

An Analysis of a Lithium-ion Battery System with Indirect Air Cooling and Warm-Up

2011-01-2249

Published
09/13/2011

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doi:[10.4271/2011-01-2249](https://doi.org/10.4271/2011-01-2249)

ABSTRACT

Ideal operation temperatures for Li-ion batteries fall in a narrow range from 20 °C to 40 °C. If the cell operation temperatures are too high, active materials in the cells may become thermally unstable. If the temperatures are too low, the resistance to lithium-ion transport in the cells may become very high, limiting the electrochemical reactions. Good battery thermal management is crucial to both the battery performance and life. Characteristics of various battery thermal management systems are reviewed. Analyses show that the advantages of direct and indirect air cooling systems are their simplicity and capability of cooling the cells in a battery pack at ambient temperatures up to 40 °C. However, the disadvantages are their poor control of the cell-to-cell differential temperatures in the pack and their capability to dissipate high cell generations. In contrast, the advantages of direct and indirect liquid cooling systems are their good control of the maximum cell temperature and maximum differential cell temperatures in the pack and their capability of dissipating high cell heat generations with good thermal uniformity. However, high ambient temperatures may limit the applications of liquid cooling systems because the performance of the radiator for cooling the liquid coolant deteriorates significantly with increasing ambient temperature. Thermal behavior is analyzed in detail of a module stacked with 12 high-power Li-ion pouch cells with indirect air cooling and warm-up. Simulation results show that with air cooling channels structured similar to that of compact heat exchangers, excellent heat-transfer performance of the air flow channels can be achieved for both cooling and warm-up. This suggests that the air-cooling-channel structure proposed in this study is appropriate for applications in active battery thermal management systems.

INTRODUCTION

Lithium-ion (Li-ion) batteries are becoming a primary candidate as rechargeable energy storage systems for hybrid electrical vehicles (HEVs) and electrical vehicles (EVs) due to their high energy density, high voltage, good stability and low charge loss when not in use. As an electrochemical system, the performance and life of a Li-ion cell varies with its working temperatures. Rates of electrochemical reactions in the cell for charging and discharging are characterized by the Butler-Volmer equation [1,2], according to which the rates of electrochemical reactions increases exponentially as temperature rises. At higher temperatures, the cell has higher power capability and the cell internal resistance decreases due to improvement in the electron/ion mobility. However, high temperatures may also initiate unwanted or irreversible chemical reactions which can cause permanent damage of the cell. This sets an upper temperature bound for cell operations. Many Li-ion battery suppliers require that the maximum working temperatures for their products be < 60 °C to avoid possible battery system failure. At lower temperatures, the cell performance deteriorates due to decrease in the rates of electrochemical reactions. If the temperature becomes too low, the electrolyte in the cell may freeze. The cell internal resistance increases rapidly with decreasing temperature. Increasing the cell internal resistance has significant impact on the cell power capability. The minimum allowed discharge power sets the low temperature bound for cell operations. For Li-ion cells, ideal cell operation temperatures fall in a narrow temperature range from 20 °C to 40 °C [3].

A battery pack usually consists of several modules connected in series to meet the required pack voltage. In each module, the cells are connected in a certain series-parallel combination to provide the required capacity and voltage. The pack power capability is affected significantly by temperatures of the cells in the pack. In low-temperature

operations the coolest cell determines the pack power capability. On the other hand, the hottest cell within the pack limits the pack power when operated at elevated temperature. The maximum cell temperature and the maximum differential cell temperature are crucial factors to the cell durability and safety. HEV and EV batteries require a thermal management system that is able to keep cell temperatures as uniform as possible and prevent the cells from overheating. A module in a battery pack is a basic unit for the battery thermal management. Heat transfer between the cells and the cooling medium generally can be specified only at the module level, at which the cooling medium flow rate, the rise in the cooling medium temperature, and heat transfer coefficients (HTC) on the cooling surfaces can be well defined. Ideally, all the modules in the pack should be thermally symmetric, allowing the maximum cell temperature and maximum differential cell temperature to be controlled at the module level. Complexity in a battery pack design leads to complexity of the battery thermal management. Thermal modeling of the cells and modules in the battery pack is an effective way to understand how the design and operation conditions could affect thermal behavior of the pack. It can play an important role to ensure the durability and safety of the pack during development. In the following sections, characteristics of various cooling systems will be reviewed and a theoretical analysis will be reported on thermal behavior of a battery module stacked with Li-ion pouch cells under operation conditions simulating HEV applications.

