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Integration Issues of Cells into Battery Packs for Plug-in and Hybrid Electric Vehicles

Ahmad A. Pesaran[1], Gi-Heon Kim, and Matt Keyser
National Renewable Energy Laboratory
1617 Cole Blvd, Golden, CO 80401 USA
[1]**Tel: +1 303 275-4441; Fax: +1 303 275-4415; Email:** ahmad_pesaran@nrel.gov

Abstract

The main barriers to increased market share of HEVs and commercialization of plug-in HEVs are the cost, safety, and life of lithium-ion batteries. Significant effort is directed to address these issuers for lithium-ion cells. However, even best cells when integrated into packs for vehicles may not perform as well because of the environment that vehicles operate. In this paper, we will discuss mechanical, electrical, and thermal integration issues and interface with vehicle that could impact the cost, life and safety of the system. We compare advantages and disadvantages of using many small cells versus a few large cells, and using prismatic cells versus cylindrical cells.

Keywords: Lithium battery, battery management, cooling, electric drive, modelling, thermal management

1 Introduction

Hybrid electric vehicles (HEV) and plug-in hybrid electric vehicles (PHEVs) have the potential of reducing significant amount of petroleum in the next 10-20 years. The major obstacle to increased market share of HEVs and mass-produced commercialization of PHEVs are batteries. They must be high-performing, inexpensive, long-lasting, and safe. Lithium ion batteries have the potential to meet these challenges. Significant amount of R&D is being globally performed around the world to improve attributes of the cells. However, integrating even good cells poorly in modules and packs may lead to lower performance, life, ands safety and increased cost. Integration must address mechanical, packaging, electrical, thermal, safety, monitoring and control, and interface with the rest of the vehicle. In case of PHEVs, packs need to be interfaced with the on-board charger getting electricity from an alternating current grid. The terminology used her is the widely used by battery developers (Figure 1). cells consist of the electrochemical unit with the lowest voltage of the associated chemistry; module consists of several cells to make up mid range voltage up to 50V; pack consists of many modules (or cells). The pack is housed in a container with electronic and thermal control that creates the total system that interface with the rest of the vehicle components. Each module or pack has its appropriate packaging, mechanical, electrical, and thermal controls. In the initial design of a battery pack, one must consider: safety (abuse tolerance), cost of packaging of the whole system, impact packaging and control on life and/durability, manufacturability for lower cost, maintenance/repair consideration, packaging for recyclability and re-use, thermal management (since temperature impacts the life and performance), electronics for monitoring, control, and gauges to know capacity, power and degradation rate. Battery pack integration must be achieved while meeting multiple requirements and balancing multiple inputs and outputs [1]. In the paper we will further explore the small versus large cell and prismatic/laminate versus cylindrical cells. Battery modelling design tools will be discussed. Different integration issues for HEVs and PHEVs will be discussed.

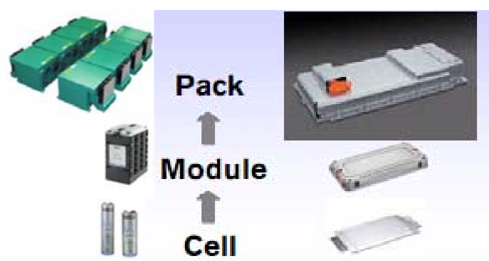

Figure 1: Cell, module, and pack

2 Battery Integration

Figure 2 shows how the battery pack or the energy storage system (ESS) integration could get impact or influence other parameters or components.

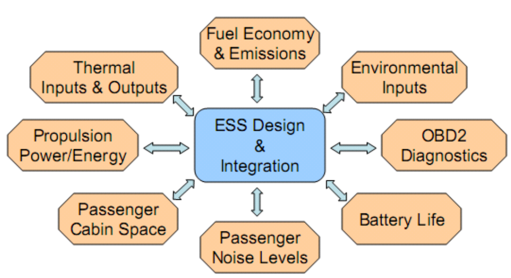

Figure 2: Components in battery pack integration and interface with vehicle; adopted from [1]

Mechanical and packaging should consider how cell to cell interconnects are designed, what is the cell, module, and electronic assembly; what is the structural protection points for shock and vibration; how the pack is crush protected, what are the desired attachment points to the vehicle and what are the mechanical interfaces with other components [2]. Electrical management includes interface with vehicle on how the DC power is going back and forth from the battery to the inverter or motor controller, how voltage, current, (pressure) and temperature are measured and monitored, how the state of charge (SOC), capacity, available energy, power capability, state of health, impedance, rate of degradation is measured. Electrical safety is also needs to be considered by appropriate use fuses and automatic interconnects. Thermal management is a must since as the battery used and power goes in and out, the in-efficiency of the battery, even though less than 5%-10% could lead to heating up of the cells, sometime not uniformly and high temperatures could lead to lower life and reduced vehicle fuel economy.

