), the forced convection heat transfer coefficient is used.

The convective loss is a function of the case surface area exposed to the cooling air and the average air heat transfer coefficient over the case. This heat transfer coefficient is estimated from correlations in heat transfer text books by Incropera and DeWitt and includes a minimum value based on natural convection. The user specifies the mass flow rate of cooling air per module. In parallel flow, the total pack airflow is the product of this per-module airflow and the number of modules in the pack. Currently the cooling air inlet temperature is set to ambient. The exit air temperature ($T_{\mathrm{air}}$) is estimated based on the assumption that 50% of the heat from the battery goes into warming the air:

$$T_{\mathrm{air}} = T_{\mathrm{amb}} + \frac{0.5 Q_{\mathrm{ess\_case}}}{\dot{m}_{\mathrm{air}} c_{p,\mathrm{air}}}$$

where $\dot{m}_{\mathrm{air}}$ is the airflow rate and $c_{p,\mathrm{air}}$ its heat capacity. The temperature rise in the battery is calculated based on the energy balance between battery heat generation, amount of heat lost from the battery, thermal mass of the battery and duration of battery use:

$$T_{\mathrm{ess}} = \int_0^t \frac{Q_{\mathrm{ess\_gen}} - Q_{\mathrm{ess\_case}}}{m_{\mathrm{ess}} c_{p,\mathrm{ess}}}\,\mathrm{d}t$$

where $m_{\mathrm{ess}}$ is the battery mass and $c_{p,\mathrm{ess}}$ its heat capacity. The heat generated by the battery is calculated from Coulombic and internal resistance losses. The above differential equations are solved in the Matlab/Simulink environment. Fig. 2 shows the block diagram of the lumped capacitance thermal model. This model is linked to the battery performance model in ADVISOR.

After specifying the module mass, its average heat capacity, case thickness, case thermal conductivity and initial battery temperature, two additional items needed: the module heat generation rate (versus time) and the heat loss from the surface of the module case. As mentioned previously, the battery heat generation is currently modeled via $I^2R$ losses plus losses due to Coulombic (in)efficiency. The Coulombic efficiency is a measure of the heat generated or absorbed due to the chemical reactions of the battery cell. For the current empirical-based model, this efficiency is assumed to be a constant.

In the future, we are planning to use data to estimate heat generation and Coulombic efficiency. For theoretical battery models, the chemical reactions can be solved for explicitly. This is the case with the fundamental lead/acid battery model incorporated into ADVISOR [4].

Fig. 3 compares the temperature rise in a lead/acid battery in a series hybrid under two different drive cycles, US06 and SC03. A series HEV with lead/acid batteries, 10 CFM cooling air per module is run on four US06 cycles and four

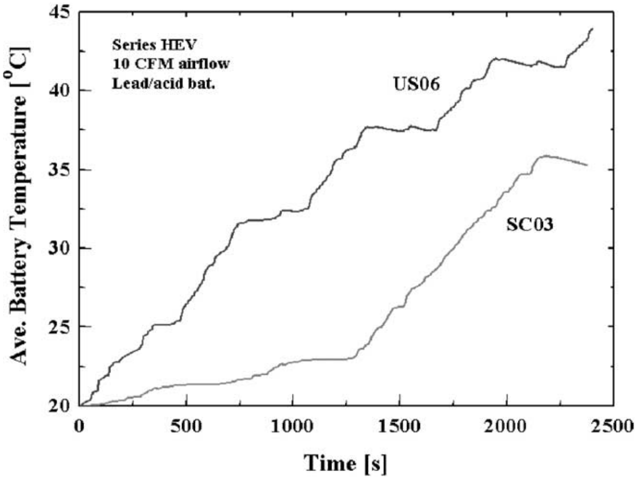

Fig. 3. Effect of drive cycle on battery temperature.

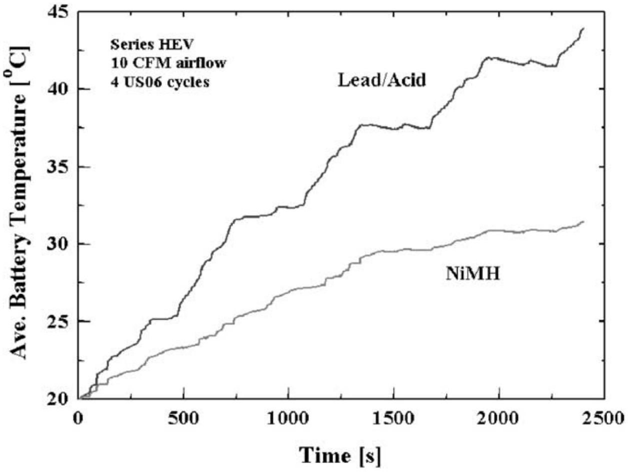

Fig. 4. Effect of battery type on battery temperature.

