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Cooling and Preheating of Batteries in Hybrid Electric Vehicles

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ABSTRACT

The performance of a hybrid electric vehicle (HEV) depends strongly on the performance of its high-voltage battery pack, which is influenced by temperature. We have been working on thermal management of batteries in HEVs, including cooling and heating issues. In cold temperatures, batteries perform poorly because of high internal resistance; the vehicle may start slowly. The battery may need to be preheated by heating the internal core, heating the external of a module with electric heaters or a hot fluid, or heating around each cell in a module with electric heaters or a hot fluid.

We used finite element thermal analysis to analyze the transient thermal behavior of a typical battery for each preheating method and compared the energy required to heat the battery. Heating the internal core with alternating current (AC) through battery terminals was the most effective and energy-efficient method. Although direct current (DC) can heat the battery, it may damage the battery. We found that 100 Amp, 60 Hz AC heating was effective for warming up a non-operating 16 Amp-h lead acid battery at -40°C to deliver an acceptable performance. However, 60 Hz AC heating is good for electric vehicle applications. For HEV applications, higher frequency currents must be used for smaller and lighter power electronics and for an on-board generator. We have tested the feasibility of a high frequency heater circuit for on-board vehicle use. Preliminary results have shown that applying a 60 A, 10 kHz current to a nickel metal hydride pack initially at -20°C restored the battery performance close to its +25°C performance in less than 3 minutes.

This paper provides an overview of battery thermal management progress for HEVs, the results of finite element thermal analysis, and experimental results of AC heating of batteries.

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NOMENCLATURE

m = module mass (kg)
C_p = specific heat of the module (J/kg °C)
Ibat = current through the battery (A)
T = module temperature (°C)
T_0 = initial module temperature and ambient temperature (°C)
t = time (S)
Δt = time difference (S)
Rbat = Battery Internal resistance (mΩ)
q = heat rate added to in the battery (W)
Q = amount of energy/heat added to the battery for preheating in Δt seconds (J or Wh)
h = heat transfer coefficient (W/m^2/°C)
HEV = hybrid electric vehicle
EV = electric vehicle
NiMH = nickel metal hydride
Li-Ion = lithium ion
W = width of a module (m)
L = length of the module (m)
A = module external surface area (m^2)
Arms = Amp root mean square (A)
Ah = Amp hour – measure of batter capacity
$\partial T / \partial t$ = rate of change of module temperature with time (°C/S)
cell = a single unit consists of all components that make the electrochemistry work, usually 1–4 volts.
module = consists of a number of cells assembled together as a packaged unit with voltage of 12–50 volts.
pack = consists of many modules in series with needed electronics for interface with the vehicle. Pack voltage can be 100–300 volts.
SOC = state of charge of battery (capacity/total rated capacity)

INTRODUCTION

Hybrid electric vehicles (HEVs)—powered by a gasoline engine and a battery-powered motor—have been introduced to markets in Japan and the United States [1], and several models will be available during the next few years. Both a gasoline engine and an electric motor move an HEV. A high-voltage energy storage device such as battery powers the motor. The performance of an HEV depends strongly on the performance of its high-voltage battery pack. Battery temperature influences the availability of discharge power (for startup and acceleration), energy, and charge acceptance during energy recovery from regenerative braking. These affect vehicle drivability and fuel economy. Temperature also affects the life of the battery and its replacement frequency. Therefore, batteries should operate within a temperature range that is optimum for performance and life.

The optimum operating temperature range varies with battery type. The batteries that could be used for HEVs are lead acid, nickel metal hydride (NiMH), and lithium ion (Li-Ion). NiMH is the leading choice because the batteries perform well, are safe, and are durable. Usually, the optimum battery temperature range (according to the battery manufacturer) is much narrower than the vehicle manufacturer's specified operating range. For example, the operating temperature for a lead acid battery should be 25°C–45°C; however, the specified vehicle operating range could be -30°C–60°C. Therefore, HEV batteries must be thermally managed for hot and cold climates and seasons. They must be cooled (by air or liquid, passively or actively with an external sink) to maintain an acceptable lifespan. They can also be heated using an external sink or through the internal resistive heating (Joules effect).