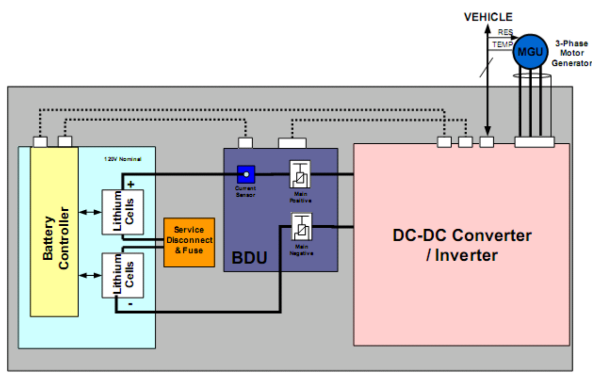

Figure 3: Electrical Components of a Battery Pack from [3]

2.1 Battery Safety

Safety is another big concern for lithium ion battery packs. During abuse tests, many have observed that over-voltage, over-discharge, over-charge, heating, arcing, crush, nail penetration, external short, internal short due to defects could lead to thermal runaway and electrolyte leak, smoke, venting, fire and even explosion [4]. Although many of the electrical and mechanical controls could almost eliminate or significantly reduce the probability of these events such as over-voltage and crush, still thermal runaway due to internal short because of native contamination is still a concern. It is estimated that today's 18650 li-ion cells (produced in high quantities for computers and other electronics) has a internal short failure rate of 1 in 5-10 million. We estimate that each battery pack for future (P)HEVs may have between 100 to 200 larger cells, of course much large Ah capacity for PHEVs. Although the battery packs in HEVs and PHEVs use much larger cells, and still their quality production is not established one can assume the same failure rate of 18650 cells for larger cells. This results that roughly 1 cell in roughly 50,000 packs may have internal short leasing to a safety event. This is too high. The back could be designed in such a way that as a cell goes to thermal runaway, design features could prevent propagation from cell to cell eventually reducing the pack safety events to 1 in 1 million or even more.

2.2 Few Large cells vs. Many Smalls Cells

Another integration issue that needs to be considered is using many small cells versus using a fewer larger cells for PHEV and EV applications. For example, EnergyCS uses more than 2000 small 18650 cells (2 Ah) for their PHEV pack conversion. Chrysler uses 200 much larger cells of (41 Ah) for it PHEV conversion pack. Using many small cells has the advantages of lower cell cost (commodity market), improved safety (faster heat rejection), and higher quality production, but the disadvantages of many interconnects, much higher integration and assembly cost, lower weight and volume efficiency, lower reliability (many components, but some redundancy), small magnitude of safety events because of smaller cell, and costly electrical management. Fewer large cells has the advantages of lower assembly cost, higher weight and volume efficiency, better reliability (lower number of components), but the disadvantages of higher cell cost, lower quality, tougher thermal management and large magnitude of safety event. The final decision of using which system must depend on a trade-off analysis for specific application. Comparison of thermal performance will be given in Section 4.

2.4 Cylindrical vs. Prismatic Cells

Another item to be considered for integration is the use of cylindrical cells versus prismatic (or laminate) cells. Cylindrical cells can be produced in high volumes and with high quality. But as the need for various shape-factor changes the cost advantages may be lessoned. Cylindrical design is robust and structurally strong, particularly for handling, shock and vibration, and has the ability to keep pressure and vent to prevent safety events. As their size gets larger, their external surface are to volume decreases and thus the heat transfer abilities goes down and the internal temperature gradient can increase. The prismatic or laminate design could have higher heat transfer surface area to volume and can be thermally managed easier. Prismatic cells could be packaged with better volume efficiency than cylindrical cells. However, if soft pouch packaging is used attention must be paid to prevent local stresses. Handling and shock and vibration must be considered in the design. These could add volume and weight and could reduce the volumetric advantage of pouch prismatic cells. Comparison of thermal performance will be given in Section 4.