BATTERY THERMAL MANAGEMENT

HEAT GENERATION IN BATTERY

Volumetric heat generation in a Li-ion cell q can be given as

$$q = I^2 \times R_i - I \times \left(T \frac{\partial U}{\partial T} \right) \quad (1)$$

where I is the current density, T is the temperature in Kelvin, R_i is the internal resistance which varies with temperature and depth of discharge (DOD), and U is the open-circuit cell voltage determined by the difference in the open circuit potentials at the positive and negative electrodes. In [Eq.\(1\)](#), the first term is the heat generation due to the internal (irreversible) resistance and the second term is known as the reversible heat resulting from the change in open circuit potentials at the two electrodes with the change in temperature. The irreversible heat dominates the heat generation in a cell.

A Li-ion cell may be modeled as an equivalent heterogeneous solid medium, through which heat conduction takes place. Changes in the cell temperature due to the cell heat can be characterized with energy balance on a unit cell volume as

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + q \quad (2)$$

where ρ , C_p and k are the local density, heat capacity and thermal conductivity of the cell medium, and t is the time. Li-ion cells are structured with multiple thin battery layers arranged in parallel in the cell [\[4,5\]](#). Thus, thermal properties involved in [Eq.\(2\)](#) should be characterized with the composite properties of the cell [\[6\]](#). For a given cell with properly defined boundary conditions for heat transfer, [Eq.\(2\)](#) can be solved with finite element method (FEM).

THERMAL UNIFORMITY OF BATTERY

As aforementioned, heat transfer in Li-ion cells may be characterized as heat conduction in a heterogeneous solid medium. The temperature gradient in a cell is influenced by the cell geometry, heat generation and heat transfer from the cell to the cooling medium [\[7\]](#). It is also affected by the cell terminal design because of high current densities near the terminals. In addition, some of the ohmic heat generated in the terminals and busbars may be transferred to the cell, causing local high cell temperatures [\[6\]](#). Although all modules in a pack may be designed to be thermally symmetric, it is difficult to make all the cells in a module thermally independent due to changes in the cooling medium temperature and/or distributions. Variations in local heat-transfer conditions cause cell-to-cell temperature differences. The cell with the best cooling condition will be the coolest and the cell with the worst cooling condition will be the hottest. Even though the battery thermal design may be sufficient to dissipate the total heat generated in a pack, there could still be localized hot spots where cell temperatures may exceed the specified limit due to variations in cooling medium temperatures and/or flow distribution in the pack.

Thermal uniformity of a battery pack can be evaluated at two levels: the maximum differential temperatures in the cells and the maximum cell-to-cell temperature difference in a module or pack. The latter is usually evaluated base on the averaged cell temperatures because it is not possible to monitor local cell temperatures for all the cells in the pack. A 5 °C spread in the cell temperature may lead to a variance in the cell power capability by up to 10% or higher relative to the peak power capacity [\[3\]](#). Without good battery thermal management, it is difficult to achieve a pack life span of 10 to 15 years for HEVs and EVs. In practice, the target for the battery thermal management is to maintain the maximum differential cell temperatures < 5 °C within the cells and between any two cells in the pack (the latter on the average temperature basis). Under this target, the difference between the maximum and minimum local cell temperatures in the pack will be < 10 °C.

BATTERY THERMAL MANGEMENT SYSTEMS

Battery cooling systems may be classified based on cooling medium into air or liquid cooling, on cooling-medium and cell-surface contact condition into direct or indirect cooling, or on cooling-medium-temperature control condition into passive or active cooling. Advantages and disadvantages of these types of cooling systems have been summarized by Pesaran [8]. All cooling systems must remove the heat generated within the battery cells and eventually discharge it to ambient air, either directly or indirectly.