The National Renewable Energy Laboratory (NREL) has been working with industry partners on thermal analysis and management of batteries in HEVs. To evaluate battery pack designs and provide solutions to battery thermal issues, we have used heat transfer and fluid flow principles, finite element thermal analysis, and heat transfer and fluid flow experiments [2,3,5]. We have used thermal imaging techniques and a battery calorimeter to measure thermal characteristics of modules and cells in support of battery pack thermal evaluation and design [2,4,5,6]. For more information and publications, visit the Battery Thermal Management Web site: http://www.ctts.nrel.gov/BTM.

This paper contains a summary of previous work on thermal management/cooling of batteries. The major focus is on battery preheating in very cold temperatures. The finite thermal analysis results on typical modules and experimental results on two types of battery are discussed.

BATTERY THERMAL MANAGEMENT

Background

The goal of a thermal management system in an HEV is to maintain an acceptable temperature range in a battery pack (dictated by life and performance trade-off) with even temperature distribution (or only small variations between the modules and within the pack) as identified by the battery manufacturer. However, the pack thermal management system has to meet the vehicle manufacturer's requirements—it must be compact, lightweight, low cost, easily packaged, and compatible with location.

A thermal management system may use air for heating, cooling, and ventilation (Figure 1), liquid for cooling/heating (Figure 2), insulation, thermal storage such as phase change materials, or a combination of these methods. The thermal management system may be passive (only the ambient environment is used) or active (special components provide heating and cooling at cold or hot temperatures).

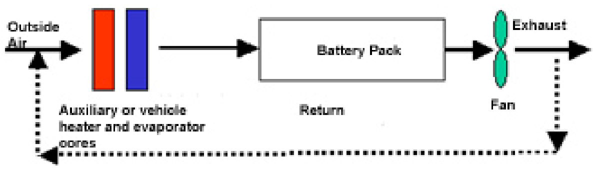

Figure 1. Schematic for air heating and cooling – outside or cabin air

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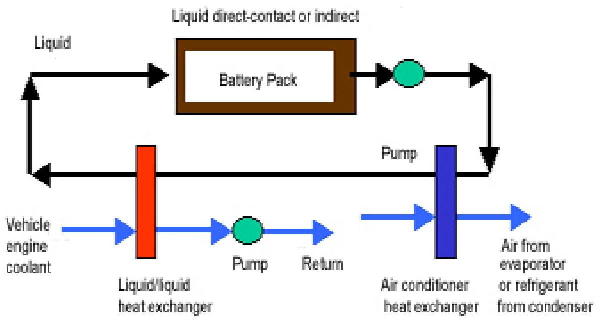

Figure 2. Schematic of Liquid Heating and Cooling

NREL has investigated various elements that affect the thermal management of battery packs and has proposed a systematic approach to designing and evaluating a battery management system [3]. With passive cooling, the battery is cooled or heated with ambient air (outside or cabin air passed through the battery pack as in the Toyota Prius hybrid [1]). Passive systems work well in mild climates; however, an active system is needed in more extreme climates. In an active system, ambient air or a circulating liquid is cooled through heat exchange with a heat sink such as evaporators run by a vapor compression system. The source and type of heat sink depends on vehicle design and the location of the battery pack. Battery location is vehicle specific, so it is not discussed here. However, we briefly discuss air versus liquid cooling and parallel versus series cooling, as they have a general impact on thermal performance.

Air Cooling versus Liquid Cooling

The heat transfer medium has a significant impact on the performance and cost of the battery thermal management system. Heat is transferred with air by directing or blowing the air across the modules. Heat is transferred with liquid through discrete tubing around each module; with a jacket around the module; by submerging modules in a dielectric fluid for direct contact; or by placing the modules on a liquid heated or cooled plate (heat sink). Using air as the heat transfer medium may be the simplest approach, but may be less effective than heat transfer by liquid.

For the same flow rate, the heat-transfer rate for most practical direct-contact liquids such as oil is much higher than with air because of the thinner boundary layer and higher fluid thermal conductivity. However, because of oil's higher viscosity and associated higher pumping power, a lower flow rate is usually used, making the oil heat transfer coefficient not only 1.5–4 times higher than with air. Indirect-contact heat transfer liquids such as water or water/glycol solutions generally have lower viscosity and higher thermal conductivity than most oils, resulting in higher heat transfer coefficients. However, because the heat must be conducted through walls of the jacket/container or fins, indirect contact effectiveness decreases.