SC03 cycles. The US06 cycle represents a much more aggressive driving profile than the SC03 and, as a result, is more energy intensive and more power passes through the battery so there are more losses released as heat. As can be seen, the battery temperature rises faster in the US06 case than the SC03 case.

Fig. 4 shows the effect of battery type. The same series HEV with 10 CFM cooling air per module is run on four US06 cycles using lead/acid and NiMH batteries. The NiMH pack remains cooler because it has a lower internal resistance and generates less heat.

A thermostat feature is also included in the model. This is similar to the strategy provided in the Toyota Prius and Honda Insight for controlling battery temperature. By specifying a set temperature, the airflow will start only after the battery temperature rises above this value. An example of the thermostat and airflow effects is shown in Fig. 5. In this case (series HEV running four US06 cycles), the set temperature was 35 °C, after which the fan comes on to deliver 2, 10 or 20 CFM per module (50, 250 or 500 CFM for the pack). It can be seen that as more air is provided for cooling, the battery temperature increases more slowly. Of course higher flower rates result in higher parasitic losses.

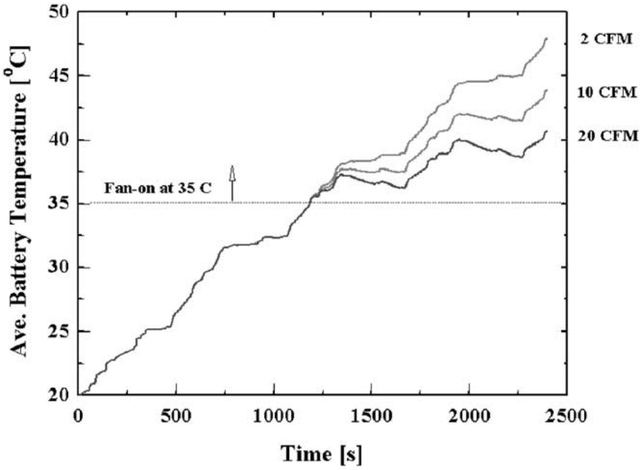

Fig. 5. Effect of cooling airflow on battery temperature.

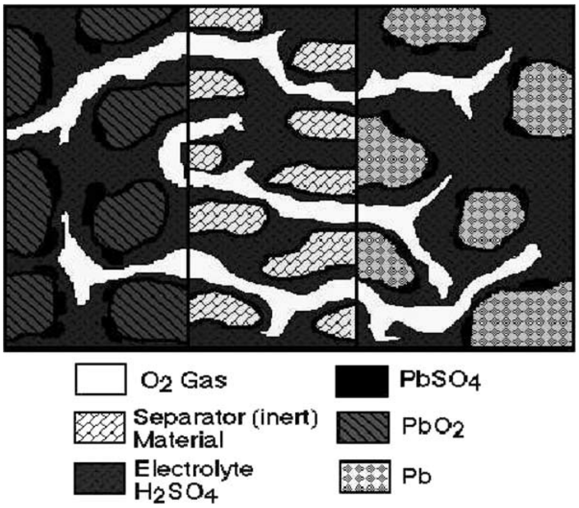

Fig. 6. Fundamental lead/acid diagram by Harb [4].

Combined with the temperature-dependent battery model in ADVISOR, the impact of changing temperature due to various factors can be evaluated on a vehicle level.

### 2.2. Thermal model in fundamental lead/acid model

The fundamental lead/acid battery model was developed by Harb of BYU [4] and was implemented in ADVISOR in 1999 [2,3]. A diagram of the model is shown in Fig. 6. The model is based on physical and chemical reactions for a plate (one-dimensional). The model includes performance and material property variation with temperature. The thermal aspects of the model include Joule heating in the electrolyte and energy dissipated in the electrode overpotentials. The temperature effects are coupled with electrochemical

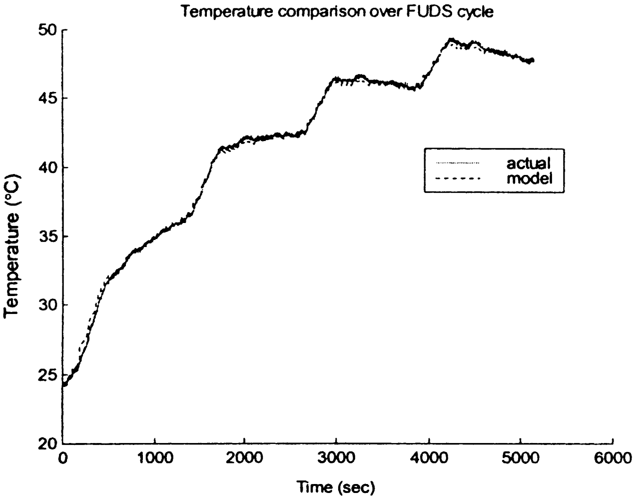

Fig. 7. Thermal model prediction vs. Optima data for fundamental lead/acid model over four FUDS cycles.