For simplicity in discussion in this section, cooling medium flows to all modules in the pack under consideration are assumed to be in parallel, i.e., the modules are thermally symmetric. It is further assumed that heat transfer from the cells to ambient air can be characterized by a representative cell or cooling unit in a module. From the thermodynamic point of view, the ambient is a heat sink (temperature = T_{air}) and the cell is a heat source whose temperature may be defined as the maximum cell temperature (= $T_{\text{cell,max}}$), e.g., the cell core temperature. Maximum differential cell temperature ΔT_{cell} (= $T_{\text{cell,max}} - T_{\text{cell,min}}$, $T_{\text{cell,min}}$ being the cell surface temperature closest to the cooling medium) is a measure of thermal uniformity. $T_{\text{cell,max}}$ and ΔT_{cell} must be monitored and controlled by the thermal management system because $T_{\text{cell,max}}$ is related to the pack safety and ΔT_{cell} influences the cell performance and life.

Direct Cooling Systems

Direct cooling is widely used for cooling cylindrical- and prismatic-cell packs. In direct cooling, each of the cells within the modules may be viewed as an internal heat exchanger where convective heat transfer takes place on the cell surfaces. Many direct cooling systems use air as the cooling medium [9,10,11]. In cases of direct liquid cooling, dielectric mineral oils are often selected as the cooling medium because they are thermally conductive but electrically non-conductive [12]. Because the liquid cooling medium is a secondary coolant and itself must be cooled by ambient air, a liquid-to-air heat exchanger or radiator is needed, which adds an additional thermal link in the heat transfer path. Figure 1 shows a schematic of direct air and liquid cooling systems. Figure 2 compares relative temperature distributions for these two cooling systems. In Figure 2, Q is the battery heat rejected and ΔT_{HT} is the differential temperature required for overcoming the resistance of the thermal link related to the cooling medium. Characteristics of different cooling systems may be viewed through distribution of the overall temperature difference $\Delta T_{\text{overall}}$ (= $T_{\text{cell,max}} - T_{\text{air}}$) among all the thermal links in the heat transfer path.

In direct air cooling, $\Delta T_{\text{cell}}/\Delta T_{\text{HT,cell-air}}$ is proportional to the ratio of the resistance for conduction in the cell to that for convective heat transfer from the cell surface to air, which is characterized by Biot number for the representative cell. (Recall that Biot number is defined as $Bi = HTC \times L_c / k$, $L_c = V_{\text{body}}/A_{\text{surface}}$ with V_{body} and A_{surface} being the volume and heat transfer surface of the cell.) If $Bi < 1$, $\Delta T_{\text{cell}} < \Delta T_{\text{HT,cell-air}}$ [13]. This is valid for most direct air cooling systems. As stated previously, ΔT_{cell} should be $< 5^\circ\text{C}$ and $T_{\text{cell,max}}$ must not exceed 60°C . An effective way to lower $T_{\text{cell,max}}$ is to reduce $\Delta T_{\text{HT,cell-air}}$ via heat transfer enhancement by increasing air flow. However, the effectiveness of this approach may be limited if air flow in the module is fully developed, at which HTC is stabilized [13]. Increasing air flow reduces $\Delta T_{\text{HT,cell-air}}$ thus lowers $T_{\text{cell,max}}$. Although the overall temperature difference $\Delta T_{\text{overall}}$ is lowered, $\Delta T_{\text{cell}}/\Delta T_{\text{HT,cell-air}}$ may increase because Bi is proportional to HTC. Note that Bi does not provide information on the value of ΔT_{cell} or $\Delta T_{\text{HT,cell-air}}$. Even if both ΔT_{cell} and $\Delta T_{\text{HT,cell-air}}$ are decreasing, Bi may still increase as long as $\Delta T_{\text{HT,cell-air}}$ drops more rapidly.