Although liquid cooling/heating is more effective and takes up less volume, it has drawbacks. It could have more mass, may leak, may need more components (comparing Figures 1 and 2), and could cost more. Maintenance and repair of a liquid cooled pack is more involved and costlier. Indirect liquid cooling, with either jackets or cold plate, is easier to handle than direct liquid cooling. On the positive side, a liquid cooled system offers the flexibility of placing the pack in areas that air could not be easily available or should be sealed from the road environment. Because of its effectiveness, better temperature distribution, and flexibility for location in a vehicle, liquid cooled systems will appear in future HEVs.

Series versus Parallel Flow Distribution

There are two methods for distributing air to a pack for cooling and heating: *series* cooling, where air enters one end of the pack and leaves through the other, exposing the same amount of air to several modules; and *parallel* cooling, where the same total airflow rate is split into equal portions each of which flows over a single module. Depending on the size and geometry of the modules, series-parallel combination could be configured. Parallel flow provided a more even flow and temperature distribution among the modules [2,3]. Battery packs in GM EV1, Toyota RAV4-EV, and Honda Insight HEV all have either series or series-parallel air distribu- tion. The Toyota Prius (model year 2000 and later) uses a parallel air distribution system for more even tempera- ture distribution. In parallel flow design, distributing airflow uniformly to a large battery pack will require a careful design of the air manifold.

So far, industry has focused most of its thermal management attention on battery cooling because of immediate concern about the impact of high operating temperature on battery life and related impacts of warranty issues. Battery heating receives much less attention because HEVs are used mostly in milder climates. They may perform sluggishly in cold temperatures (around -10°C to -30°C). In the next section we present the results of our recent work for heating batteries at very cold temperatures. We refer to this method as *preheating*.

BATTERY PREHEATING

Background

All batteries suffer in cold temperatures because their electrochemical processes slow and overall internal resistance increases. Figure 3 provides NREL's data showing an example of loss of power capability of a NiMH battery as temperature decreases. Tests performed per PNGV Battery Test Manual [10]. Little power is available to assist the engine at –30°C. Although all vehicles suffer in performance at very cold temperatures, HEVs may suffer even more because of poor battery performance, leading to consumer rejection. Therefore, at very cold temperatures HEV batteries must be preheated to achieve acceptable power and energy performance.

There are two questions for preheating batteries:

- What sources of energy and heat are available?
  - Engine heat using a fluid (air or liquid). This could be slow because engine performance is sluggish at cold temperatures.
  - Battery energy. Drawing electric power from high voltage battery pack, even at low current, can warm the battery because

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the resis- tance (and resistive heating) is very high.

  - Electricity from a generator/inverter to preheat a battery. Additional hardware is required. Ashtiani and Stuart [7] have discussed this and the previous option.
- How are the energy and heat transferred to the battery?
  - The battery core could be heated internally by applying electricity (electrochemical components).
  - A module could be heated externally using an electric heater.
  - Each cell in a module could be heated externally using an electric heater.
  - Each cell could be heated internally using a hot fluid.
  - Each module could be heated externally using a hot fluid.

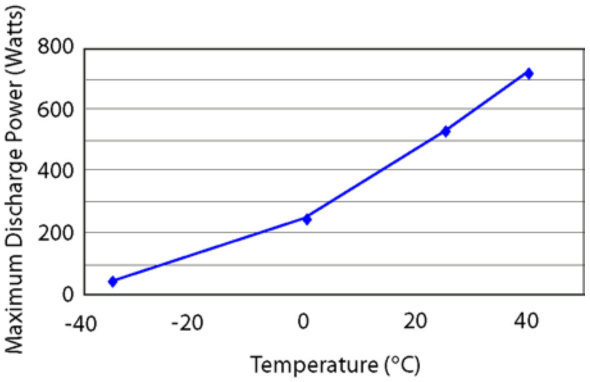


Figure 3. Maximum Discharge Power from a Panasonic Prismatic 6.5 Ah NiMH Module (7.2 Volts) and 55% SOC (based on 18 s discharge pulses performed at NREL)

In the following sections, we assume that energy or heat is available for preheating the battery and we will focus how to transfer this energy to the battery.