3 Battery Management System

3.1 Battery Electrical Control System

The battery management system for a battery pack is used to monitor the voltage differences between cells and the temperature of individual cells within the pack. The battery management system ensures that the cells are not allowed to exceed the manufacturer's specified voltage and temperature for the battery system. In order for the cells to remain balanced during and after cycling, a balancing circuit is required. Most balancing circuits consist of a buck boost circuit or a buck, resistive balancing, circuit. The balancing resistors for large capacity cells may need to be larger in order to handle the voltage differences between cells during HEV and PHEV cycling – more energy may be wasted to bring the cells into balance. Furthermore, a cooling circuit may be required for the balancing board. Also, when smaller cells are placed in parallel to increase the capacity of the pack, the voltage of the parallel string is monitored as compared to the voltage of each individual cell. By monitoring the parallel string of cells, a failure of a single cell may be missed and may lead to a damaging situation.

3.2 Battery Thermal Control

Thermal management of batteries is critical in achieving the desired performance at low temperature environment and the desired life at the high temperature environment. High temperatures degrade the life of the li-ion batteries while cold temperature reduced power and energy capabilities thus limits their driving range or performance capabilities. Thermal management system is needed to either heat the batteries for cold temperatures or cooled hem from high temperatures. Either of these cooling and heating systems adds cost, weight and volume to the battery pack. Electrochemistries that are more tolerant to low and high temperatures are being pursued but it is a challenging R&D effort. To cool the batteries, air, liquid, refrigerant, or fin cooling is considered. For all of these systems, heat has to be rejected outside the vehicle. Some air cooling techniques such as in Toyota Prius uses the cooled cabin air (using vehicle air conditioner) for passing through the batteries. In liquid or fin cooling systems, a secondary refrigeration loop to reject the heat may be needed. In most cases either air or liquid cooling, with the aid of refrigeration system, are sufficient for keeping the battery temperature below damaging limits. However, depending on the location of battery pack in the vehicle and magnitude of cooling availability the air or liquid cooling are not sufficient and phase change material should be used. One important factor in thermal management is not to only maintain the maximum battery temperature below the high limits, but also to maintain uniformity of the temperature between cell-to-cell. It is desirable to have this variation to be less than 5°C for improved balancing of the pack.

4 Cell Thermal Analysis

Figure 4 shows schematics of procedure for 20Ah cell power profile evaluation with US06 driving scenario for mid-size PHEV10 application. During initial drive (about first 10 minutes), the vehicle consumes electric energy stored in the on-board battery system; charge-depleting (CD) drive. After that, the system maintains the state of charge of the battery and drives the vehicle in normal hybrid mode; charge-sustaining (CS) drive. So, the battery is more intensely used at initial drive. Impacts of size (capacity) of unit cell and form factor on the thermal response of the cell are investigated focusing on CD drive condition through simplified thermal analysis; electrical/electrochemical impacts of designs were not considered. (Capacity and dimensions of the compared prismatic and cylindrical cells are shown in Table 1 and Table 2.)

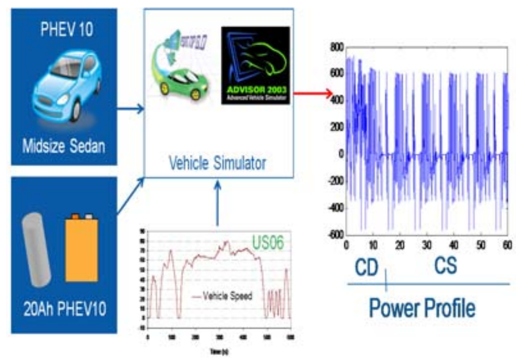

Figure 4: Schematics for 20 Ah Cell Power Profile Evaluation with PHEV10 application (120 Wh/kg-cell, 78 BSF)

Table 1: Capacity and dimension of compared prismatic cells

PRISMATIC	Base (AP)	Small (BP)	Thin (CP)
Capacity	1 x 20Ah	3 x 6.7Ah	1 x 20Ah
Dimension(mm)	100x140x15	100x140x5	140x200x7.5

Table 2: Capacity and dimension of compared cylindrical cells

CYLINDRICAL	Base (AC)	Small (BC)	Thin (CC)
Capacity	1 x 20Ah	3 x 6.7Ah	1 x 20Ah
Dimension(mm)	R:42.2 H:150	R:28.5 H:110	R:36.6 H:200

Heat generation rate per 20 Ah cell was calculated and presented at Figure 5. For modelling purpose, time-averaged values were evaluated for given period of time as shown in the graph, and applied as inputs to the following thermal simulation analysis. All external boundaries of each cell are assumed to be used for surface cooling where convective heat transfer coefficient is fixed as 20 W/m^2K for 30^oC ambient temperature. Orthotropic thermal conductivities (27 W/mK in electrode layer parallel direction and 0.8 W/mK in layer normal direction) are applied to composite jelly roll volume.