Many HEVs and EVs require that the battery pack can be operated at ambient temperatures up to 40°C . If $T_{\text{cell,max}} = 55^\circ\text{C}$, $\Delta T_{\text{overall}} = 55^\circ\text{C} - 40^\circ\text{C} = 15^\circ\text{C}$. There is no requirement for the minimum or maximum overall temperature difference from the thermal management point of view. For a given battery pack, $\Delta T_{\text{overall}}$ varies with ambient temperatures and pack duties in a wide range [9,10]. Lower values of $\Delta T_{\text{overall}}$ can be observed at higher ambient temperatures and higher values for $\Delta T_{\text{overall}}$ are encountered at lower ambient temperatures. In general, $\Delta T_{\text{overall}} > 10^\circ\text{C}$ because it is not practical for air flow to be greater than necessary. Although direct air cooling is widely used in commercial battery packs, it has one drawback that limits its applications: if the cell heat generation is high, air temperature rise over the pack can be significant, causing a large cell-to-cell temperature difference in the pack. Figure 3 shows the air temperature rise as a function of the air flow for a 96-cell pack under different heat rejection conditions (note that the overall air temperature rise is independent of the air flow distribution in the pack). If the maximum air flow is limited to 200 CFM, the cell heat rejection should not exceed 6 W/cell in order for the air temperature rise to be $< 5^\circ\text{C}$.

As shown in Figure 1, there are two heat exchangers in a direct liquid cooling system: an internal heat exchanger (the battery pack) and an external heat exchanger (the radiator). $T_{\text{cell,max}}$ in direct liquid cooling is generally lower than in direct air cooling due to two reasons: (1) $T_{\text{cell,min}} \rightarrow T_{\text{coolant}}$ due to high HTC of liquid; (2) higher cell effective thermal mass which includes that for the cell and the liquid around it, resulting in a lower cell temperature. The effect of the coolant

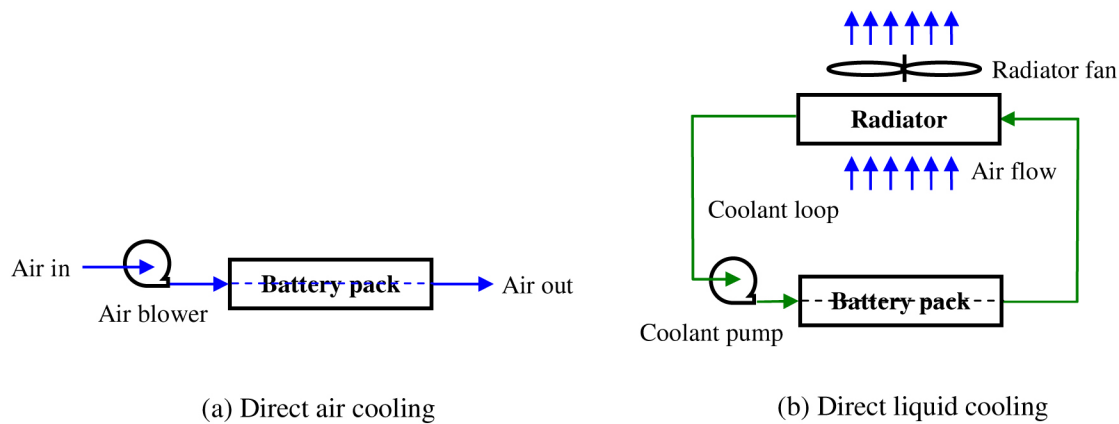


Figure 1. Schematic of direct cooling systems.