Minimum Heat/Power Calculations

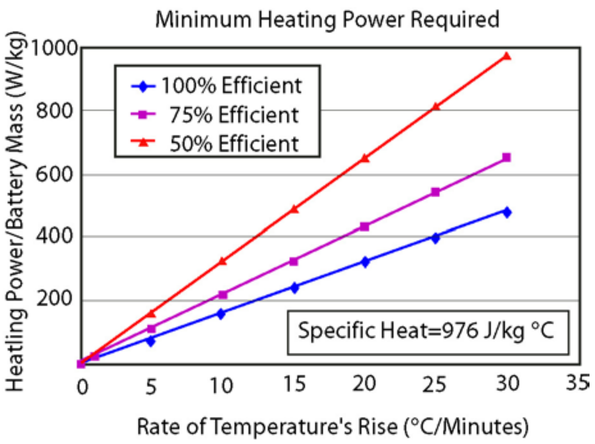
We made a simple lumped capacitance calculation to estimate how much energy and power is needed to raise the internal temperature of a battery by a particular amount in a specific time. We assumed that a battery module behaves isothermally as it heats up, and that its thermal conductivity is very high. The transient lumped capacitance energy balance (heat transfer equation) can be written as:

Eq. (1) $$mC_p \partial T / \partial t = q - hA(T - T_0)$$

Total energy needed to heat battery in Δt is calculated from

Eq. (2) $$Q = q\Delta t$$

For simplicity, the term " $hA(T - T_0)$ ", which represents the heat loss from the battery module, is assumed to be negligible compared to q. We further assumed that the efficiency transferred from the source to the module could vary 50%–100%. Figure 4 shows the results of these assumptions and calculations for a typical battery (such as Panasonic NiMH modules used in a Toyota Prius with mass of 1.083 kg C_p of 976 J/kg°C, [6]). The results are given for the minimum heat required per unit mass of each module. Values for a battery pack can be obtained by multiplying the power and energy requirements by the number of modules. For example, to raise the temperature of a 40 kg battery pack from -30°C to 0°C in 2 min, 9.76 kW of power (or about 325 Wh (of heat energy) is required for a 100% efficient process. For a 50% efficient process 19.52 kW (or about 650 Wh energy) is required for 2 min. Based on discussions with automakers' engineers, such energy and power are available on-board for preheating the battery.



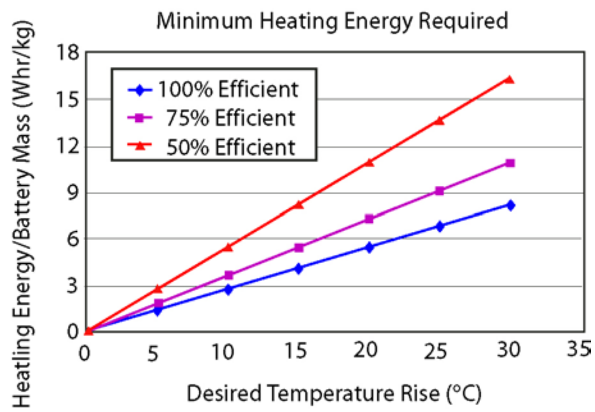


Figure 4. Minimum specific energy and power needed for raising the temperature of a typical battery.

Finite Element Analysis

We used a rectangular battery design and finite element analysis to evaluate four heating methods: 1.) internal core heating, 2.) external electric heating of a module, 3.) internal electric heating in the module around each cell, and 4.) internal fluid heating around each cell. Details are presented in Vlahinos and Pesaran [8].

A parametric three-dimensional transient thermal finite element model of a typical battery module with six cells was built and analyzed using widely used commercial software called ANSYS (www.ansys.com).