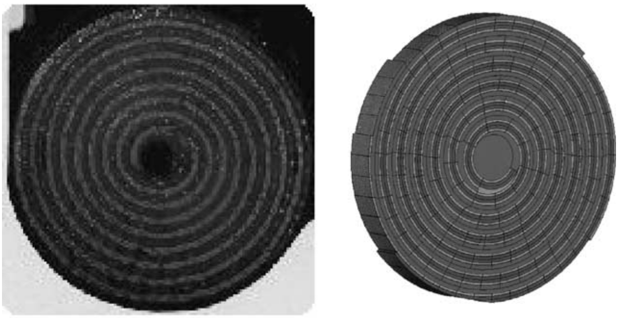
a. cell cross section
b. computer model

Fig. 8. (a) Cross-section of a spiral wound lead/acid cell (from Optima batteries) and (b) its finite element model.

effects. Fig. 7 shows that the average temperature predicted by the thermal model agrees well with data from tests with Optima batteries [4].

## 3. Finite element analysis battery model

In order to evaluate the thermal performance of a battery module or design modules and packs with better thermal performance, we have used finite element analysis software for performing two- and three-dimensional thermal analysis. We have used ANSYS, a widely accepted commercial software package. In this section, a summary of work done previously is provided.

The first example provided here is a finite element thermal analysis of a slice of a spiral wound lead/acid battery from Optima batteries. Fig. 8a shows the cross-section of one of the cells. The cell consists of layers of positive plate, active material, separator and negative plate windings. Fig. 8b shows the finite element model representation of the same cell cross-section. Fig. 9 shows the temperature distribution in the finite element model for 20 A discharge. Although the temperature distribution was asymmetrical due to the locations of the two terminals, there was relatively little temperature (<2 °C) difference in the cell. This was due to high thermal conductivity in the radial and tangential directions. From this observation, one can conclude that treating the core of the module as a homogeneous material but with different thermal conductivities in different directions is a reasonable assumption.

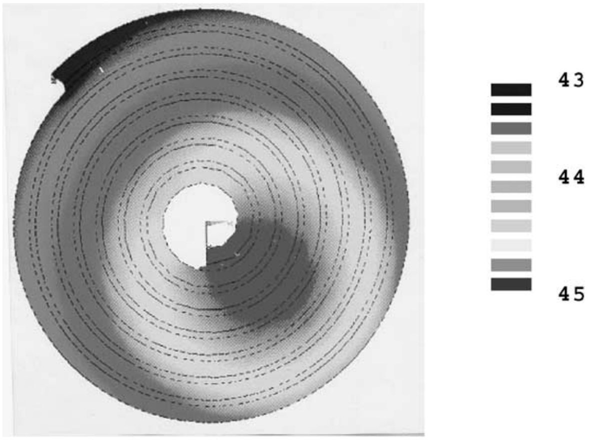

Fig. 9. Temperature distribution in the spiral wound cell of Fig. 8.

Fig. 10 shows how the two-dimensional finite element thermal analyses can help improve the thermal performance of a battery design without any changes in the electrochemical design [5]. By adding cooling holes to an Optima module, the maximum temperature in the battery dropped from 53 to 44 °C under the same discharge profile. The temperature gradient in the module also decreased from 13 to 9 °C.

Three-dimensional finite element analysis reveals information about internal temperature gradients in all directions. Fig. 11 shows a computer model of half of an Optima (16.5 Ah, 12 V lead/acid HEV) battery. We assumed that the active core of each cell consisted of one homogeneous material with average/effective properties of all of its constituents. Based on an electrochemical model of the Optima cell, developed by Harb [4], we varied the internal local heat generation along the axis/length of the cell/module. Fig. 11

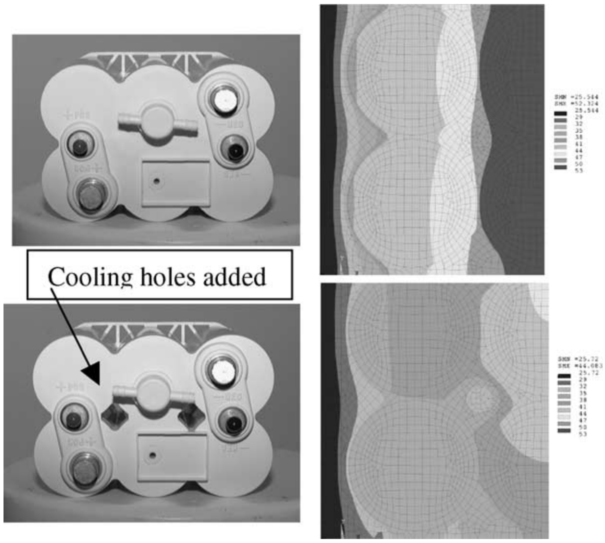

Fig. 10. Two-dimensional finite thermal analysis of an Optima battery. Top is the design and the results with no cooling holes, bottom is with cooling holes (dark is higher temperature.)