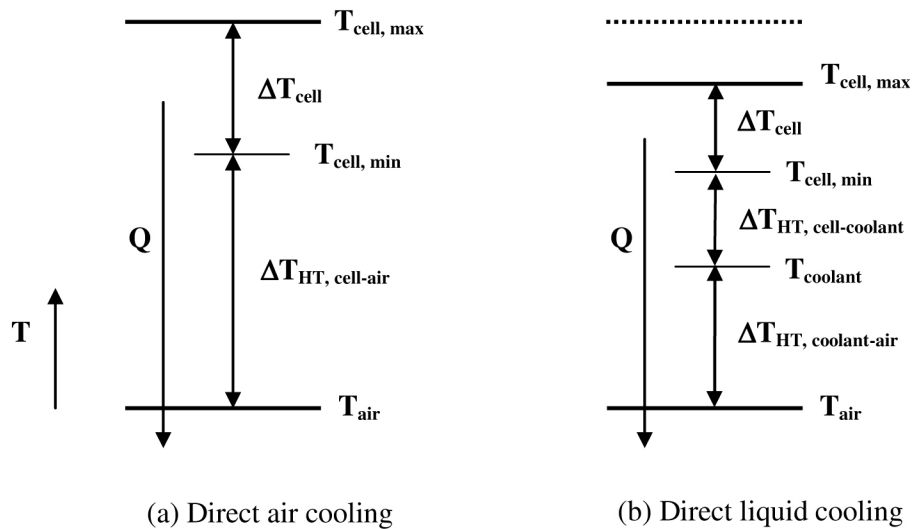


Figure 2. Relative temperature distributions in direct cooling systems.

thermal mass on the cell temperature can be significant for a battery pack with low packing efficiency because all the gaps between cells are filled with liquid. The volumetric heat capacity ($= \rho \times C_p$) of liquid is much greater than that of air and thus liquid cooling allows much higher cell heat generation. Figure 4 shows the coolant (assuming dielectric mineral oil) temperature rise as a function of the coolant flow for the same 96-cell pack under different heat rejection conditions. It is seen that if the maximum coolant flow is limited to 20 LPM, the cell heat rejection can be up to 20 W/cell with the coolant temperature rise $< 3^\circ\text{C}$.

The heat transfer driving force for a radiator is the inlet temperature difference between coolant and air or ITD ($= T_{\text{coolant-in}} - T_{\text{air-in}}$). The coolant temperature cannot be too low because the effectiveness of the radiator deteriorates with decreasing T_{coolant} and/or increasing T_{air} . Figure 5 shows variation of the cooling capacity with ITD for a 12"×12"×1" (core) radiator with air flow = 300 CFM and coolant flow =

15 LPM (coolant being 50/50 ethylene glycol). It is seen that ITD must be 15°C in order to reject 1.5-kW of heat for this particular radiator. If the coolant is dielectric mineral oil, a greater value of ITD is required because 50/50 ethylene glycol has better heat transfer performance than mineral oils. Under the conditions that $T_{\text{cell,max}} = 55^\circ\text{C}$ and $\Delta T_{\text{cell}} + \Delta T_{\text{HT, cell-coolant}} = 8^\circ\text{C}$, the coolant temperature at the radiator inlet $T_{\text{coolant-in}} \approx T_{\text{coolant}} = 47^\circ\text{C}$. If the radiator performance is similar to that in Figure 5, the maximum ambient temperature must be $\leq 32^\circ\text{C}$ in order to reject 1.5-kW heat. The upper limit for the maximum ambient temperature will be less than 32°C if the coolant is dielectric mineral oil. In direct liquid cooling, $\Delta T_{\text{HT, coolant-air}}$ represents a large fraction in the overall temperature difference and the effectiveness of the radiator may limit the capability of the cooling system at high ambient temperatures. Another drawback for direct liquid cooling is the sealing of the coolant flow channels, especially for a large pack. Loss in coolant during pack operations may lead to