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We modeled the battery cell using a homogeneous core, a plastic case, and a contact resistance (or a spacer) between cells. The same amount heat was applied to the battery either externally through electric heaters or internally in the core. For Cases 1 through 3, we assumed natural convection on the exterior surfaces. The heat transfer or convection film coefficient for the side surfaces was assumed to be 2.0 W/m^2 K. The film coefficient for the top surfaces was assumed to be 3.0 W/m^2 K. The film coefficient for the bottom surfaces was assumed to be 1.0 W/m^2 K. The environment (bulk temperature for all convection surfaces) and initial module temperature were considered to be -40°C. In Case 4, the heat provided using hot fluid (air or liquid) around each cell was modeled by forced convection on all exterior surfaces. The heat transfer or forced convection film coefficient for the side surfaces was assumed to be 25.0 W/m^2 K. The film coefficient for the top surfaces was assumed to be 5.0 W/m^2 K

Figure 5 shows that for a battery module with a small aspect ratio (width/length), electric core heating is more effective than external jacket electric heating (around each cell).

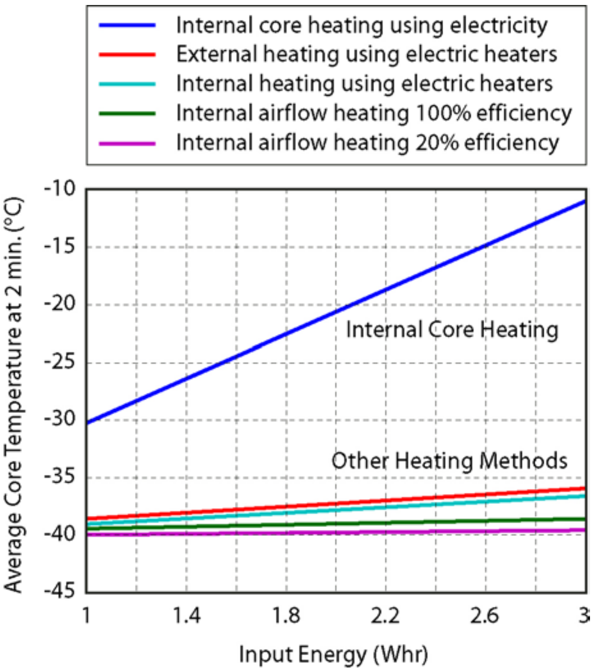

Figure 5. Comparison of various methods to heat a battery with small aspect ratios (width/length)

Thermal finite element analysis also showed that core heating or internal heating (around each cell) methods were more effective than internal heating using hot fluid around each cell. Electric heating raises the battery temperature faster than heating with fluids. In addition, internal core heating provides more even temperature distribution.

To investigate the impact of aspect ratio on these results, we conducted another set of finite element analysis comparing a rectangular battery with aspect ratio of 2 to the same battery type with aspect ratio of 17 (Figure 6). The battery with aspect ratio of 17 resembles the dimension of the Panasonic NiMH battery in a 2002 Toyota Prius. For the same amount of heat per unit weight the core (6.62 Wh/kg), Figure 7 shows that core heating is still better than internal jacket heating for either large or small aspect ratios. Increasing the aspect ratio improves the external jacket heating by a slight margin. These results indicated that core heating is the most efficient method for battery preheating. Based on this conclusion, we initiated tests to apply heat to core of the battery. Next section provides the results of experiments we conducted to evaluate the feasibility of core heating.

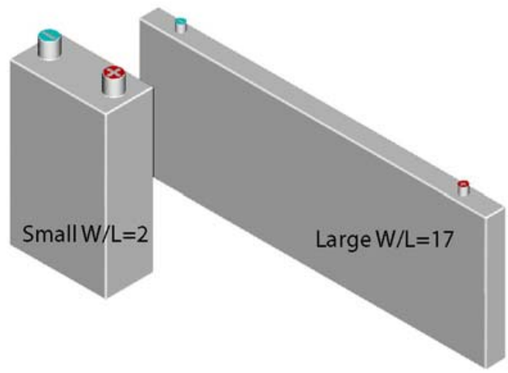

Figure 6. Three-dimensional view of two rectangular batteries with different aspect ratios