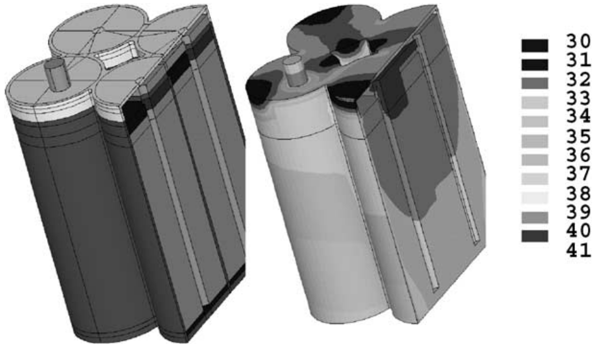

Fig. 11. Three-dimensional model (left) and temperature distribution (right) for a lead/acid battery.

shows the results of the steady-state temperature distribution in the module, assuming the module is charged–discharged continuously. The axial temperature gradient observed is due to the variation in heat generation across the length.

Finite element analysis can also aid in evaluating battery pack designs [5]. For example, we conducted two-dimensional thermal performance for two air cooling methods for an EV or series HEV battery pack (Fig. 12). The first method is series cooling, where air enters from one end of the pack and leaves from the other, exposing the same air to several modules. The second method is parallel cooling, where the same total airflow rate is split into equal portions and each portion flows over a single module. Note that in series cooling, the temperature of the modules varies from one side of the pack to the other. Parallel airflow provided a more even temperature distribution among the modules in the pack. Toyota's Prius hybrid uses parallel cooling for its prismatic battery pack.

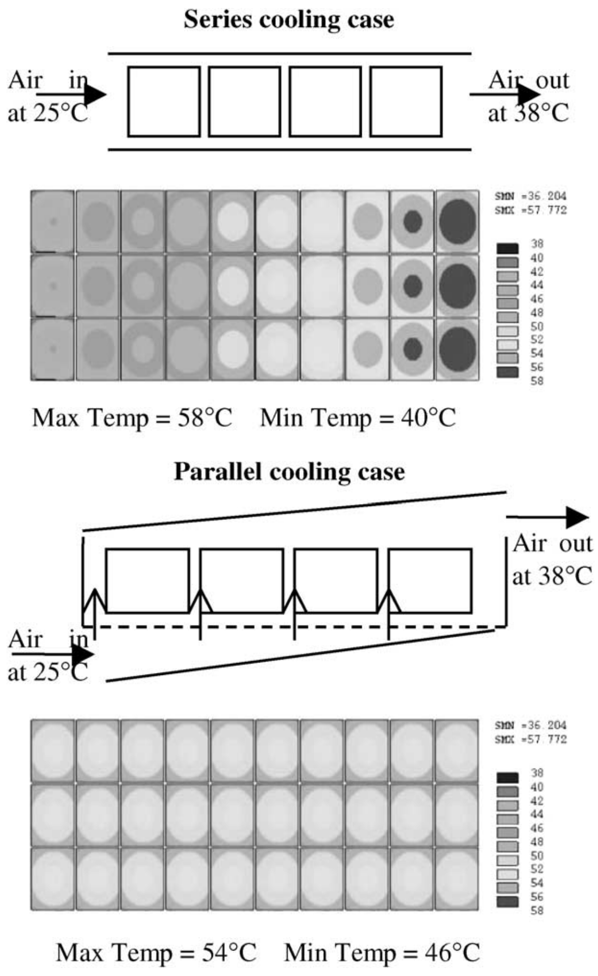

Fig. 12. Two-dimensional analysis of a 30-module battery pack with two types of air cooling.

## 4. Summary and future work

We use different thermal modeling approaches to predict thermal performance, predict the impact of temperature on vehicle level performance and evaluate and design battery modules and packs. The lumped capacitance thermal model in the ADVISOR simulation tool is integrated with its battery performance models and allows us to predict the temperature changes in a vehicle's battery according to the drive cycle, air cooling flow rate and battery type. Since the battery performance model is temperature-dependent, the impact of varying temperature on battery performance automatically affects the vehicle performance. We used a finite element analysis method to evaluate thermal behavior of modules and packs based on their physical geometry. This approach allows us to study temperature distribution in a module and a pack and to come up with better designs.

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