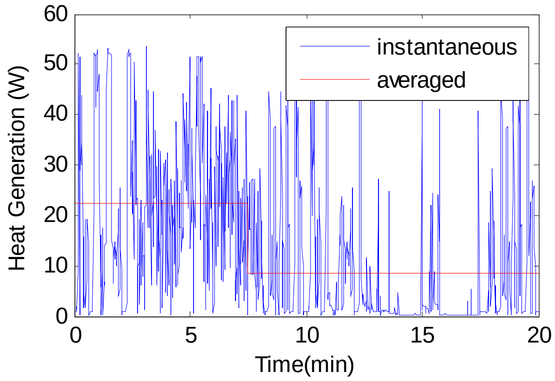

Figure 5: (a) Instantaneous and (b) averaged heat generation rate per cell (20Ah)

Figure 6(a) compares average temperature rise and internal temperature variation of Cell AP and Cell BP. They are prismatic cells having same base area (100mm by 140mm) but different thicknesses and capacities. As shown in the graph, constructing a battery system with multiple small cell parallel banks (Cell BP) rather than with single large cell string in series (Cell AP) could provide a chance for better thermal management. The large cell (AP) shows about 15°C temperature rise with 2°C internal temperature difference, while the small cell (BP) shows less than 10°C temperature rise with 1°C or less spatial temperature imbalance due to increase in available cooling surface area and decrease in thermal diffusion distance. However, using small cells quickly increase the complexity and the cost of coolant flow pathway design and system assembly. Cell AP and Cell CP have same capacity but different form factor. Cell CP is thinner and has wider base area so to have larger cooling surface and shorter thermal diffusion length in layer normal direction. Making a cell thinner would be help for thermal management as seen in Figure 6(b), but larger base area would cause severe current convergence and non-uniform material use issue where tabbing design becomes critical for cell performance and degradation. Figure 6(c) shows the importance of material property change. When thermal conductivity in layer normal direction decreases in four folds, internal temperature difference increases from 2°C to 5°C for the given case.

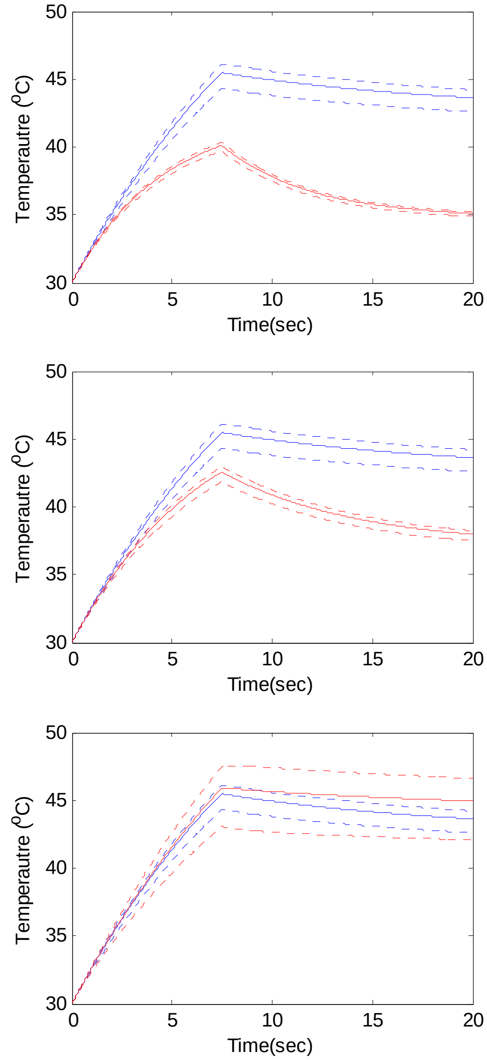

Figure 6: (a) Comparison of average temperatures (solid) and maximum/minimum temperatures (dotted) time variation for Cell AP(blue) and Cell BP(red) with mid-size PHEV10 US06 driving scenario, (b) same for Cell AP(blue) and Cell CP(red), (c) same for Cell AP with different layer normal conductivity, 0.8 W/mK (blue) and 0.2 W/mK (red)

Large cylindrical format cells are having difficulty in thermal management compared with prismatic cells. Similarly, thermal responses of a large cylindrical cell (AC) and a small cylindrical cell (BC) are compared at Figure 7(a), and impacts of form factor are compared at Figure 7(b). In large cylindrical cell (AC), temperature still increases during CS drive, which implies heat rejection from the cell is slower than heat generation even at CS mode. Temperature difference between cell center and the surface reaches 5°C for AC and 3°C for BC. Tall and thin cylinder would be better in thermal aspect as seen in Figure 7(b). However, thin cylinder could cause longer electron current path.