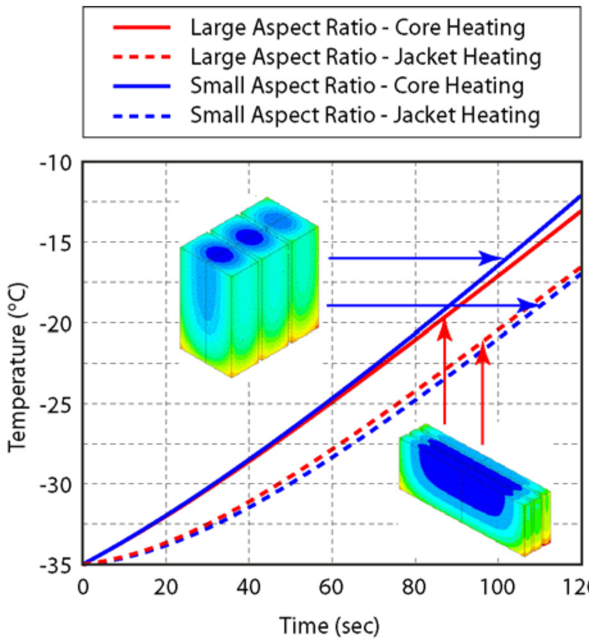

Figure 7. Comparing results of heating two rectangular batteries with different aspect ratios for heating rate (Energy input of 6.62 Wh/kg in 2 min)

Experimental Results—Battery Preheating

To heat the core, electrical energy must be applied to the battery through its terminals. The energy can be from the battery or from an external source such as an on-board generator/inverter. Working with the University of Toledo, we investigated practical methods to apply this technique to lead acid and NiMH batteries.

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Battery electrical resistance is high at cold temperatures because of lower mobility of electron transfer and diffusion of ions. Thus, charging or discharging can heat the battery because of Joules effect heating. However, applying direct current (DC) at very cold temperatures (-30°C) could damage batteries [9]. Applying high frequency alternating currents (AC) may heat up the battery without too much energy loss and battery damage. When AC power is applied, the battery cycles quickly through brief charge and discharge pulses. This saves energy by cycling energy back and forth. In addition, it prevents local overheating and thus prevents the battery from being charged or discharged beyond safe limits.

We performed feasibility work (three sets of tests) in collaboration with the University of Toledo. In each set, the resistance and power capability of a cold battery were measured before and after applying the AC power. In the first set of tests 60 Hz AC power were applied to a 12 volt, 13 Ah valve regulated lead acid battery from Hawker Energy. The battery weight was 4.9 kg with the following dimensions: length = 0.175 m, width = 0.083 m, height = 0.130 m. The battery with 67% state of charge was soaked at -40°C and then tested with AC heating. Table 1 shows that its 2-s pulse power capability is about 100A, and its internal resistance is 108 mΩ. After applying a 110 Arms (root mean square), 60 Hz AC power, the pulse power capability of the module was measured. When the AC power is applied, the battery starts warming up to approximately -4°C in 3 min and to +6°C in 6 min. At these temperatures, the battery can provide sufficient current (210–250A) to assist the engine.

Table 1. Maximum 2-s Pulse Current Capacity of a 13 Ah Hawker Lead Acid Battery with AC heating at -40ºC

AC Heating	R_B mΩ	I_{bat} A	Estimated T_{bat} (ºC)
None	108	100	-40
3 min	19.6	210	-4
6 min	14.7	250	+6
9 min	13.5	270	+9

In the next set of experiments, 60 Hz AC heating was applied to a NiMH module to determine the suitability of AC heating for a 6.5 Ah, 7.2 V, 1.038 kg Panasonic NiMH battery. This technique can preheat the battery without damaging the NiMH chemistry. Although 60 Hz AC heating may work, it is only good for EV charging (through wall charging in the United States). For on-board use, the size of the electronics must be smaller, so higher frequencies must be used.

In the next set of experiments, we applied high frequency (10–20 kHz) AC heating to a 115V NiMH pack consisting of 16 Panasonic NiMH battery modules connected in series. A heater circuit based on the Ashtiani and Stuart patent [7] (available at the University of Toledo) was used to apply the high frequency power. In this heater circuit, the battery pack is divided into two halves; a small amount of energy from one half is temporary discharged into an inductor. The inductor will charge the second half of the battery with that energy. The energy is cycled between the two halves and the inductor until the battery heats up.