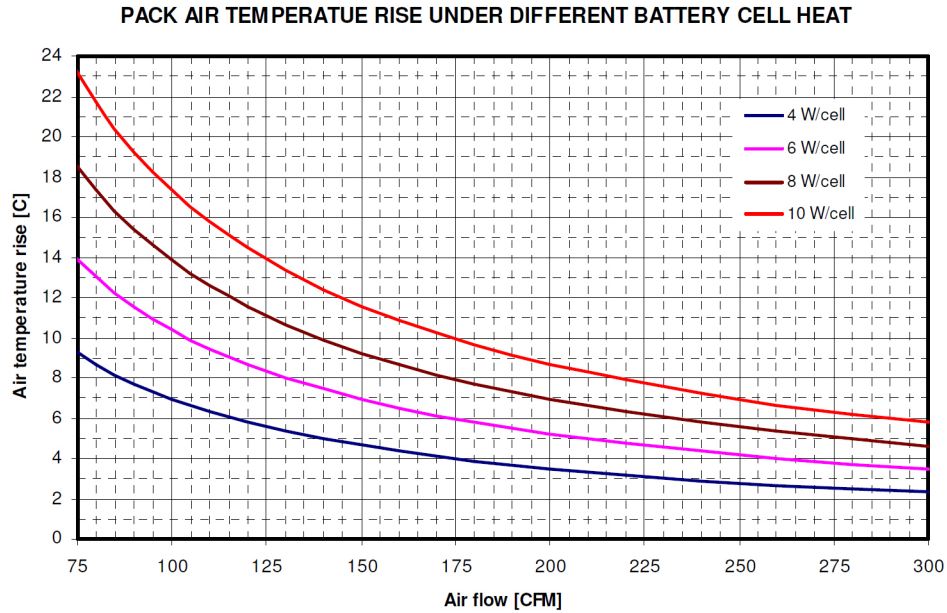


Figure 3. Air temperature rise over a 96-cell pack as functions of air flow and cell heat rejection.

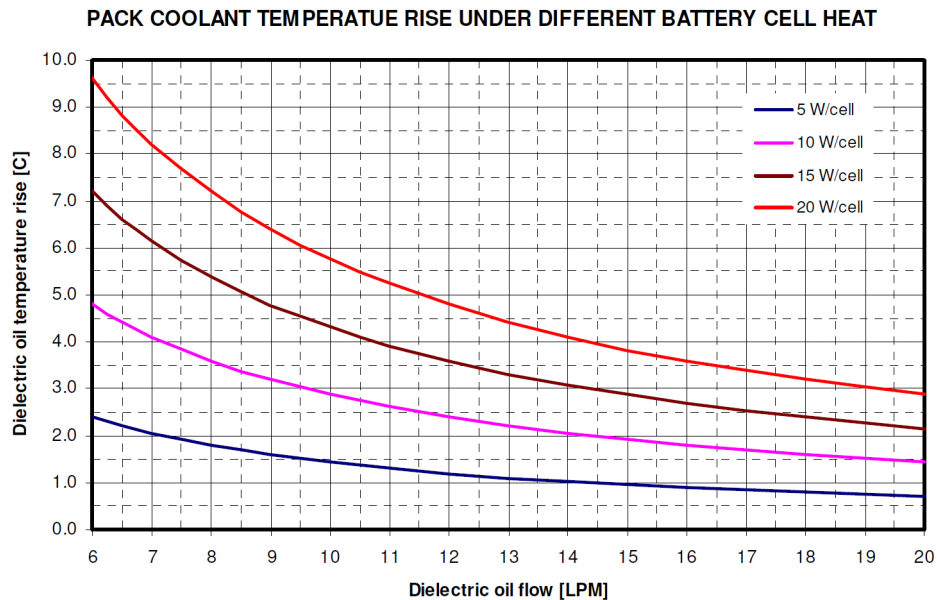


Figure 4. Dielectric oil temperature rises over a 96-cell pack as functions of oil flow and cell heat rejection.

pack failure. A direct liquid-cooling system has two fluid movers (the coolant pump and the radiator fan) thus it has higher power consumption to dissipate the same amount battery heat. The radiator fan generally consumes more power than the air blower because its size is greater than the blower impeller size (note that the fan power is proportional to $n^3 D^5$, where n is the fan speed and D is the fan diameter).

Indirect Cooling Systems

Indirect cooling is used for battery packs that have difficulties with direct cooling. Prismatic and pouch cells can be arranged with minimum gaps between cells in a pack. Thus, they have higher packing efficiency than cylindrical cells. Prismatic cells are generally designed as high energy cells for EV applications, which has the lowest cooling requirement and may be cooled with air directly. Pouch cells are often designed for HEV applications. High-power pouch cells may not be cooled effectively with air directly due to high air temperature rises as a result of narrow cooling channels