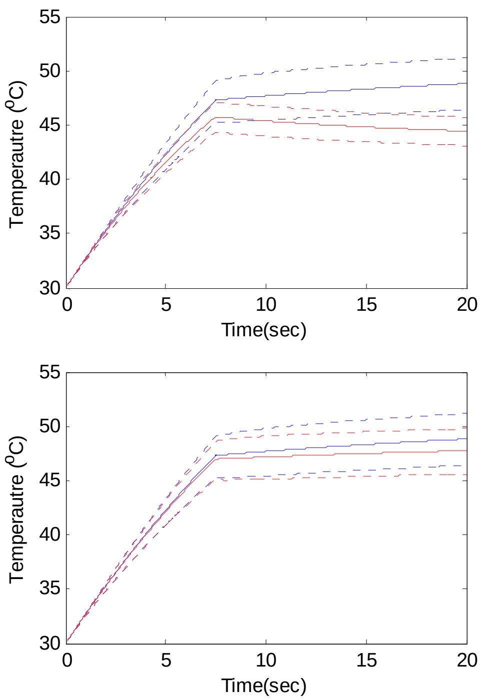

Figure 7: (a) Comparison of average temperatures (solid) and maximum/minimum temperatures (dotted) time variation for Cell AC(blue) and Cell BC(red) with mid-size PHEV10 US06 driving scenario, (b) same for Cell AC(blue) and Cell CC(red)

Figure 8 simply compares the thermal responses of nominal 20 Ah prismatic (AP) and cylindrical (AC) cells.

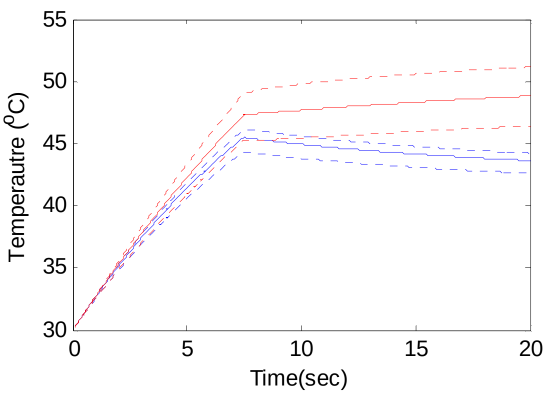

Figure 7: Comparison of average temperatures (solid) and maximum/minimum temperatures (dotted) time variation for Cell AP(blue) and Cell AC(red) with mid-size PHEV10 US06 driving scenario

5 Concluding Remarks

Integration of cells into modules and then into battery packs is critical in achieving the desired cost, performance and life. Many electrical, thermal, and mechanical issues must be considered. The smaller capacity cells allows for easier packaging of the battery system but results in a higher number of interconnects and failure points. The smaller capacity cells are also easier to keep isothermal due to their smaller size but providing consistent, velocity and temperature, cooling air to the cells becomes a more difficult problem. Incorporating larger capacity cells in a HEV or PHEV limits the number of interconnects but also limits how the cells can be packaged within a vehicle. They are also more difficult to keep the center of the cell isothermal due to the thermal path length. A computer-aided-engineering tool must be developed to address integration issues.

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Authors

Ahmad A. Pesaran is a Principal Engineer at NREL and leads the energy storage team. Ahmad manages several projects for Department of Energy and industrial partners, which include thermal characterization and analysis of batteries, modelling and simulation for hybrid and plug-in hybrids. He holds a Ph.D. from UCLA.

Matt Keyser is a Senior Engineer at NREL and manages the Energy Storage Lab for performing thermal and electrical characterization. Matt has tested many li-ion batteries and recently has designed and fabricated the largest battery calorimeter in the world that could measure heat from large modules and battery packs.

Gi-Heon Kim is a Senior Engineer at NREL. His recent research interests in advanced vehicle energy storage system tasks include development of a three-dimensional lithium-ion battery thermal abuse model, a 3D electrochemical modelling of Li-Ion cells, and modelling hybrid electric vehicle/electric vehicle battery thermal management systems. He holds a Ph.D. from Colorado State University.