The initial result, presented in Figure 8, is based on applying 10 kHz, 60 Arms AC power to the NiMH battery pack soaked at -30°C. Table 2 provides average internal resistances of the NiMH battery pack at various temperatures based on additional pulse power tests. Using Table 2 and Figure 8, we found that after 6 min of applying 10 kHz, 60 Arms current to the pack, battery internal resistance reaches that of room temperature (25°C). At 3.5 min, the battery temperature is estimated to reach 0°C, at which the battery could provide enough power to assist the engine in an HEV.

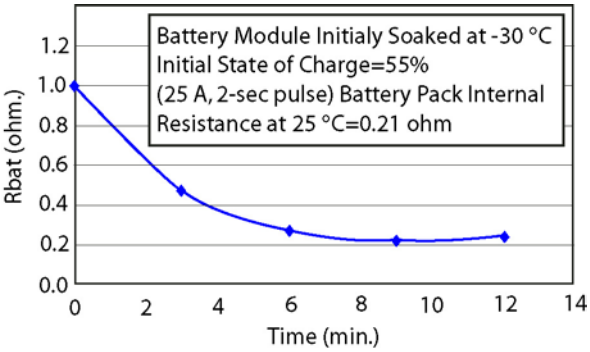

Figure 8. Internal resistance of NiMH battery pack as a function of time and current amplitude, based on 25, 2-s pulses

Table 2. Average Internal Resistance of the NiMH Battery Pack at Various Temperatures

Temp (ºC)	45	35	25	10	0	-10	-20
Resist. (Ohm)	0.179	0.179	0.205	0.333	0.410	0.614	1.024

Figure 9 shows the results of AC heating at various amplitudes after soaking the battery pack at -30^{o}C with an SOC≅ 55%.

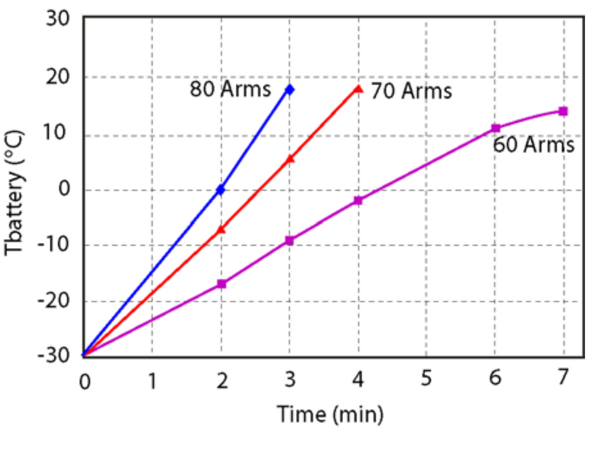

Figure 9. NiMH **battery pack temperature as a function of amplitude of AC current (initial battery SOC = 55%) derived from 2-second pulse tests**

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Before applying AC, battery pack internal resistance was about 1.36 ohm at about -30°C. After applying AC power the battery heated up and resistance dropped and the battery could deliver more power. As the amplitude of AC was increased, the heating process sped up. With 60 Arm, 6 min. was needed to reach a temperature of 10°C, while with 70 Arms, only about 3.5 min. were needed, and with 80 Arms, only 2.5 min. were needed.

These tests show the feasibility of preheating the core of batteries by applying high frequency AC power. Further tests with various frequencies, currents, temperatures, states of charge, and battery types are underway.

CONCLUDING REMARKS

Battery thermal management is needed to achieve the desired performance and life cycle of a battery in hybrid vehicles. In the last few years automakers and their battery suppliers have focused on cooling batteries in warm temperatures because of the immediate impact of high temperatures on battery life and warranty issues. In this paper focused on methods to heat the battery when for improve performance/operation at very cold temperatures. Using finite element thermal analysis, we analyzed the transient thermal behavior of a typical rectangular battery heated with four different methods. Battery core heating was the most effective method for warming the battery quickly with the least amount of energy. To achieve core heating, we applied AC power to battery terminals. We conducted tests on two types of batteries (lead acid and NiMH) and found that AC heating is effective in warming the very sluggish batteries at cold temperatures to temperatures that can provide enough to assist an HEV engine. We are continuing AC heating tests at various temperatures, states of charge, frequencies, and currents. The impact of AC heating on battery life needs to be studied. We plan to investigate prototype battery preheating hardware for on-board vehicle applications.

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